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Progressive tool flank wear monitoring by applying discrete wavelet transform on turned surface images

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ABSTRACT

In this paper, a method for on-machine tool progressive monitoring of tool flank wear by processing the turned surface images in micro-scale has been proposed. Micro-scale analysis of turned surface has been performed by using discrete wavelet transform. A novel methodology for proper selection of mother wavelets and its decomposition level dependent on the feed rate parameter has also been shown in this research. The selected mother wavelets are utilized to decompose the turned surface images at the chosen decomposition level and two features, namely, G_{RMS} and *Energy* are extracted as the highly repeatable descriptors of tool flank wear. An exponential correlation of G_{RMS} and *Energy* values with progressive tool flank wear are found with average coefficient of determination values as 0.953 and 0.957, respectively.

1. Introduction

Tool condition monitoring (TCM) is inevitable in unmanned machining to reduce machine tool downtime, to maintain the desired dimensionality, surface finish and overall product quality with less cost by monitoring mainly the cutting tool flank wear ($VB_{average}$) in conventional machining (viz. turning, milling, and drilling). Bhuiyan and Choudhury [1] reviewed various TCM systems which consist of signal acquisition phase through intelligent sensors, signal processing phase to extract useful features as $VB_{average}$ descriptors and decision making phase to predict $VB_{average}$ based on extracted features. Visual measurement of $VB_{average}$ by using optical microscope or camera is performed in direct TCM. But, the inaccessibility of tool flank region is the main drawback to use direct TCM in industrial environment. In indirect TCM, signals of cutting force, power, current, sound energy, vibration, surface finish, temperature, are analyzed to monitor $VB_{average}$. Force signals acquired using piezoelectric dynamometers are commonly used for indirect TCM. However, according to Dutta et al. [2], the high cost, intrusive nature, poor overload protection capability in collision, sensitivity to small frequency band are main drawbacks of force sensors. According to Ertekin et al. [3], vibration signals acquired by accelerometers are dependent on the location of the sensors from the cutting area. However, the vibration signals are also affected from inaccuracy of signal features, chance of damage of sensors, specific range of cutting speed. AE sensors are disadvantageous for progressive monitoring of tool wear due to difficulty in positioning, complex calibration and sensitiveness to noise of machining. Power sensors are more sensitive to machine tool condition than the condition of cutting tool. Though the current sensors are low-cost but non-linearity, complex calibration, limited frequency range and inaccuracies are the main obstacles for their practical utilization in TCM. Temperature sensors are dealt only

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with the average temperature around the cutting tool which affects the accuracy of TCM. On the other hand, in any machining process, ultimate goal is to obtain a good surface finish. Thus, measurement of machined surface topography can solve this purpose. Surface profiler is used to measure machined surface topography by tracing a linear path perpendicular to the lay direction of the machined surface. But, only one-dimensional measurement at a time is possible and there is a chance of surface damage in soft material due the invasive nature of contact type surface profiler. Due to the drawbacks of these commonly used sensors in indirect TCM, there is a need to develop a flexible, low-cost, non-invasive and precise technique for progressive monitoring of $VB_{average}$ which should be independent of frequency range and location. Since, all these needs can be fulfilled by processing of machined surface images acquired by an area scan camera to monitor $VB_{average}$, progressively, as suggested by Dutta et al. [4] in their review paper about application of image processing in machining. Therefore, in this work, an attempt is made to monitor progressive $VB_{average}$ by processing turned surface images by utilizing discrete wavelet transform (DWT) based texture analysis.

2. Literature survey

2.1. Texture analyses in indirect TCM

Texture is a repeated pattern consisting of a set of local statistics or slowly varying primitives. As per Tuceryan and Jain [5] texture primitives are connected set of pixels characterized by coarseness and directionality. Useful features are extracted after image texture analysis of a surface. As the machining progresses, cutting tool wear progresses and machined surface quality deteriorates with an increase in $VB_{average}$. Surface quality is mainly dependent on the $VB_{average}$ due to its abrasive nature. Research works carried out over the years in this field by various researchers are discussed briefly in the following sub-sections.

Distribution of troughs and crests become uneven with an increase in $VB_{average}$ and the resulting surface becomes rough. Damodarasamy and Raman [6] found that the reflection of light from rougher surface gets more diffused than that from a smoother surface. Thus, there may be a significant change observable in machined surface images with progressive machining time. These phenomena can be utilized by performing texture analysis on properly acquired machined surface images for extracting suitable features to determine the degree of tool flank wear. Statistical based, geometrical based, signal processing based and model based texture analyses were used in indirect TCM.

In statistical texture analysis, spatial distribution of gray levels using histogram based first order statistics, spatial correlation based higher order statistics using gray level co-occurrence matrix (GLCM) and run length statistical (RLS) analysis were performed on machined surface images for extraction of useful texture features for TCM. Lee et al. [7] predicted average surface roughness from turned surface images by utilizing first order statistical analysis and adaptive neuro-fuzzy inference system (ANFIS). But, this first order analysis is highly dependent on the illumination system utilized for image acquisition as found by Elango and Karunamoorthy [8]. To overcome these limitations, researchers applied micro-texture analysis techniques by utilizing second order or higher order statistical texture analyses [5]. Run length statistical (RLS) texture analysis, founded by Galloway [9] is a higher order statistical texture analysis, in which a run length matrix is evaluated from an image whose elements are carrying information about the number of runs of gray level values with a defined length of run. Consecutive pixels of the same gray level in horizontal, vertical or diagonal directions constitute a length of run. Kassim et al. [10] utilized RLS analysis method for useful feature extraction and afterwards they utilized those features to classify fresh and worn tool by using Mahalanobish distance classifier. However, progressive monitoring of $VB_{average}$ was absent in their work. Datta et al. [11] extracted micro-texture features by applying gray level co-occurrence matrix (GLCM) based texture analysis utilizing the information about co-occurrence of pixel pairs oriented in a particular spacing and orientation to monitor $VB_{average}$ in turning. They pointed out that there is a requirement to optimize pixel pair spacing to obtain accurate monitoring of $VB_{average}$. Therefore, an improvement of this technique was made by Dutta et al. [12] in their another research, by proposing a novel technique to optimize pixel pair spacing for accurate progressive monitoring of $VB_{average}$ utilizing power spectral density of extracted features with the variation of pixel pair spacing parameter. However, waviness information of turned surface can only be obtained by utilizing GLCM based texture analysis technique. Gadelmawla et al. [13] tried to find out a correlation of extracted features from GLCM of face turned surface images (obtained using optical microscope) with machining time. However, they did not show any correlation of extracted features with progressive $VB_{average}$. Dutta et al. [14] performed GLCM based and RLS based texture analyses on optical microscopic images of end milled surfaces to extract useful features for describing progressive $VB_{average}$. However, the image acquisition method by using optical microscope cannot fulfill industrial needs for on-machine tool monitoring. RLS based texture analysis can only discriminate the surfaces depending upon the feed mark information.

In geometrical texture analysis, the geometrical properties of surface images are extracted from the placement rules or neighborhood allocations of texture primitives. Hough transform (HT) and Voronoi tessellation (VT) are two geometrical texture analysis techniques used in surface texture analysis. Kassim et al. [15] extracted surface features from machined surface images using HT technique to predict tool condition. They tried to perform progressive monitoring of $VB_{average}$ without quantifying the correlation of extracted features with measured $VB_{average}$ values. Datta et al. [16] quantified the correlation of progressive $VB_{average}$ values with the features extracted from VT of turned surface images. However, only the information about change in feed mark distribution due to tool wear can be extracted using HT and VT based texture analysis techniques. Also the computation time of VT method is high, which is the main obstacle to apply this method in industries.