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Automated wear characterization for broaching tools based on machine vision systems

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ABSTRACT

Monitoring tool wear is essential to ensure consistently high quality of machined products. In the past, tool wear has been well characterized in common machining processes such as turning or milling. However, for cutting complex profiles, such as linear broaching, the only method reported for quantifying tool wear has been manual characterization of flank wear. This leads to significant information loss and large measurement variability. In response to these limitations, this paper presents a new measurement system that quantifies broaching tool wear based on the overall wear area. The proposed method uses automated image cropping and digital imaging processing tools to determine the affected area without requiring any manual intervention. A measurement system analysis has been performed on a hexagonal linear broach to determine the variance introduced by the measuring procedures and the image processing analysis. After implementing this measurement system, tool wear characterization for broaching tools becomes more precise, facilitating cross-industry collaboration, making operator training less intensive, and improving quality control practices.

1. Introduction

Linear broaching is a metal cutting process that gradually removes material by pushing or pulling a multi-toothed broaching tool through a work piece. Due to its carefully designed progression from rough-cutting to finish-cutting along the broach's entire length, broaching can achieve intricate contours with precise geometry and outstanding surface finish. Currently, broaching is the most commonly used process in complicated contour machining of high-strength and heat-resistant super-alloys (e.g., titanium and nickel alloys).

The quality of the final products in a broaching process is highly dependent on the condition of the broach. Tool wear is an unpreventable and irreversible process that can lead to nonconforming geometry, poor surface finish, and even catastrophic failures like tool breakage. This results in costly downtime and damaged components [1]. Thus, developing a tool condition monitoring (TCM) system is quite useful for proactive condition-based maintenance scheduling. There has been extensive research on TCM in broaching based on indirect monitoring of online process data such as cutting force, acoustic emission, vibration, and hydraulic pressure [2]. However, few attempts have been made to directly measure the tool wear on a broach. For many manufacturers, however, the wear condition of broaches is examined based merely on expert opinion by classifying the wear conditions into multiple levels or stages. For example, based on the technician's experience, the wear condition can be classified as low, medium, and high levels. However, tool wear is a continuously accumulative process which is responsible for cutting performance degradation. The qualitative nature of current industry methods results in huge information loss and heavily relies on operators' process knowledge and experience, which could lead to high variability between tool inspectors.

In recent years, flank wear has been recommended as the sole descriptor of wear for a broaching tool. Flank wear is defined as the maximum width of the wear land on the relief face of the cutting edge. Mo et al. [3] used scanning electron microscopy and chemical composition analysis to measure flank wear; Shi and Gindy [4] used flank wear as the benchmark of a linear broach's wear in the development of an on-line indirect tool wear predictive model. However, due to the irregular shape of almost all wear lands, the maximum width of the wear land provides very limited information of the tool condition, and therefore, geometric descriptors should be used to provide more detailed tool condition assessment.

Tool wear quantification methods based on machine vision systems have been extensively explored in other machining processes. Jurkovic et al. [5] developed a tool wear measurement technique for turning using a flexible and accurate charge coupled device vision system by evaluating their proposed parameters. In their study,

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a repeatability analysis was performed to evaluate the absolute value of the variance introduced by the measurement system, but their analysis did not consider various levels of wear and variability introduced by different operators. Barreiro et al. [6] used moment-based features to classify turning insert wear images, and suggested that the Hu and Legendre descriptors are most successful. Similarly, Castejon et al. [7] used linear discriminant analysis to discover that three of nine selected tool wear descriptors—eccentricity, extent, and solidity—provided 98.63% of the information necessary for proper wear classification. Kurada and Bradley [8] reviewed machine vision sensors for TCM in grinding, milling, and turning, and made recommendations for future research which included the use of texturing and local gray thresholds. In the same year they also explored the use of textural and gradient operators to determine flank wear land in CNC turning operations [9].

Research also shows that digital image processing (DIP) methods are effective for processing images obtained from machine vision system for various tool types, especially turning and milling tools. Kurada and Bradley [8] recommends the use of texturing and local gray thresholds, and the use of textural and gradient operators to determine flank wear land in CNC turning operations. The study of Kerr et al. [10] on the use of DIP for on-line TCM showed that this method is effective for assessing turning insert wear. Its indication of good relationships between image texture measures and wear characteristics is promising for the application of DIP monitoring methods to broaching. However, all the analysis reported in their paper are based on the Region of Interests (ROIs) manually cropped from the original image. Though this procedure might be trivial for single-point cutters like turning inserts, it will be really time-consuming for multi-toothed cutting tools like broaches which may have tens or even hundreds of cutting points per tool. Dutta et al. [11] discuss fourteen advantages of using DIP in TCM has over conventional monitoring methods, including that this methods are non-intrusive, flexible, required inexpensive implementation, and can be supported remotely. They also bring attention to lighting as being the most critical factor of DIP measurement. In their review of 30 direct and 47 indirect TCM DIP techniques, no application of DIP to broaching tools can be found. They conclude their research with ten important observations to which researchers in the field must give attention.

Extensive research has been conducted for the tool wear characterization system development and image processing for turning, milling, and drilling processes. However, there is very limited research performed for tool wear quantifications in broaching process, even though final part quality highly depends on the tool condition in broaching processes. Developing a reliable tool wear quantification system can help to reduce quality cost due to poor tool condition, perform cost effective condition-based maintenance scheduling, and avoid downtime due to catastrophic accidents during the machining operations.

From the literature review, it can be seen that current tool wear characterization tools are not effective to quantify tool wear for broaches. Therefore, the objective of this paper is to develop a reliable and automatic wear characterization system that can be used to characterize the condition of broaching tools without requiring an expert's knowledge. The developed system is designed to integrate image acquisition and image processing methods. A measurement system analysis was performed to quantify the repeatability and reproducibility of the system based on the tool wear for a hexagonal broach. This analysis considered different levels of tool wear and different operators. It should be noted that this system is designed to quantify tool wear on all kinds of broaches for which texture left by relief operations during broach production is not parallel with the cutting direction of broaching. This property applies to a large variety of manufactured broach bars. A couple of examples are shown in Fig. 1.

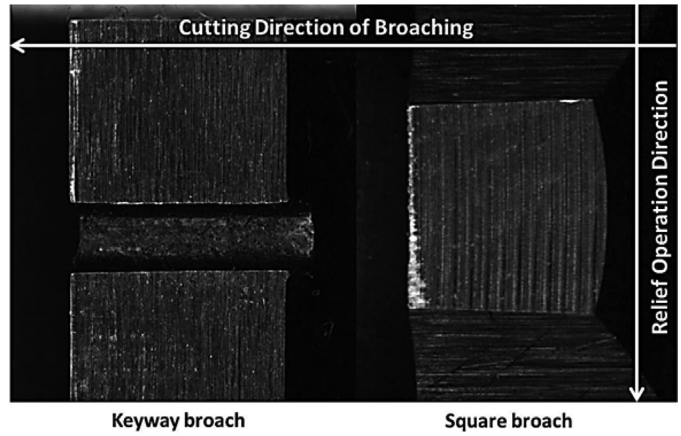

Fig. 1. Directions of cutting in broaching and relief operations.

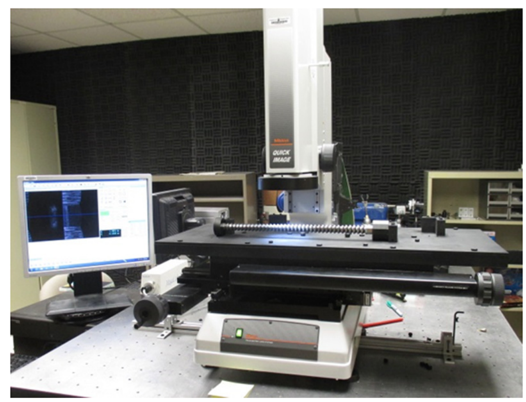

Fig. 2. Mitutoyo Quick Image microscope, broach fixture, and accompanying computer.

2. Setup and procedures

In this section, the experimental setup of the proposed broach wear characterization system is introduced. In addition, the operational procedures for the system implementation are proposed. The procedures include both image acquisition and image processing steps.

2.1. Experimental setup

The proposed system records image data via a Mitutoyo QI-B3017B Quick Image Telecentric Lens System digital microscope (Fig. 2), which has the following properties for wear quantification:

- Large field of view (12.8×9.6 mm) and high resolution (1280×960) images—therefore, it can contain the cutting edge in one single image while include highly detailed information in the images;
- Fine scales (0.001 mm) in positioning stage that makes the positioning of the part highly repeatable;
- Good measuring repeatability $(5 + 0.8L)$ µm, where L represents the measuring length (in mm) that makes it possible to obtain highly repeatable measurements of the same dimension assuming the positioning and operations are identical;
- LED ring light is switchable by quadrant to enhance contrast of different texture directions (Fig. 3).

The analysis used in this paper was done operating a hexagonal broach, made of High Speed Steel, size 0.75″ with 38 teeth and