Measurement 93 (2016) 541–551

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Design and validation of a grinding wheel optical scanner system to repeatedly measure and characterize wheel surface topography

Andrew McDonald, Robert Bauer *, Andrew Warkentin

Department of Mechanical Engineering, Dalhousie University, Halifax, Nova Scotia, Canada

ARTICLE INFO

Article history:
Received 12 June 2016
Received in revised form 18 July 2016
Accepted 19 July 2016
Available online 20 July 2016

Keywords:
Measurement
Wheel
Topography
Optical
Scanner

ABSTRACT

This paper describes the design and validation of an upgraded grinding wheel scanner system that controls the position of a Nanovea CHR-150 Axial Chromatism sensor along the *x*- and *y*-directions of the wheel surface to measure and characterize wheel surface topography. The scanner features a novel homing system that enables the wheel to be removed from the scanner, used on a grinding machine and then re-mounted and re-homed so that the same location on the wheel surface can be repeatedly measured and monitored. The average standard deviation for homing was 27.6 μm and 19.3 μm in the *x*- and *y*-directions, respectively, which is more than adequate for typical area scans of 25 mm^2. After homing, the scanner was able to repeatedly measure features that were similar in size to an abrasive grain (~200 μm diameter) with an average error of 9.3 μm and 5.9 μm in the *x*- and *y*-directions, respectively. The resulting topography measurements were compared with Scanning Electron Microscope images to demonstrate the accuracy of the scanner. A custom particle filter was developed to process the resulting data and a novel analysis technique involving the rate of change of measured area was proposed as a method for establishing the reference wheel surface from which desired wheel topography results can be reported such as the number of cutting edges, cutting edge width and cutting edge area as a function of radial depth.

1. Introduction

Grinding is a key manufacturing technology as it is the most cost effective method of creating very smooth, high accuracy surfaces on very hard materials. The grinding process is known to be heavily dependent on the wheel's surface topography which consists of abrasive grains that are random in shape, orientation and location. The spindle power, workpiece roughness and workpiece temperature are all influenced by the wheel's topography; however, these relationships have not yet been fully quantified. In order to effectively study and understand the grinding wheel's surface to improve process outcomes and advance the design of grinding wheels, tools are needed that can monitor the changes in the wheel's surface topography throughout the process. In order to be useful for studying the effects of grinding wheel surface topography on grinding mechanics, a grinding wheel measurement system should be able to accurately measure individual abrasive grains, it should be able to measure a statistically significant portion of a grinding wheel (ideally the entire wheel), it should be able to measure the same area on a grinding wheel between grinding experiments and it should be able to distinguish between abrasive cutting edges and grinding debris. This paper describes the design and validations of a system that meets these requirements.

Grinding wheel measuring techniques are typically divided into two categories: contact or non-contact. The use of a stylus, which is similar to standard surface roughness measurements, is an example of a contact method. In this method a stylus coupled with a displacement transducer is dragged along the wheel's circumference producing a profile of the wheel topography. Wheel surface measurements acquired by a stylus have been used to characterize multiple topographical characteristics including: number of cutting edges [1–3], active surface area [4], grain sharpness and wheel coarseness [1,3]. Xie et al. [5], for example, used a coordinate measurement machine to characterize the protrusion height and rake angle of the wheel's grains. A significant drawback inherent in stylus measurements is that the size of the stylus tip limits the resolution of the measurement, and the small features of the grains are often not captured [6]. It is also difficult for the stylus to obtain measurements below the outermost layer of the surface without getting caught in the crevices. The measurement method is also limited in scanning speed. If the stylus moves too fast it can lose contact with the wheel surface resulting in the loss of detail throughout the measurement [7]. Additionally, using the stylus

---

* Corresponding author.
E-mail address: Robert.Bauer@dal.ca (R. Bauer).

http://dx.doi.org/10.1016/j.measurement.2016.07.061
0263-2241/

or probe on very rough hard surfaces such as a grinding wheel surface can cause accelerated wear to the stylus [8].

To overcome these issues, several non-contact measurement methods have been developed in order to characterize a grinding wheel. For example, Scanning Electron Microscope (SEM) images provide a very detailed view of the grinding wheel's surface with excellent depth of field. Researchers have used SEM to study the grain geometry [9], cutting edge density [10], dressing effects [11] and active surface [12]. It is even possible to acquire a 3D measurement from an SEM by using stereo photographs and a triangulation process [13]. The drawback to an SEM is that it requires a small sample size and, therefore, the grinding wheel must be destroyed preventing any further process monitoring. Conventional optical microscopes have been used to characterize the wheel surface in 2D. Lachance et al. [14], for example, developed a system that could measure wear flats automatically from microscopic images without removing the wheel from the grinding machine using a custom positioning system and image processing techniques. Feng and Chen [15] were able to monitor the wheel loading using microscopic images and image processing with a similar method to Lachance et al. [14]. Fathima et al. [16] used an LED and a phototransistor to measure the profile around the circumference of the wheel to study the basic shape of the wheel. As the wheel is rotated it interrupts the light traveling to the phototransistor, and the interruption pattern is used to describe the wheel surface. In addition, auto-focusing systems have been incorporated with lasers to measure the distance from a feature on the wheel using the theory that, when in focus, the light intensity measured will be higher than when out of focus [5]. White light interferometers (WLI) have also been used to obtain a variety of grain topography parameters [17–20]. WLI works on the principle that if the distance to one light source is known, the interference pattern between it and another light source can be used to determine the distance to the second source. Generally, small samples are required for this method although Hecker et al. [17] used a combination of a WLI and the imprint method to scan an imprinted surface of the grinding wheel in order to compensate for the curvature of the wheel in larger scans. Confocal laser scanning microscopes have recently been implemented into grinding research. They have the ability to acquire optical images and 3D topographical data at the same time. Tahvilian et al. [21], for example, used a digital image to create a mask of the grains in the scan, which allowed for the removal of bonding material from 3D topographical data. Small samples were again required for this work, resulting in the destruction of the wheel. Darafon et al. [22] recently developed a promising system capable of scanning an entire grinding wheel with the use of a white light chromatic sensor and a custom positioning control system.

While the previously described systems have the accuracy required to measure grinding wheels, there are three notable shortcomings with both contact and non-contact measurement methods. The first is that the myriad randomly-shaped and randomly-positioned grains within a grinding wheel make it difficult to validate the resulting topography data. The second issue is that the majority of scanners cannot re-position the wheel between grinding experiments so that the same area can be repeatedly scanned. Without such a repeatable measurement, it is difficult to monitor the grinding wheel's surface features as they wears throughout the process. The third shortcoming with these measurement methods is that, once a measurement of the grinding wheel surface is obtained, any swarf contaminates on the wheel surface and any inherent measurement noise makes it difficult to identify within the data where the outermost wheel surface actually starts – especially since this swarf and noise are on the same scale as the cutting edges themselves. To overcome these issues this work modifies the scanner originally developed by Darafon et al. [22] in order to produce more accurate and repeatable measurements, systematically validates the scanner results using groove measurements, Quick Response (QR) code measurements, grinding wheel measurements and SEM images, and then proposes a new analysis method to help determine at what threshold depth within the measurements the outer-most surface of the wheel actually occurs.

2. Grinding wheel scanner design

The grinding wheel scanner was designed so that the optical pen from a white-light chromatic sensor can scan an entire wheel as shown in Fig. 1. The pen used for the work reported in this paper had a measurement range of 1200 mm, a spot size of 4 μm, and a theoretical resolution of 0.2 μm. The x-axis for the system is in the direction tangential to the grinding wheel surface. The drive system for this axis is comprised of an Automation Direct Sure Step stepper motor connected to a 41 mm diameter friction wheel by a 50:1 zero-backlash planetary gearbox. When the friction wheel is brought into contact with the wheel's surface they both rotate. This friction-wheel positioning system was selected because relatively low forces need to be applied to the grinding wheel to make it rotate, and an alternative direct-drive design would require an encoder with an unrealistic number of counts per revolution to achieve the desired positioning resolution. For example, the original scanner developed by Darafon et al. [22] used a Teledyne-Gurley Series 825 encoder with 48,000 counts per revolution attached to the grinding wheel hub. For a 350 mm diameter grinding wheel, however, the resulting theoretical resolution in the x direction at the wheel's surface was only 23 μm. Since the average grain size of a grinding wheel with medium sized grains is about 200 μm, this resolution is barely adequate. To try to achieve higher-resolution samples, Darafon et al. used constant velocity interpolation between encoder pulses; however, in this work, the present authors have directly increased the scanner's wheel-positioning resolution by attaching a 4000 counts-per-revolution US Digital E5 encoder to the friction wheel's stepper motor. This new encoder is then used to interpolate between the hub encoder pulses resulting in a theoretical resolution in the x-direction of 0.65 μm at the wheel's surface regardless of the grinding wheels size which changes as the wheel is worn and dressed. Linear stages move the optical pen with respect to the grinding wheel. The y-axis is defined to be across the face of the grinding wheel while the z-axis is normal to the grinding wheel face. The y-axis consists of a Zaber TLA28A linear actuator with a 1.0 μm theoretical resolution. Gross motion in the z-direction is accomplished using a custom-built lead-screw stage and a Parker Series 4000 stage with micrometer thread. The optical pen obtains the z-axis depth information with respect to the stage location.

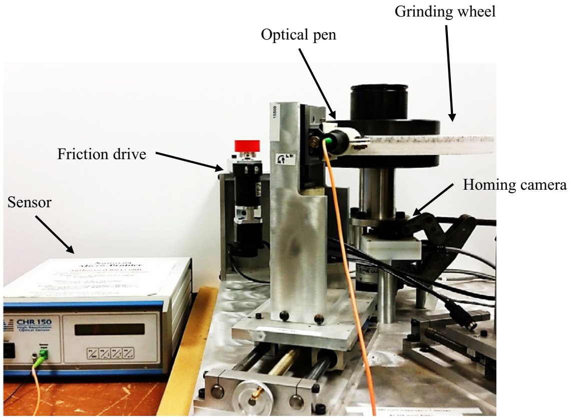

Fig. 1. Grinding wheel scanner.