G Model
CIRP-1798; No. of Pages 4

ARTICLE IN PRESS

CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

A novel approach for real-time prediction and prevention of tool chipping in intermittent turning machining

M. Hassan [a], A. Sadek [b], A. Damir [b], M.H. Attia (1)[a,b,*], V. Thomson [a]

[a] *Department of Mechanical Engineering, McGill University, Montreal, QC, Canada*
[b] *Aerospace Manufacturing, National Research Council Canada, Montreal, QC, Canada*

ARTICLE INFO

Keywords:
Cutting
Condition monitoring
Prefailure prediction

ABSTRACT

An integrated tool condition monitoring system, based on a novel signal processing approach, for online prediction and prevention of tool chipping in intermittent turning is presented. It identifies the unstable crack propagation features of the prefailure phase, independent of the cutting parameters and workpiece material. A correlation between the chipping size and these features was developed for decision making, to protect machined surfaces. Experimental validation results confirmed the accuracy of the proposed system. The time required for signal processing, decision making and communication with the machine controller allows stopping the operation before part damage. No such system is presently available.

1. Introduction

In intermittent cutting, the periodic mechanical and thermal loading on the tool cutting edge can generate unstable crack propagation, leading to chipping, when the stresses exceed critical values. This stage is defined as the tool prefailure phase [1]. Chipping affects the produced part's surface integrity and geometrical accuracy, and can result in part rejection. Tool condition monitoring (TCM) systems has successfully predicted the tool life deterioration and captured tool fracture in real-time applications of different machining operations using indirect measurements, such as the cutting forces, vibrations and/or acoustic emissions (AE) signals [2–4]. However, *sudden* tool fracture is currently captured only after its occurrence, which does not allow us to act and prevent part damage. Hence, it is crucial to detect tool prefailure and take corrective actions before chipping.

AE waves associated with the generation of new surfaces during unstable crack propagation, have high potential to be used as a tool prefailure indicator. In intermittent cutting processes, however, identifying these waves is challenging due to the bursts coming from other process sources; e.g., impacts at inlet and exit, chip formations, rubbing between the tool and workpiece, and the plastic deformation [5]. The objective of this work is to present an integrated TCM system based on a novel signal processing approach to reliably detect the tool prefailure and to stop the intermittent turning operation, in real-time, before tool chipping and part damage. No such system is presently available.

* Corresponding author at: Aerospace Manufacturing Technologies Centre, National Research Council Canada, Montreal, QC, Canada.
E-mail address: helmi.attia@nrc.ca (M.H. Attia).

https://doi.org/10.1016/j.cirp.2018.04.065
0007-8506/

2. AE signal characteristics in the prefailure phase

The signal processing approach developed in this research for tool chipping prediction needs to consider the complex features of the AE signal. The model developed in Ref. [6] is considered in order to understand the AE signal response to the fracture of carbide inserts in intermittent cutting. Such model describes the AE root mean square peak voltage (AE_{rms}) as a function of the change in the crack area 'ΔA' and the resultant cutting forces 'F':

$$AErms \approx CF(\Delta \text{[illegible]})\Delta.\Pi \tag{1}$$

where C is a material and geometry dependent constant. The main challenges of detecting the unstable crack propagation phase, preceding tool chipping, using the AE_{rms} raw signal are: (i) the nonlinear relationship between the AE_{rms} response and the change in the crack area 'ΔA', as shown in Eq. (1), (ii) the non-stationary nature of the stochastic unstable crack propagation process, which induces high frequency/amplitude bursts in the AE_{rms} signals, (iii) the contamination of the crack propagation bursts in the AE_{rms} signal by the bursts coming from the force variation in intermittent cutting, and (iv) the infinitesimal time spans of the high frequency bursts inherent in unstable crack propagation. This leaves a relatively short time (on millisecond-scale) for taking corrective actions after detection. As the AE_{rms} raw signal is *insufficient*, by itself, to be an indicator for tool prefailure detection, a special signal processing approach is required to accentuate the high frequency/amplitude events in the signal to ensure a reliable and robust tool prefailure indicator.

3. AE signal processing for real-time prefailure detection

This work proposes a two-stage novel approach that can deal with the aforementioned challenges of using the AE_{rms} raw signal for tool prefailure detection. In the first stage, the Hilbert–Huang

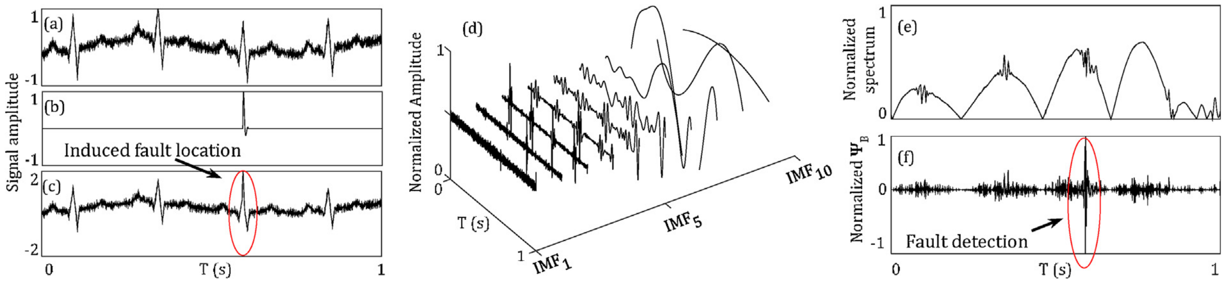

Fig. 1. (a, b and c) Simulated signal (d) normalized IMFs (e) normalized HHT spectrum (f) normalized Bartlett-TKEO-HHT Ψ_B.

Transform (HHT) method [7] is used to overcome challenges (i) and (ii) by representing the AE_{rms} in the time–frequency domain. In the second stage, the Teager–Kaiser Energy Operator (TKEO) [8] is applied to highlight the prefailure phase and to suppress the bursts coming from the force variation and signal noise in the cutting process; overcoming challenge (iii). To demonstrate the performance of this approach, Fig. 1(a) shows an ideal nonlinear periodic signal. An artificial fault signal has been added to the original signal, as seen in Fig. 1(b) and (c). This sinusoidal decaying signal represents the AE_{rms} generated by the non-stationary crack propagation process. In the HHT method, the signal is first decomposed into superposition natural modes termed the 'intrinsic mode functions' (IMF), using the 'mode decomposition' method [7], as seen in Fig. 1(d). This is a direct and adaptive method with a posteriori-defined basis, to define the linear and nonlinear harmonics of the processed signal. Each mode represents a frequency range, varying from signal noise, e.g. IMF_1, to the main signal trend, e.g. IMF_{10}. The instantaneous frequency is calculated for each IMF, in the time domain, using HHT to identify the intra-frequencies of the prefailure phase. The HHT spectrum, generated by the summation of the IMFs' transforms, is a function of the IMFs instantaneous amplitude, frequency and the phase between them. Hence, a peak in the Hilbert spectrum represents the *abnormal events* in the time domain, shown in Fig. 1(e). To emphasize the relatively high frequency/amplitude events of the crack propagation and to suppress the effect of the impact cutting forces on the AE_{rms}, the TKEO is applied, as shown in Fig. 1(f). Its output is the vector (Ψ) which is proportional to the product of the instantaneous amplitude and frequency of the input signal. Hence, physical events with relatively high frequency and high amplitude will be accentuated, while events with relatively high energy only or high frequency only will be depressed. Combined with its low computational time, the TKEO is therefore ideal for online applications [8]. Finally, a Bartlett window function is applied to the TKEO output to localize the local maxima by calculating (Ψ_B), which is proportional to the square of the product of the instantaneous amplitude and frequency of the input signal [8].

For real-time implementation of the proposed signal processing approach, challenge (iv), stated earlier, needs to be addressed. The processing time is affected by the signal segment length and sampling rate. Small windows may cause losing some information in the prefailure phase. Hence, to select a representative segment for the repetitive load on the cutting tool, a full workpiece rotation window was used. To ensure no loss of information related to the relative changes in the instantaneous amplitude and frequency of the processed signal interval, a 50% segments overlapping is implemented. This assures that the beginning and ending of the prefailure phase is captured and compared to steady state cutting. Additionally, The AE_{rms} was calculated from the analogue raw AE signal, before digitalization, in order to not lose signal contents, while minimizing the required sampling rate and data storage. AE raw analogue signals were filtered using a narrow band from 100 kHz to 900 kHz to isolate the high frequency sound emission signals and to improve the signal-to-noise ratio. Moreover, signal de-trending was applied to remove the signal gradual change due to tool path. The maximum peak value of the processed signal for each window (Ψ_{BW}) was used as a prefailure detection parameter.

4. Experimental setup and tests

This work mainly focuses on cracks due to mechanical loads only while avoiding the occurrence of tool wear and build-up edges. Therefore, a method was devised to induce cyclic impact load on the cutting tool tip in an intermittent turning operation, as shown in Fig. 2. Dry turning operations were carried out using carbide inserts (1) on a 6-axis Boehringer-NG200 CNC turning centre. This machine tool has a maximum spindle power and rotational speed of 36 kW and 4000 rpm, respectively. The experiments were designed to validate the independence of the proposed approach of the cutting parameters and workpiece material. The insert types, workpiece material, and cutting conditions are given in Table 1. Inserts 1 and 2 have the same geometry, coating (CVD TiCN/Al_2O_3/TiN), and nose diameter of 0.4 mm but different suppliers, whereas insert 3 has a PVD (Ti, Al) N/TiN coating and a 0.8 mm nose diameter. Insert 4 is rotary uncoated with a diameter of 10 mm. To reduce the thermal effect on the tool tip, workpieces plate thickness to width ratio was selected to reduce the cutting time and allow an air cooling of 85% of the cutting revolution. Additionally, workpieces (2) were shaped as shown in Fig. 2 to minimize the inlet transient stage. Three different types of steel and aluminum materials were used. The plate fixture seat (3) were designed to guarantee the workpiece balance during cutting. A FASTCAM high speed camera HSC type UX100-800K-M has been used to record the chipping events in real-time during cutting. The imaging of this HSC was used to measure the chipping size on the rake face. The chipping area of the new generated surface was calculated as the product of the chipping size and depth, as shown in the inset in Fig. 2. The cutting forces were measured using a three component KISTLER dynamometer type 9121 (5) and amplified using a KISTLER 5010 amplifier. A tri-axial ICP accelerometer model 356A71 (6) and a KISTLER Piezotron AE sensor type 8152C (7) were used to capture the process vibration and AE signals, respectively. Both sensors were mounted on the tool shank. KISTLER AE coupler model 5125C1 was used to calculate the AE_{rms}. Acquired signals were digitalized and stored using a National Instrument data acquisition system. The time of onset of chipping captured by the HSC imaging and the cutting force and vibration signals were compared to Ψ_B peak location.

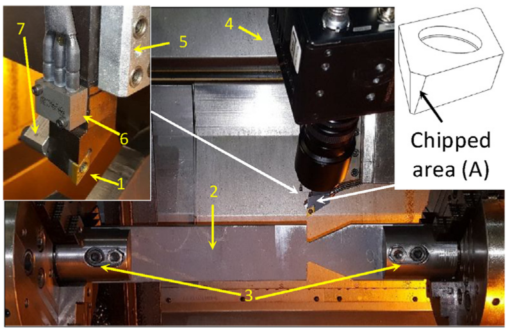

Fig. 2. Experimental setup for intermittent turning.

Please cite this article in press as: Hassan M, et al. A novel approach for real-time prediction and prevention of tool chipping in intermittent turning machining. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.065