Measurement Of The Cutting Tool Edge Recession With Optical Methods

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ABSTRACT

The cutting tool wear is a natural phenomenon occurring while machining wood. The tool wear rate, dynamics of the wear progress and mechanisms of recession are very complex and depend on several factors such as; cutting angles, tool material, processed wood properties, machine dynamics, and processing speeds among others. Even if from practical point of view the cutting tool edge geometry is not such important as generated surface roughness, it is crucial for understanding of the wear physics. Consequently it is very important information for tool producers and researchers. Several methods have been applied for estimation of the tool wear. The goal of this work was however to design and verify novel optical instruments (such as laser micrometer and triangulation scanner) in scrutinizing of tool wear and scanning of the cutting tool geometry.

INTRODUCTION

Wood cutting is a complex process in which many phenomena interfere together. The cutting tool type and edge geometry, kinematic parameters of machining and material properties decide of machined surface geometry, cutting forces, energy consumption, vibrations, noise level and many others. Sharp cutting edge has a positive impact on widely understood machining quality and therefore it is crucial from industrial point of view to increase the life-span of tool (until it is still sharp enough to ensure quality demands). For this reason new, more wear-resistant coatings [21] and bulk materials are introduced into tool production (e.g. Polycrystalline Diamond, Diamond Dispersed Cemented Carbides). Mechanisms of tool blunting are also considered, Ramasamy and Ratnasingam [18] point that tool wearing might be caused by: gross fracture or chipping (catastrophic) abrasion, erosion, micro fracture, electrochemical corrosion and oxidation. On the other side a worn tool – particularly when catastrophic wear occurred – has a great impact on the surface quality and on dynamic of machine [15]. For all these reasons it is important to recognize the tool wear.

It has been of interest of many researchers during years to recognize the tool wear during wood machining. Klamecki [5] states that: “The change in the cutting tool with use has generally been monitored in two ways, by observing the change in the edge geometry, and by observing changes in the forces acting during cutting”. He also notices that some authors have used other measures of tool dulling e.g. time needed to plane a given length of wood while applying a constant feed force and the resultant deflection of a string before cutting by a worn knife; also a size of sawdust chips has been used as an indicator of tool wear. All the tool wear measurement methods are usually divided into: direct and indirect measures.
**Direct methods**

The most obvious way of controlling the tool wear is a direct measurement of tool geometry. It has some disadvantages like time consuming (dismounting, measuring and remounting a tool or a blade) or difficulties in remounting in exactly this same position, but gives an objective and absolute wear data [2]. Three general methods of direct tool tip geometry measurement are utilized: contact, optical, and SEM.

Contact methods rely on tip or wedge type stylus moved along the cutting edge (e.g. Miklaszewski et al. [11]) or perpendicularly to achieve tool wedge profile [12].

Optical method has several varieties. In the simplest setup optical microscope is used to observe the tool tip or, if equipped with camera to save the image, analyze afterwards [1, 6, 8]. The variation of this method includes putting Vickers indentation marks [2, 4] or surface scratches [10] on observed face for comparing the distance from the marks to the cutting. In this way the measuring base is constant and the measurement does not depend on the initial edge wear.

Rarely – due to high work and time consumption required, a non-destructive silicone cast cross-section method is used to obtain geometry of tool cross-sections [11, 21].

Methods utilizing laser light are also considered as optical methods. Some trials have been undertaken to acquire a measure of tool geometry in-situ on the rotating spindle: Ochuchi et al. [13] have used laser curtain instrument for detecting outer diameter of a router bit. They successfully compared results with a stylus method.

Scanning Electron Microscope (SEM) is used to measure the tool wear. In many cases [3, 14, 21] SEM is used in the same manner as an optical microscope to make a high resolution image which are then subjected to geometry measures or simply qualitative analysis.

When higher resolutions are used more detailed analysis of wear geometry and mechanisms are analyzed [11, 21].

Regardless of measuring method different parameters are used by authors to quantify tool wear.

![Figure 1 Geometrical parameters of the cutting edge wear as considered by McKenzie and Karovich (1975) (a), Porankiewicz et al. (2003) (b) and Sheikh et al. (2003) (c)](image-url)
McKenzie and Karpovich [10] have utilized many parameters (Figure 1a) in order to provide a wide spectrum of tool blunting relations to cutting forces. None of their parameters was linearly related to the cutting forces. Porankiewicz et al. [17] noticed that edge recession on the clearance face (VBF) is in wood cutting the most intensive of all measured (Figure 1b). This is confirmed by Sheikh-Ahmad and Bailey [21] basing on replica cross-section. Sheikh et al. [22] have used nose width – wear land measured in a surface perpendicular to the tool angle bisector (Figure 1c). Alternatively, a cutting edge rounding (tool tip radius) might be used for quantification of the tool wear [2].

**Indirect methods**

On the other side strong effort is put onto on-line indirect methods of tool wear recognition. From practical point of view it is not the geometry of the tool itself which is important but the effect it makes on the process (quality of generated surface, energy consumption, sound intensity etc). For this reason, as well as because of possibilities of on-line capabilities, indirect measures of tool wear seem to be very attractive alternative for adaptive controls of cutting processes. So far, besides of cutting forces considered by many researchers [1, 5], several other physical effects of cutting have been researched in order to predict the tool wear. These include energy consumption, vibrations [7, 8], acoustic emission [9], and temperature of machined surface [23] among others. It must be mentioned anyway, that for calibration of the indirect measurement systems in most cases detailed information on the cutting tool micro geometry are required as a reference.

**OBJECTIVES**

Even if a lot of research has been dedicated to development of tool wear monitoring techniques there is still, in our opinion, a need to construct a direct cutting edge measurement technique to be utilized for in-line applications. In the principal it should exclude contact with the measured edge. It should allow measurement of the tool without uninstalling it from the spindle (or at least without uninstalling inserts from the tool holder). It should be able to reproduce whole cutting edge length and provide information about the geometry in three dimensions. Some other minimum requirements to be considered for such scanner could be pointed as bellow:

- Minimal radius of the tool tip to be detected: 10µm
- Length of the measured edge: up to 30mm
- Measurement speed: reasonable for in-line applications (in order of minutes, preferably seconds)
- Size of the scanner: compact and rigid
- User interface: automatic and intuitive

The goal of this project was therefore to develop a novel methodology for estimation of the cutting edge geometry, sensitive enough for industrial applications and with potential for on-line measurements.

**METHODS AND RESULTS**

Several optical techniques have been pre-selected for analysis within the framework of this project:

- laser micrometric scanner
• laser displacement sensor
• laser line triangulation
• shadow triangulation
• depth-from-focus

**Laser micrometric scanner**
The successful example of the laser micrometric scanner in estimation of the cutting tool conditions has been reported by Ohuchi et al. [13]. The work presented here was an attempt to extract additional information from their results and to reproduce three dimensional shape of the cutting edge. A dedicated experimental set-up has been developed as presented in Figure 2. The cutting tool 1 has been installed on the rotary stage 4 of the scanner. The contour of the tool was scanned by the laser micrometric system 2 (Mitutoyo LSM-503) while the tool was rotated. The tool (together with rotary stage) was translated horizontally by linear moving stage 5 in order to scan subsequent sections. The position of the light shadow has been acquired by the micrometer and recorded by computer together with linear and rotational positions.

3D contour of the whole cutting tool can be scrutinized as a result of scanning with laser micrometric system. An example of such result is presented in Figure 3a. The same 3D map, but represented in the Cartesian space is shown on Figure 3b (the horizontal axis corresponds to rotation angle). The highest points belong to the cutting edges. To visualize an effect on the tool wear two maps scanned from the sharp and extensively used tools are presented in figure 3 (c and d respectively).

![Experimental platform #1 for scanning cutting edge geometry](image)

**Figure 2 Experimental platform #1 for scanning cutting edge geometry; tool 1, laser micrometer 2, laser displacement sensor 3, rotary stage 4, horizontal moving stage 5**
Figure 3 Results of the diamond tool scanning with laser micrometric system; 3D shadow contour of the tool (a), map of the tool (b), result of sharp tool scanning (c), result of extensively used tool scanning (d)

Laser displacement sensor
On the same experimental platform #1 as the one used for laser micrometer scanner an additional triangulation laser displacement sensor was installed. The sensor used was Keyence LKG-32, connected to PC by RS-232. The triangulation is a widely used optical method to calculate a distance between sensor and illuminated spot. In principal the focused spot of laser light is emitted to the surface with a specific (constant) angle. Part of the light is reflected from the surface in to direction of the detector. Analyzing intensities of the pixels illuminating the detector it is possible to calculate distance between surface analyzed and sensor. In case of laser displacement sensor it is possible to estimate only one point, however after rotating and moving the tool (by means of rotary and linear stages) it become possible to scrutinize 3D shape of the tool.

Even if the resolution of the laser displacement sensor used was superior to the scanning resolution required (10µm), the performance of such system was disappointing. Due to the peculiar geometry of the cutting edge tip (highly polished and curved surface) the laser light was reflected not in to direction of the detector (in diffuse manner), but rather reflected specularly in to direction different than detector. As a result the signal acquired in those areas was an error. In consequence the laser displacement sensor was rejected from further tests.

Laser line triangulation
Next a series of tests were performed on the surface roughness evaluation experimental platform described in detail in [20]. First attempt was a variation of the laser displacement sensor extended
in to line scanning instead of spot. The hardware for the experiment is presented in Figure 4. The source of laser light 2 (ultra thin laser line projector Stocker Yale Lasiris, 635nm, 1mW) illuminated measured cutting edge installed on the tool 1 with a structured light (laser line). The image of the laser line shape on the cutting edge was acquired by video camera 3 (6.6 Mpixels, Pixelink PL-A782) equipped with macro/zero-distortion lenses 4 (Optoengineering MC3-03X). The focus of the camera and minimization of the laser line with was performed by moving the optical system vertically by means of linear moving stage 7. The tool was also moved horizontally with a help of moving stage 6 in order to generate 3D shape of the cutting edge. A dedicated software controlled all parts of the scanning systems, captured/processed images and generated 3D maps of the cutting edges.

An advantage of the laser line triangulation system over laser displacement sensor was radically reduction of the scanning time. Unfortunately, the laser line triangulation method possessed analogous (to laser displacement sensor) limitation – misrepresentation of the cutting edge shape due to extensive laser line width, elevated laser speckle and high specular reflection of the laser light from metallic surface. The signal captured by the camera was very weak and in consequence representation of the cutting edge geometry was poor. It should be mentioned here that it might be possible to improve the set-up (by means of more powerful laser light source or replacing camera by more sensitive one); however it was not considered within the framework of this project.

![Figure 4 Experimental platform #2 for scanning cutting edge geometry; tool 1, laser line projector 2, shadow projector 3, macro/zero-distortion telecentric lenses 4, camera 5, horizontal moving stage 6, vertical moving stage 7](image)

**Shadow triangulation**

Light section shadow triangulation was also tested as an alternative to laser line triangulation scanner. The hardware used was very similar to the above mentioned (Figure 4); however instead of the monochromatic and highly polarized laser source 2, the light section was created by structured light projector 3 in a form of the half-plane shadow. The source of light (3W LED white light projector LTPR3W/W produced by Optoengineering) was equipped by telecentric lenses. In consequence the scanner hardware was optimized in order to increase the quality of images acquired and reduced, as possible, all optical distortions. Image processing algorithm was
developed on the bases of previous work [19], with slight adoption due to peculiarities of the cutting edge.

Examples of the 3D scans of the cutting edge (at different stages of wear) are presented on Figure 5. The cutting tool was engaged in processing of particle boards and was measured before and after 500, 1000 and 1500 meters of the cutting distance. Even if the toll was still reasonably sharp at the end of test, clear marks of the wear were observed. As the quality of the results obtained was superior, it was possible to analyze the wear mechanism in detail (such as dynamics of the recession on the rake and clearance faces, etc.).

![Figure 5 3D reconstruction of the cutting edge geometry after cutting particle board; 0 m (a), 500 m (b), 1000 m (c) e 1500 m (d)](image)

**Depth of focus**
The last technique evaluated was adoption of the depth-from-focus approach (or focus stacking) to reconstruct 3D maps of the cutting edge geometry. The principle of this technique bases on the phenomenon of the focus depth of the lenses. The focal depth of typical lenses is relatively small, and it depends on the quality of optics, numerical aperture and optical magnification. It could be utilized for measurement of the depth, assuming that it is possible to quantify focus numerically. Various algorithms could be applied for focus quantification. The one selected in this project based on maximization of the standard deviation of the pixels intensity.

The experimental set-up based on the experimental platform #2 (Figure 4). Images of the cutting edge 1 at different focal lengths were captured by the camera 3. The focal length was controlled by moving vertically camera and lenses 4 by means of the vertical moving stage 5. The tool was illuminated by the white light projector 6. A series of blurred images (with different distance of the camera to the edge) were obtained as a result of scanning (Figure 6). Dedicated software post-processed all these images in order to determine the altitude of the maximum focus for all pixels. The “best focus” assessment algorithm applied within this project based on the maximization of the standard deviation of the light intensities in small regions of image; however several alternative algorithms (open source or commercial) are available. It becomes possible to reconstruct the 3D image of the cutting edge basing on the “best focus” information, as presented on Figure 6e. It should be mentioned here that due to not optimized software the image reconstruction of high definition images was rather time consuming (in order of hours). In consequence improvements for the software (and/or hardware) are necessary in order to apply...
this technique on-line. Beside that, the depth-from-focus method seems to be very effective and relatively accurate.

![Images of the cutting edge corner with four different focal distances (a-d), and resulting 3D map of the edge scrutinized by analyses of these images (gray color corresponds to the depth) (e)](image)

**Figure 6** Depth-from-focus measurement of the tool edge; images of the cutting edge corner with four different focal distances (a-d), and resulting 3D map of the edge scrutinized by analyses of these images (gray color corresponds to the depth) (e)

**CONCLUSIONS**

Basing on the results presented and other experiences acquired during conducted studies the conclusions can be summarized in a form of table 1. Each technique described possesses potential for measurement of the cutting edge geometry; however some improvements to the set-up, hardware and software might be recommended. The most reliable method of all presented here
seems to be shadow triangulation. However laser micrometer might be the most suitable for in-line application.

| Table 1 Summary of the cutting edge geometry measurement techniques researched |
|-------------------------------------------------|---------------|----------------|----------------|----------------|----------------|
|                                   | performance  | potential      | hardware simplicity | computation/scanning time | 3D reconstruction of the cutting edge | on-line potential |
| laser micrometric scanner          | ✓             | ✓              | ✗               | ✗              | ✓              | ✓ |
| laser displacement sensor          | ✗             | ✗              | ✓               | ✓              | ✓              | ✗ |
| laser line triangulation           | ✗             | ✓              | ✗               | ✓              | ✓              | ✗ |
| shadow triangulation               | ✓             | ✗              | ✗               | ✓              | ✓              | ✓ |
| depth-from-focus                   | ✓             | ✓              | ✗               | ✓              | ✓              | ✗ |

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