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On-line tool wear measurement for ball-end milling cutter based on machine vision

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A B S T R A C T

Cutting tool wear is known to affect tool life, surface quality and production time. In this paper, a new on-line tool wear measuring algorithm is proposed to acquire tool wear using machine vision in order to establish on-line tool wear monitoring model for assessing degree of wear and remaining useful tool life. The algorithm first adopts machine vision to acquire tool wear images from CCD camera on-line for ball-end cutter. Tool tip points are determined and wear detection areas are optimized within captured tool wear images. Tool wear images before machining and in machining process are captured to compare the corresponding image column for judging whether this image column has emerged wear. Then the initial detection of wear edge points with pixel accuracy is given to scan pixel columns within the constructed wear detection areas in vertical direction. The exact detection algorithm of wear edge points with sub-pixel accuracy is proposed to increase the precision of detected wear edge points. The tool wear can be computed based on the detected wear edge points. Experimental work and validation of the established on-line tool wear measurement method are performed in a five-axis milling center by using stainless steel 1Cr18Ni9Ti and ball-end cutter of cemented carbide. The obtained measurement results by using the proposed method are compared with those gotten by measuring directly with microscope. The proposed method is shown to be reliable and effective for on-line tool wear measurement.

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1. Introduction

Milling is one of the main operations in the manufacturing process. According to Malekian et al. [1], cutting tool failures (wear and breakage) typically represent about 20% of the downtime of a machine tool, and tool wear is found to have a direct impact on the quality of surface finish, dimensional precision and ultimately cost of the finished product, and the cost of cutting tools and their replacement accounts for between 3% and 12% of total production costs. Therefore, the detection of tool failures is essential to improve manufacturing quality and to increase productivity. Consequently, real time tool wear estimation in machining processes is also an important task in automated manufacturing. In order to improve the quality of machined parts, reduce production time and machining costs, tool condition monitoring systems have been extensively studied by researchers since the late 1980s as stated by Shao et al. [2]. At present tool wear measurement studies carried out so far provide interesting information about tool condition during the machining operation. Generally, tool wear monitoring technology can be classified into two main categories: indirect methods and direct methods.

Some researchers directed their research to find an efficient and effective tool condition monitoring method, mainly focusing on indirect methods for estimating tool wear. These indirect methods are on-line and use machining process signals, such as cutting forces, current and power for various drives, vibration and acoustic emission, which are known to be significantly affected by tool wear. Indirect methods correlate or match appropriate sensor signals to tool wear states. The advantages are little complicated setup and great suitability to practical application. In indirect methods, tool condition is not captured directly, but estimated from the measurable signal feature. This signal feature is extracted through signal processing steps to obtain a sensitive and accurate representation of tool wear state. Rehorn et al. [3] found that cutting force is generally considered one of the most significant variables in the turning process. It has been widely recognized that variation in the cutting force can be correlated to tool wear, as a result of the variations produced by friction between cutting tool flank and workpiece [4]. Bhattacharyya et al. [5] proposed real-time estimation of tool wear in face milling by using combinations of signal processing techniques, in which signals is from cutting force signals. Sensor fusion at feature level is used in search of an improved and robust tool wear model in their studies. According to Li et al. [6], tool dynamometers are commonly used to record cutting forces. However, Dimla [7] have recently shown that dynamometers are not suitable instruments for shop floor use due

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to their high cost, negative impact on machining system rigidity, geometric limitations and lack of overload protection. Scheffer and Heyns [8] adopted simultaneous vibration and strain measurements on wear monitoring system. In their works data from the manufacturing process was recorded with two piezoelectric strain sensors and an accelerometer, each coupled to a DSPT Siglab analyser. A large number of features indicative of tool wear were automatically extracted from different parts of the original signals. Chen and Li [9] attempts to develop a tool wear observer model for flank wear monitoring in machining nickel-based alloys. The model can be implemented in on-line tool wear monitoring system which predicts the actual state of tool wear in real time by measuring the cutting force variations. Lim [10] found that at various cutting speeds, the vibration amplitudes consistently produce two peaks throughout the life of the tool. Thus a strong correlation between the tool flank wear and the acceleration amplitude of vibration is established to indicate the onset of tool failure. AE-based tool wear monitoring in turning is an important method for improving and developing new tool wear monitoring methodology [6].

Indirect methods can monitor the tool condition in real time, but it is connected with cutting parameters and complicated to deal with. In these methods, the signals come from the machining points or fields, such as vibration, sound, AE, cutting force, temperature, etc. The detected signal changing characteristics with tool wear process will be compared with those of the wear-free tool to access the tool wear states. The relations between tool wear development and the characteristic parameters must be prepared preliminarily in different cutting conditions and need hardware monitoring equipment. Evidently, these problematic situations would make these methods difficult and is not very convenient for tool wear estimation. The precision achieved with indirect measurements is not as good as that achieved with direct methods, since the measurement is affected by noise signals.

In the other hand, surface roughness and high quality of workpiece is mainly related to the cutting tool wear state. In this context Vacharanukul and Mekid [11] presented and reviewed various contact and non-contact techniques of in-process and in situ dimensional inspection sensors for quality control of machined parts, where the efficiency of each technique has been evaluated. They have shown that the optical methods are more reliable than the others; consequently, they can be used to monitor tool wear.

Direct methods such as visual inspection, measurements of volumetric changes and those based on surface textures are used for wear estimation, in order to have an effective and reliable tool wear monitoring system. In the last decades, researchers have been conducting research on tool condition monitoring (TCM) using image processing techniques as a direct means in flank and crater wear measurement. Pfeifer and Wiegers [12] have shown that the advances in machine vision and image processing technology have led to the development of various vision sensors which is used to obtain information about the cutting tool and machined part. It has been demonstrated that image processing techniques can be effective in measuring wear, particularly in those regions where other method do not allow it. While, tool wear monitoring based on machine vision is a direct technology with advantages of totally independent from the machining parameters and high adaptability [1]. Wang et al. [13,14] proposed a system based on successive image analysis for periodic measurement of flank wear in milling, and described an image processing procedure to detect and measure tool flank wear area. Su et al. [15] used machine vision to develop an automated flank wear measurement scheme using vision system for a microdrill. Castejon et al. [16] proposed a method based on a computer vision and statistical learning system to estimate the wear level in cutting inserts in order to identify the time for its replacement. Jurkovic et al. [17] suggested a reliable direct measuring procedure for measuring different tool wear parameters. Kim et al. [18] gave a reliable technique for reduction of error components by developing a system using a CCD camera and an exclusive jig to be able to precisely measure the size of tool wear in a direct manner. Devillez et al. [19] used white light interferometry for measurement of wear craters on cutting tool inserts. Prasad and Ramamoorthy [20] proposed a new technique for the measurement and visualization of tool wear in three dimensions. Kurada and Bradley[21] have established a simple and inexpensive vision system to monitor flank wear during CNC turning using the implementation of texture-based segmentation. Nowak and Wiklund [22] have proposed a new approach to improve the reliability of on-line prediction of tool life without the need of pre-process data using applied multisensing which is based on the cutting force ratio correlated with in-process measurement of the flank wear by a vision system. The acquired process data are evaluated and handled by means of the modified and combined statistical methods. Although a lot of researches have been done on the tool wear monitoring based on machine vision and great progress has been made, there are some issues need to be studied further about convenience, adaptability and robustness for on-line tool wear monitoring, especially in end milling process. In the respect, this paper suggests a novel technique for the measurement of tool wear in end milling process.

In this paper, a new approach to acquire tool wear on-line is proposed based on machine vision for establishing tool wear model during milling operation. In this method, tool wear images of ball-end cutter are captured by using the established tool wear on-line measurement system. For ball-end cutter, the paper gives a new tool wear measuring mode, which has more flexibility. The tool tip points are determined and wear detection areas are optimized for the captured tool wear images by using the proposed tool wear measuring mode. Then the initial detection of wear edge points with pixel accuracy is given to scan pixel columns within the constructed critical area in vertical direction. The exact detection algorithm of wear edge points with sub-pixel accuracy is proposed to increase the precision of detected wear edge points. The tool wear of ball-end cutter can be computed based on the detected wear edge points. Experimental work and validation of the established tool wear on-line measurement method are performed in a five-axis milling center by using stainless steel 1Cr18Ni9Ti as machining material and cemented carbide ball end milling cutter. An attempt was made to validate the proposed tool wear on-line measurement method based on machine vision by comparing the detected tool wear values with the measuring value of microscope. The proposed on-line tool wear measurement method provides a new way for modeling, simulation and prediction of tool wear and does not require the change of the machine tool. At the same time experimental results show that the proposed on-line tool wear measurement method by using sub-pixel detection has more precision than hand-measurement precision of microscope.

The paper is organized as follows. First foundation of on-line tool wear measurement based on machine vision is given in Section 2. In Section 2, tool wear mechanism, the principle of tool wear measurement, tool wear image capturing and analyzing is described for ball-end cutter. Section 3 presents an on-line tool wear measurement algorithm. In Section 3, the details of selection of tool wear measuring mode, determination of tool tip point, optimization of wear detection area, the initial detection of wear edge points with pixel accuracy, the exact detection of wear edge points with sub-pixel accuracy and extraction of tool wear based on wear edge points are given. Section 4 is experimental verification including experimental setup, experimental process, experimental results, and discussion. Conclusions are given in Section 5.

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