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INVESTIGATION OF THE RELATIONSHIP BETWEEN VIBRATION DATA AND TOOL WEAR DURING END-MILLING OF GAMMA-PRIME STRENGTHENED ALLOYS

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ABSTRACT

Condition Based Maintenance (CBM) systems are crucial for today's high accuracy machining of exotic materials. For reliable results, CBM systems need early and reliable warning based on prediction models that use multiple types of sensors. In this study, tool flank wear during end milling difficult-to-machine alloys was measured using an optical microscope. Then, vibration data collected with an accelerometer was investigated for its relationship to tool flank wear. The developed relationship between accelerometer output and tool flank wear was validated with further experiments. It was observed from frequency domain responses of these outputs that specific harmonics of the tool pass frequency were dominant, and tool flank wear can be related to the amplitude of these harmonics during machining. This way, it was shown that through accurate online prediction of tool wear, premature interruption of the process as well as machining with a worn tool can both be avoided, improving end-product quality as well as reducing machining costs.

INTRODUCTION

Tool Condition Monitoring (TCM) techniques and Condition Based Maintenance (CBM) systems are becoming more important in machining in order to achieve lower cost, optimization, reduced time and higher product quality. Effects of different types of sensors and the effect of a fusion of these sensor outputs were studied by several researchers in order to create robust models of tool wear prediction, and ultimately monitoring the total health of the CNC machine [1]. The first step in doing so is to define methods for TCM in order to obtain good quality products. TCM methods are classified into direct and indirect [2]. Indirect methods involve sensors that keep track of one or more parameters of the cutting process and correlates their variance with tool wear (such as acoustic emission, ultrasonic, spindle motor current, vibration, cutting forces, surface roughness). The direct method involves the direct measurement of the wear, which includes the use of optical scanning, electrical resistance, measurement of tool geometry, change in workpiece size, and distance between the workpiece and toolpost [3]. One of the parameters that are commonly used with the indirect method is the vibration output due to several reasons including ease of implementation, its indications on surface quality, dimensional accuracy, and chatter, and the significant change in amplitude between new and worn tools that provides higher efficiency in applications [4].

There are several studies about the effect of tool wear and vibrations signals, both in turning and end milling processes, using steel and aluminum [5] and γ'-strengthened alloys [6]. The tool wear measurement used is Flank Wear (*VB*), which is defined as the loss of tool material from the tool flank during cutting, *i.e.*, the surface of the tool that is parallel to the workpiece [7]. Both time and frequency domain analysis were utilized [8], concluding that frequency domain features correlated well with tool wear, although the amplitude or the frequency of the vibration signal that correlates are not quantified. The main goal of this study was to analyze the relationship between vibration data and tool wear in a view to developing a model to predict tool wear from online outputs.

BACKGROUND & DESIGN OF EXPERIMENT

It is well known and studied [9] that with increased tool wear, tool vibrations and chatter also increase. Analyzing the vibration data in the frequency domain, certain frequencies such as the tooth pass frequency and its higher order harmonics subsequently have different amplitudes, caused by the variation of the vibrations [10]. Tooth pass frequency is defined as the characteristic frequency of the cutter, namely how many times the cutter hits the material in a second. Consequently, in a two flute tool, it is twice the frequency of the spindle speed.

In order to study the evolution of tool wear and distinguish the characteristics relating the vibration data to tool wear, cutting conditions must be held constant and the tool that is being worn must be used until failure. Therefore, standard machinability tests were conducted for difficult-to-machine alloys using consecutive parallel passes with a down milling approach [11]. This setup allows to follow certain characteristics of the milling process, with the use of sensors and due to the dimensions of the material, each pass lasted for a relative short time (<1min.) allowing for multiple set of data (with low computing need) and the ability to check of-line the inserts by direct measuring tool wear (microscope) after each pass.

In this study, three different sets of cutting conditions were used and at each condition, multiple tests were conducted until tool failure. Feed and depth of cut were kept constant and surface speed was varied for consistency in identifying the relationship between tool wear and vibration output. When these correlations are identified, then in future tests, both these parameters (feedrate and depth of cut) will varied in order to explore their quantitative and qualitative significance in the process. Pushing the operational envelope of the tool in a predetermined set of cutting conditions will lead to identifying changes in the amplitude of certain frequencies that are closely related to tool wear, thus allowing to establish a relationship between the two as the tool surface and actual tool is degrading.

EXPERIMENTAL SETUP

The workpiece material used was a γ'-strengthened alloy. The dimensions of the part are specific to the test monitoring methodology established at 80 x 60 x 25 mm. In order to prepare the specimen, a wire EDM was utilized to cut the part to size (dimensions allowed by the fixture), followed by face milling on all sides to ensure size consistency and parallelism. The inserts used were Sandvik Carbide R390-11 T3 08M-PM 1030 fitted to a 2-flute toolholder. The sensors are mounted on the spindle case using epoxy and are connected to CompactRio DAQ, which communicates with the host PC via Ethernet link. The main components of the setup are: The 3-axis CNC vertical milling machine (OKUMA ACE Center MB-46VAE or M460-VE), 6-component dynamometer (KISTLER 9257B), and the cutting tool (Figures 1-4).

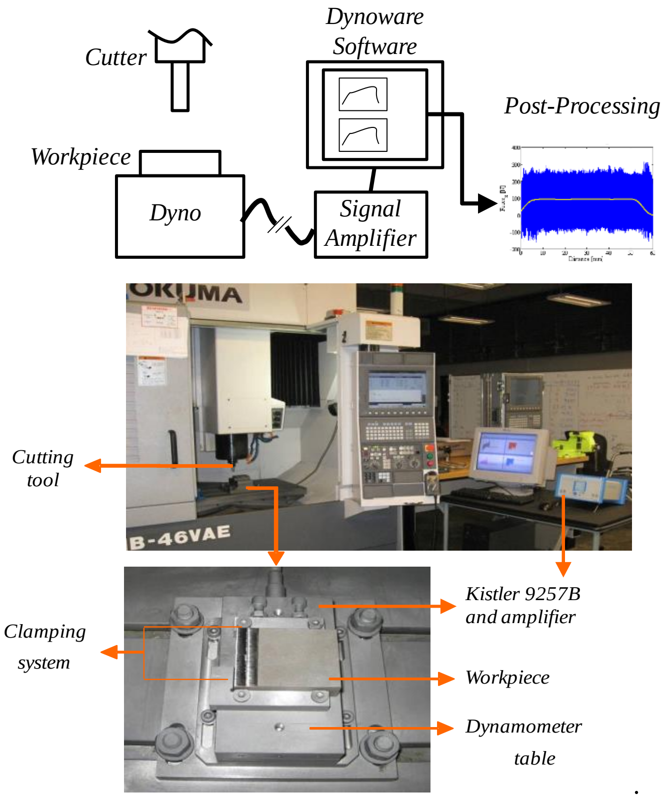

Figure 1: Experimental setup of machine tool, dynamometer, and data acquisition system

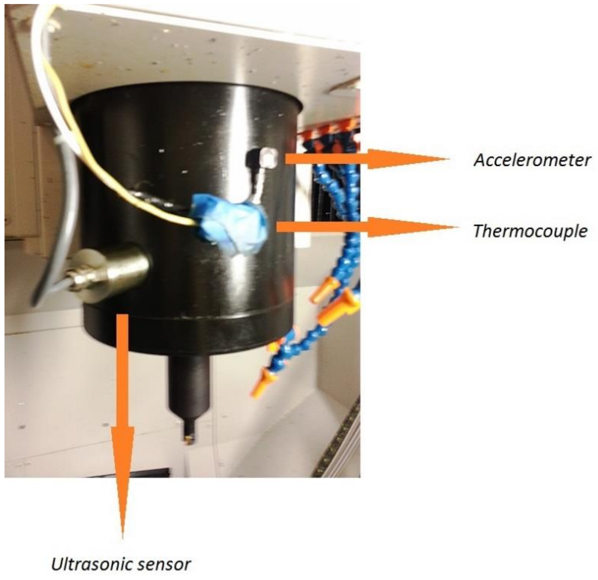

Figure 2: Experimental setup of sensors

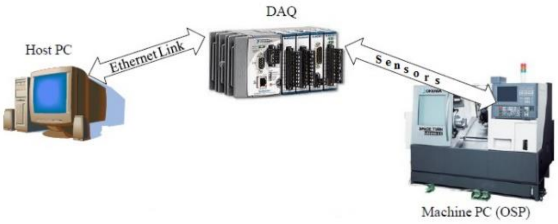

Figure 3: DAQ setup

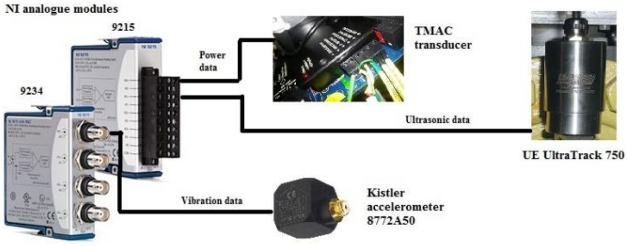

Figure 4: Sensors connectivity with NI modules

Researchers have used accelerometers, placed both on spindle [1] and the workpiece [5] in order to measure vibrations. Both placements have their own merits based on the scope of the study. In this study, the sensors were placed on the spindle, which were an Omega K-type thermocouple, a Kistler Type 8772 A50 Ceramic Shear Accelerometer and a UE systems, UltraTrak 750 ultrasound sensor. Down milling approach was used in these tests (Figure 5) due to its much higher chatter stability [12], and standard machinability test parameters were used for the experiments: 9.5 mm width of cut that corresponds to 60% of the tool engagement where the tool diameter is 15.875 mm. Depth of cut and feed were kept constant at 0.5 mm and 0.1 mm/rev. Cutting speed was varied between 30-50 m/min (Table 1). As it can be observed on Figure 6, the workpiece was machined in passes, where a pass has the specified width of cut (9.5 mm) and utilizes the whole width of the part (60 mm), which corresponds to a 285 mm^3 of material removed. The same inserts were used in the toolholder for an entire test.

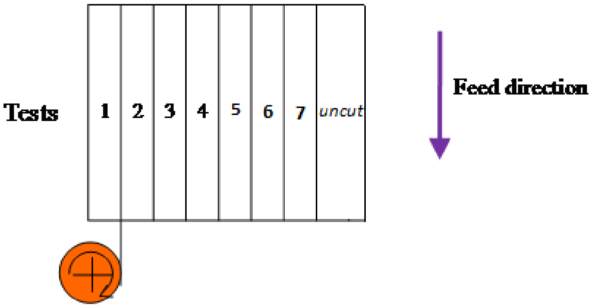

Figure 5: Schematic of test design

Table 1: Cutting parameters

Cutting Speed [m/min]	Feed [mm/rev]	Spindle Speed [rpm]	Depth of Cut [mm]	Tests
50	0.1	1003	0.5	5
30	0.1	602	0.5	2
40	0.1	802	0.5	1

RESULTS & DISCUSSIONS

Thermocouple output showed small variance with a mean temperature of 23.5°C (±0.5°C), even when catastrophic insert failure occurred. Therefore, temperature data were not included in the analysis. In addition, due to a failure of the data cable used to transfer data from the dynamometer to the host computer, force data is missing for some of the tests

The first set of tests was performed using the more aggressive cutting parameters (50 m/min) in order to induce significant tool wear in a relatively smaller amount of time. In some tests, catastrophic failure of the inserts occurred which limited the number of passes that were available for the analysis for that specific test. In most cases, the inserts lasted the full 8 passes. An Olympus SZX12 optical microscope was used to measure *VB*, imaging the flank of the inserts (Figure 6).

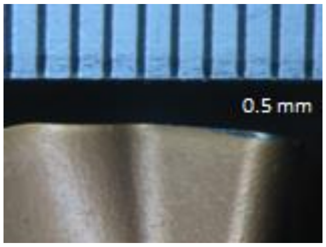

Figure 6: Microscope image of measured *VB*

The tool flank wear (*VB*) was found to be less than 300µm in all tests – the ISO 8688 standard threshold. It was also observed that *VB* was consistent between tests with catastrophic failure in 6 - 8 passes (Figure 7). Catastrophic failure is defined as the rapid deterioration of the tool's cutting surface or erosion severe enough that entire flakes of the tool are ablated [7]. In this graph, up to 1710 mm^3 of removed material (6 passes), the values are the mean of 5 tests whereas the rest are the mean of 2 tests only, because the tool failed at 6 passes at the remaining tests.

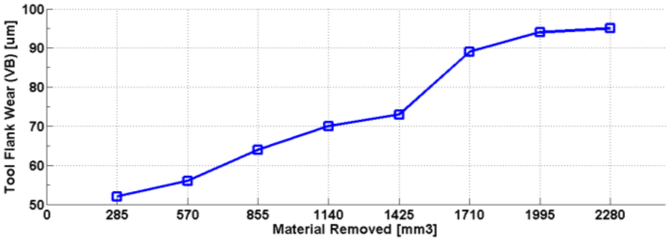

Figure 7: Tool flank wear (*VB*) during 5 tests (50 m/min)

Correlating *VB* measurements with vibration data in the frequency domain through a Fast Fourier Transform (FFT) has led into the discovery of a significant relationship between the two [5]. An interesting phenomenon found in the FFT vibration data was that the higher order harmonics of the tooth pass frequency had greater amplitude than the tooth pass frequency itself [10]. This phenomenon can be explained due to the increased degradation of the tool surface. As the tool wears, higher amplitude short time vibrations occur between the tool and the workpiece. When correlating those data [13], using statistical methods and plotting each “candidate” frequency with tool wear, it was found that under these cutting conditions, the 6th harmonic of the tooth pass frequency (200Hz) was closely correlated (R^2=98%) to tool flank wear. Plotting the tool flank wear against the 6th harmonic amplitude, a pattern similar to a Gaussian Cumulative Distribution Function (CDF) can be identified (Figure 8).

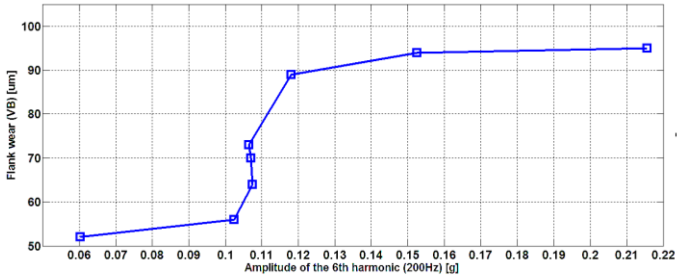

Figure 8: Tool flank wear (*VB*) vs. 6th harmonic amplitude (200Hz) (50 m/min cutting speed)

It was observed that the inserts rapidly wore starting pass 3, but this deterioration stopped after pass 6. This was the first indication that another type of tool wear might have been playing a major part in tool degradation. Since the tool wear rate follows a normal distribution, it was deduced that the tool wear evolution (integral of tool wear rate) can be represented using the CDF of the normal distribution (integral of the probability distribution function). Therefore, a normal CDF was fitted to the experimental data (Figure 9).

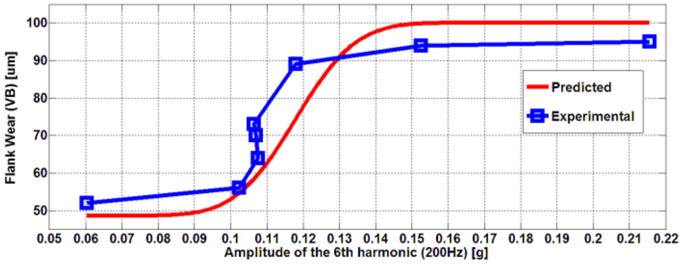

Figure 9: Experimental data vs. fitted normal CDF (evolution of tool flank wear with 6th harmonic amplitude for 50 m/min cutting speed)

The next series of tests were utilized milder cutting parameters, with a surface speed of 30 m/min. Due to these parameters, the inserts could hold more passes before a catastrophic failure, thus producing data up to 10 passes. However, it was found that although tool flank wear was within the ISO limits (300 μm), it was higher than previous tests at the same number of passes (Figure 10), while the machining conditions were milder. A possible explanation might be that the inserts were exposed to the material for a greater time. Furthermore, it was observed that after pass 6, *VB* became stationary and another form of tool wear became more dominant (crater/notch wear - *KT*).

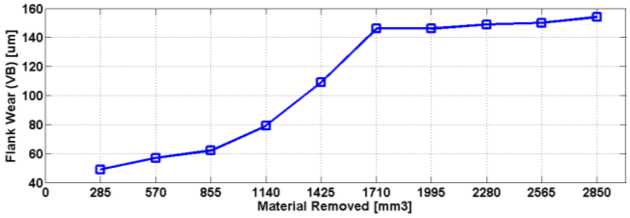

Figure 10: Tool flank wear (*VB*) during 2 tests (30 m/min cutting speed)

Up to these tests, the microscope images acquired were focused on measuring *VB*, thus images dedicated to measuring *KT* are not available. However, pictures taken for measuring *VB* were used to predict *KT*. Since a new measurement could not be done on the already worn inserts, *KT* was approximated using *VB* microscope images and correlating them with actual *KT* microscope images of later tests. This method gave an approximation and it is believed that the data are accurate enough to give an indication, since *VB* measurements in both tests produced similar data. The harmonic of the tooth pass frequency that was most closely related to *VB* (R^2=97%) was found to be the 10th, which in these cutting conditions is 200 Hz (Figure 11). The same Gaussian CDF curve pattern was found to be followed by the inserts with these tests too, indicating again the “switch” between two types of tool wear; *VB* and *KT*.

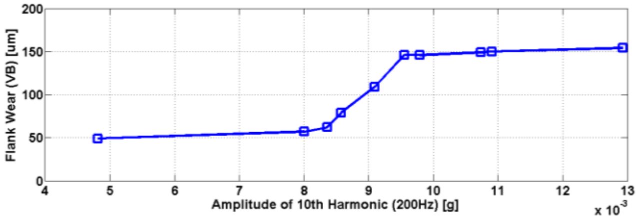

Figure 11: Tool flank wear (*VB*) vs. 10th harmonic (200Hz) (30 m/min cutting speed)

Since the amplitude of the harmonic’s frequency was the same, a third set of tests was performed at 40 m/min surface speed in order to investigate the significance of the 200Hz frequency. Also, in these tests, additional images were acquired for measuring *KT*, in order to validate the switch between *VB* and *KT*. With these cutting conditions, the values of flank wear was found to be between the previous two set of tests (Figure 12).

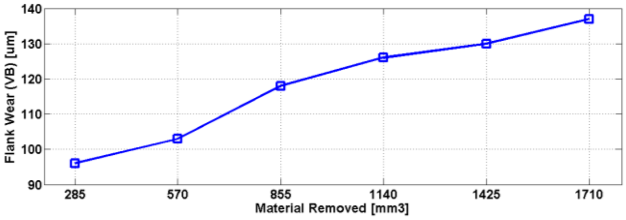

Figure 12: Tool flank wear (*VB*) (40 m/min cutting speed)

In this test, the harmonic of the tooth pass frequency that was most closely related (R^2=97%) to *VB* was found to be the 8th, which in these cutting conditions is 214 Hz (Figure 13).

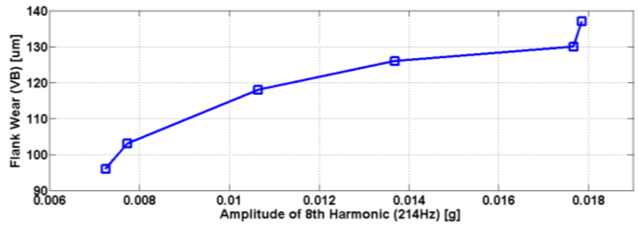

Figure 13: Tool flank wear (*VB*) vs. 8th harmonic (214Hz) (40 m/min cutting speed)

Although the frequency of the harmonic is not at the exact same level (200Hz), but at slight increased one (214Hz), it is suggested that further tests and analysis should be done, due to the fact that the results suggest a correlation between *VB* and this range of frequency. From the last test, it was observed that although *VB* threshold was not reached, *KT* was on the limit (300 μm) after pass 3 (Figure 14). It was also in a state of catastrophic failure, since part of the outside flank surface had been completely eroded.

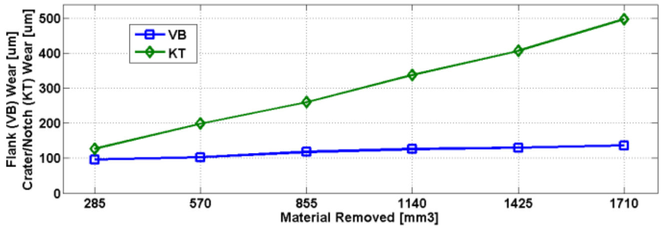

Figure 14: Flank and crater/notch wear (*VB* & *KT*).

Continuing up to pass 6, and collecting data for surface roughness (using Zygo New-View 7200 scanning white light interferometer), it was observed that there was no critical change in the quality of the output (Figure 15). Therefore, one can conclude that the tests can be conducted at more aggressive conditions without compromising much from end-product quality.

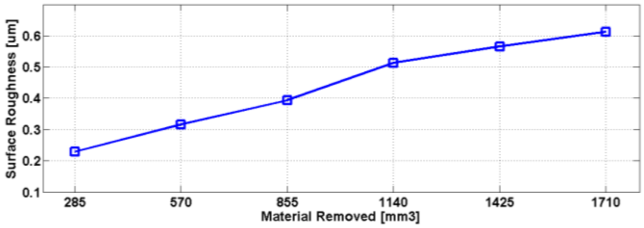

Figure 15: Surface roughness

Revisiting the data from the previous tests and using the microscope images acquired for *VB* measurements, it was possible to approximate *KT* in retrospective. The threshold of 300 μm was achieved after pass 8 in all cases and there is a strong indication that the point to "switch" between *VB* versus *KT* dominance is when *VB* reaches approximately 150 μm (Figure 16).

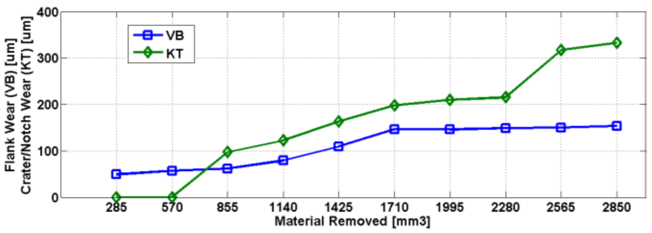

Figure 16: *VB* and *KT* plotted against material removed

This was observed in all three sets of tests, and it was found to be unrelated to the total amount of material removed, material removed up to the "switch" point, or whether catastrophic failure is experienced. A plausible explanation of this phenomenon can be based in the mechanics of tool wear, due to the idiosyncrasies of the challenges in machining these difficult-to-machine alloys compared to conventional materials. It can be hypothesized that when the initial coat of the insert is eroded, the heat on tool rake face accumulates and rapidly increases *KT* wear, whereas *VB* remains almost constant.

CONCLUSIONS & FUTURE WORK

This work deals with the relationship between the vibration output and tool wear during end-milling of γ'-strengthened alloys, and a preliminary analysis toward using this relationship for online tool wear prediction. Following a series of tests at different cutting conditions the following conclusions are drawn:

- Vibration data are giving a robust indication of tool flank wear, when the frequency domain response is analyzed.
- The high order harmonic of the tooth pass frequency in the neighborhood of 200 Hz gives the highest correlation to tool flank wear (*VB*).
- There is a "switch" in the dominant tool wear mode from flank wear (*VB*) to crater/notch wear (*KT*) when *VB* reaches approximately 150 μm.
- The quality of the output product remains acceptable even when the tool wear threshold (300 μm) is violated in either flank (*VB*) or crater/notch (*KT*) wear modes.

The results of this study can be used as a preliminary indication that through vibration measurements with an accelerometer, tool wear can be monitored. However, several gaps in understanding such a relationship and predicting tool wear are yet to be filled:

- The quantitative relationship between the amplitude of a specific harmonic to measured tool wear,
- A robust procedure for finding the most closely correlated harmonic to tool wear,
- A linear relationship between harmonics and tool wear to be used in industrial applications, and
- A detailed model that predicts tool wear based on the amplitude of the harmonics.

Some preliminary work has been done on the mathematical model, using a normal CDF, though more tests and data are needed for validation and optimization of the coefficients used.

Future work also includes the investigation of different type of sensors (ultrasonic, force, and power), and the fusion of all sensor data in order to make the model more robust.

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