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# Machine vision micro-milling tool wear inspection by image reconstruction and light reflectance

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ABSTRACT

The paper presents a method for micro-milling tool wear inspection using machine vision. An original Wavelet-based Extended Depth of Field image reconstruction is proposed. The method enables geometrical measurements required to locate the cutting edges of the micro-tool. In the proposed method, variable light intensity is used during image acquisition to detect regions of different reflective properties. Geometrical information and reflective properties are then used to evaluate the tool wear. The proposed method is introduced to a prototype inspection machine. The results were compared to SEM images creating interesting conclusions.

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## 1. Introduction

There are several approaches to tool wear monitoring and tool wear measurements used in the machining industry and in research work. Most of the authors focus on signals that can be registered during machining process such as cutting forces, acoustic emission and accelerations. Various methods of indirect monitoring of machining operations in macro-scale and micro-scale are described in [1] and in [17], respectively. These indirect methods are suitable for practical applications but do not give accurate information about tool wear. In [2], authors describe strategy based on a large number of acoustic emission, cutting forces signal features and a hierarchical algorithm. Malekian et al. [3] examined factors affecting tool wear and a tool wear monitoring method using accelerometers, force and acoustic emission sensors in micro-milling. An optical microscope was used to observe the actual tool condition, based upon the edge radius of the tool, during the experiment.

Direct methods are more accurate, e.g., machine vision methods can actually measure tool wear. A review of the development of digital image processing techniques for tool condition monitoring is discussed in [4]. One group of direct methods that can be applied in macro-scale are three-dimensional techniques that are used to measure the crater wear depth. Usually these methods employ structured light for 3D crater wear measurement [5,6].

A classical method that uses fringe projection system is proposed in [6]. Shape evaluation of the cutting tool is realised by measuring insert from six different views. Lateral resolution of the system is 39 μm and vertical resolution is 4 μm; however, authors do not mention if they performed calibration of the system. The deviation of method proposed in [6] does not exceed a value of 50 μm, which is not acceptable in micro-milling tools wear measurement. In [5], authors used laser diode for laser beams projection on the blade surface which has accuracy greater than fringe projection. The system proposed by authors was calibrated in order to determine wear parameters in SI units. A set of parallel lines with known distances between them were focused under the microscope and their distances were measured in terms of pixels. Authors performed measurement of the maximum depth of crater and other factors that can indicate tool wear: maximum wear land width, wear land area and wear land perimeter. This method has precision reliability of 5 μm for maximum wear land width measurement and 10 μm for other measured indicators.

Another approach that can be used for crater tool wear measurement in macro-scale is white light interferometry [7]. Authors claim that this method is the most accurate from all other methods mentioned by them, but they do not specify the accuracy of their method. They also did not mention if they had preformed any calibration of their method. Moreover, this method requires white light interferometer which is costly.

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The most common and frequently used method is directional light which is frequently used for flank wear measurements with machine vision, e.g., [8] where authors proposed a methodology to design artificial neural networks for automatic tool wear recognition using images of cutting tool. Wang et al. in [18] proposed capturing images of tool blade with high-speed camera while the spindle is rotating. Tool flank wear area measurement based on geometric active contour model was presented in [21]. Authors used a microscope to verify accuracy of their method. Value measured by their system was very close to the value measured by the microscope.

Measurements of micro-drills wear used for PCB manufacturing were presented, for instance, in [9,10]. The authors focused on flank wear measurements of micro-drills. In [10], authors measured tool wear in pixels and square pixels. Actual tool wear measurement in length unit is presented in [9]. Both in [9,10] authors do not estimate errors of their method. The methods used by the authors are reliable and effective for the automated flank wear measurement of micro-drills, but they are not suitable for micro-milling tool wear measurements. This is due to tool geometry differences. Otieno et al. [11] focused on tool wear monitoring in micro-milling with machine vision; however, they did not perform tool wear quantification. Also, Ng and Moon presented an attempt to measure micro-mills [12]. They claimed that the method was capable of micro-tool wear measurements, but actual wear assessment was not performed.

The tool nose wear measurement is proposed in [20]. Authors do not use tool wear factors suggested in ISO 3685. They also do not define error of their method. Nose wear of tool is not commonly used as a factor that can determine tool wear; however, values of tool nose wear indicators can be higher than flank wear indicators. This makes them easier to be seen by an optical microscope.

The inspection of micro-tools is difficult due to the shallow depth of field, especially when using telecentric or microscopic lenses. The Extended Depth of Field (EDoF) [13] is an approach known in microscopy imaging. A set of images with different focusing planes is necessary to observe the object without the lens blur effect. Acquiring images of the same object with a differently placed depth of field reveals elements otherwise hidden (due to shallow depth of field effect). EDoF methods are usually based on local micro contrast or on local variance maxima estimation. This approach is widely used in microscopy [13–15,19]. However, these methods are prone to noise and the reconstructed images have artefacts.

This paper presents a new EDoF image reconstruction method based on a statistical analysis of Two-Dimensional Continuous Wavelet Transform allowing image reconstruction without artefacts. As far as the authors know, there are no micro-milling tool wear assessment methods ready for automation. It is due to optical limitations and the fact that wear can by assessed by comparing new and used tool. The change of surface reflective properties is assumed as a criterion for wear occurrence.

The authors' goal was to construct an inspection machine and develop algorithms that could enable full automation of the micro-milling tool wear assessment. The presented algorithm uses EDoF reconstructed images along with a computed depth map to autonomously find the wear regions of a micro-milling tool. Variable light intensity is used during image acquisition to detect regions of different reflective properties. As a result, it enables automated tool wear assessment using image processing. During the experiment, presented SEM measurements were used as reference.

## 2. Tool wear inspection method

The tool wear inspection was carried out using an experimental stand shown schematically in Fig. 1. The stand is equipped with two 5Mpx CCD cameras, a bi-telecentric lens for the main camera and macro lens for the secondary camera monochromatic ring and backlight illuminators. A step motor powers the spindle, thus changing the $\varphi$ angular position of the tool required for flank and rake face inspection. The camera is mounted on a stage of the $z$-axis allowing precise positioning and depth measurements. The motor encoder is used to measure the position of the camera. The method can be divided into four main steps as follows:

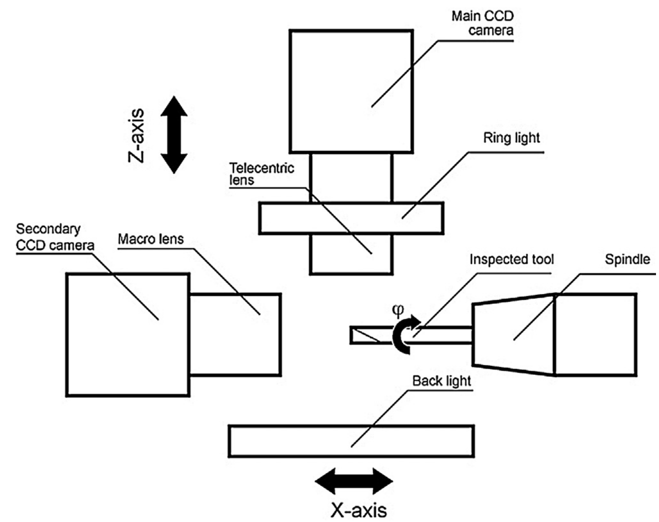


**Fig. 1.** The schematic of the inspection machine.

1. The images of the tool are captured with different focal planes for given $\varphi$ angular positions. At each focal plane, images are acquired with various light intensities.
2. EDoF reconstruction is applied using the proposed method, where the depth map and EDoF image is computed.
3. Identification of the wear area on the flank face is performed using map of light intensity changes for a given angular position $\varphi$.
4. Tool wear assessment using typical morphological operations and object assessment methods.

### 2.1. Acquisition

Before the acquisition process starts, a calibration procedure is executed. A known precise dot test pattern is used for the lens and camera calibration. The calibration enables optical distortion compensation, as well as evaluation of pixel size in the current setup. First, a specific acquisition procedure is performed. Images are captured for each angular position $\varphi_i$. For a given angle $\varphi_i$, images are taken from different distances $z_i$ spaced with an interval of $\Delta z$. Furthermore, for every $z_i$ position, five different light intensities are illuminating the inspected tool required for the identification of the wear area. A secondary camera is used to determine the $\varphi_i$ positions. The optical axis of the secondary camera is aligned with the tool's main rotary axis. In order to calculate a depth map, the focal distances or the interval $\Delta z$ has to be measured during the acquisition process.

### 2.2. The extended depth of field reconstruction

The method proposed in the paper is based on statistical analysis of Two-Dimensional Continuous Wavelet Transform (2D CWT) [21]. Fig. 2. illustrates the concept of EDoF imaging. On the image plane (the camera sensor), the object is replicated, but only a part of the object is sharp due to limited depth of field.

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