CIRP Annals - Manufacturing Technology 57 (2008) 533–536

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Process monitoring in non-circular grinding with optical sensor

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ARTICLE INFO

Keywords:
In-process measurement
Optical
Grinding

ABSTRACT

Cylindrical grinding machines are increasingly used to produce workpieces with non-circular contours. This means that new demands are made on process monitoring and in-process measurements due to these non-circular contours. A new optical sensor system was integrated into such a grinding machine, making it possible to take measurements for quality assurance, optimisation of the grinding process and reduction of setting-up and machining time.

1. Introduction

The cylindrical grinding machine (CGM) is subject to a variety of disturbances such as tool wear, temperature drifts, path control deviations, etc. This leads to loss of productivity and to dimensional deviations in the workpiece. A variety of monitoring tools can help to improve the grinding process [1]. Measurement controls can be used to compensate for most disturbances during cylindrical grinding. This is done by automatically measuring and positioning the tool during machining. The measuring head used has touch probes. Nowadays those measurement controls are widely used and well established; they are necessary for efficient, robust manufacturing processes when highest precision is required. It can be predicted that the intelligent monitoring of grinding processes will play an increasingly important role [2]. The majority of touch probes are used only in coordinate measuring machines (CMMs) [3]; some of them are also suitable for use in machine tools.

The modern CGMs of today can also be used for the high-precision grinding of non-circular contours. For this purpose the CGMs has continuous path control in the *X*- and *C*-axes, e.g., for eccentric grinding. Contact measuring heads will not work here as the probe is distorted by shearing forces acting on it [4]. As measuring has not been possible for non-circular grinding, the tremendous potential of this new technology could not be fully exploited up to now.

When non-contact measuring heads are used, there are no disturbing shearing forces. For that reason they are particularly useable for circular grinding [5]. For a long time high demands and unfavorable ambient conditions prevented optical sensors from being used in CGMs. That is why an optical principle of measurement capable of measuring very different materials was used in the non-circular grinding machine.

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0007-8506/$ – see front matter © 2008 CIRP.
doi:10.1016/j.cirp.2008.03.133

2. Machine concept and optical sensor

The distance measurement sensor is arranged on the wheel head in the grinding machine (Fig. 1). This can automatically be put in place for measuring, as an alternative to the wheel head; otherwise it is located in the rear portion of the cabin.

Criteria for the choice of the measurement principle to be integrated in the CGM are [6]

- Static tests, e.g., repeatability, local reproducibility, reproducibility over operating/measuring range
- Slope limit, e.g., point to point probing error on sphere
- Dynamic tests, e.g., scanning probing error on sphere

Following a variety of tests, a chromatic confocal distance sensor [7] was chosen for the measuring head. The sensor uses a polychromatic point source. As chromatic aberration is used, each focal point, or the distance between the sensor and the surface of the workpiece, corresponds to a particular wavelength.

A spectrometer is used to measure the wavelength of the reflected light. The most significant advantage of this measuring principle over other principles is its insensitivity to different surfaces with different reflectivities and it is also suitable for shiny surfaces. As the sensor is mounted on the wheel head, it moves along the *X*-axis just like the grinding wheel. It only needs a small measuring range of 1 mm for high-precision measuring over a large working distance. Synchronisation of the measuring head on the *X*-axis (incremental line encoder) with the sensor signal increases the measuring range and though allows measuring the whole traversing range on the *X*-axis.

3. Design and functionality

The optical sensor is completely integrated into the CNC unit of the CGM. This allows information from the sensor, the *X*-, *C*- and *Z*-axes to be recorded and linked simultaneously. In order to check

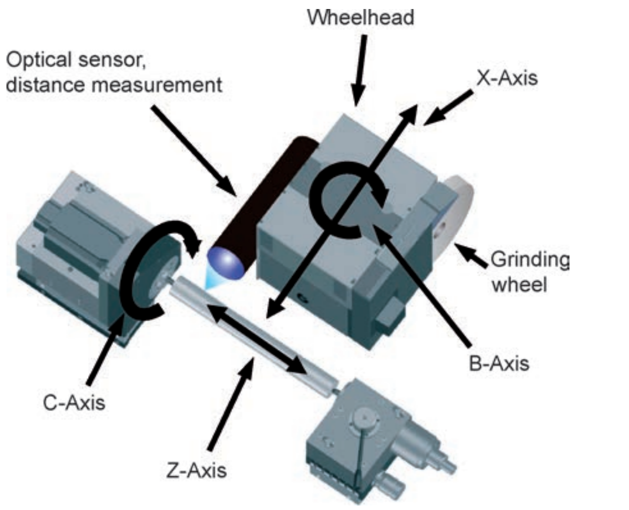

Fig. 1. Arrangement of the optical sensor on the wheel head in the grinding machine.

communication between the individual components and the coordinate transformations and to design the whole system, a simulator was developed and used (Fig. 2). With the simulator it is possible to visualise and to test different arrangements of the sensor in the CGM similar to a 3D CAD system. In addition, different contours of workpieces can be measured and the results of the virtual measurements are presented.

The simulator was also used to develop the calibration procedure and to check the measuring functions. The calibration procedure is used to determine the position and orientation of the sensor in the CGM. This information is stored in the system, making it possible to link distance information from the sensor with position information about the CGM axes with the precision required. The calibration procedure is carried out by means of an eccentric plate (Fig. 3).

The eccentric plate serves as the calibration artefact, is mounted on the CGM and measured using the measuring head. The advantage of using an eccentric plate for calibration is that the eccentric plate itself is easy to calibrate and to measure in the grinding machine. All three variables for the position and orientation of the sensor can be determined with the measured data taken in one measurement. A sinusoidal signal will be produced on measuring if the arrangement is optimal. If the position and orientation of the sensor is not ideal, there will be deviation from the sinusoidal signal. The distance between sensor and the workpiece (Δt), the perpendicular distance between the measuring axis and the rotating axis (Δs) and the offset angle (Δu) of the sensor – all shown in Fig. 3 in sensor coordinate system – can be determined from these deviations.

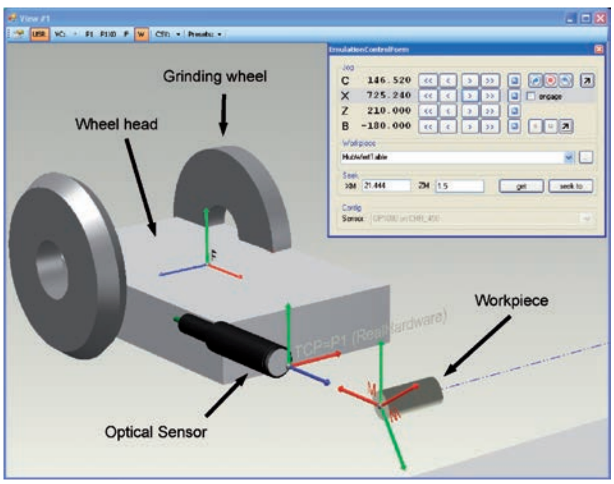

Fig. 2. Simulator of arrangements, coordinate transformations and tests.

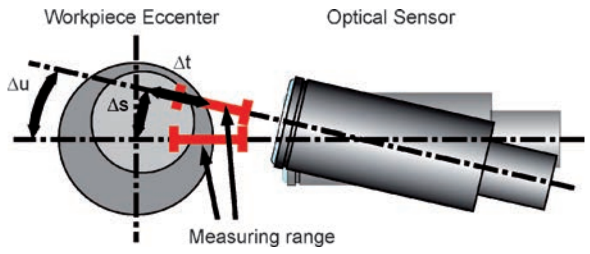

Fig. 3. Calibration of measuring system with an eccentric plate artefact.

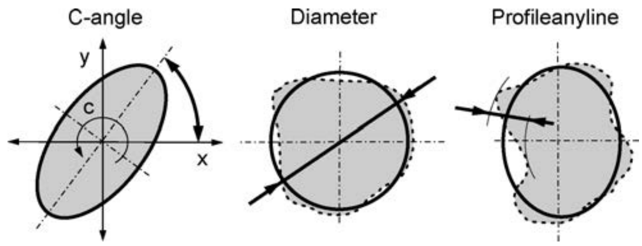

Fig. 4. Measuring functionality of the system.

The measuring system includes the following functions (Fig. 4):

- *C*-angle measurement
- Diameter measurement
- Profile measurement

Determining the orientation (*C*-angle) of a workpiece in the CGM allows setting-up time to be reduced in precision grinding of non-circular workpieces. Determining diameter and profile serves to optimise the grinding process and to assure the quality of the workpieces. It should be noted that only the measurement of unmachined parts is worthwhile because the system does not work accurately enough for the tolerances of machined parts generally used at present.

Optical distance sensors can be realised according to a great variety of measuring principles [8]. Each measuring principle has its advantages and disadvantages. This was taken into consideration when the measuring system was designed; it is designed in line with the Optical Sensor Interface Standard (OSIS) [9], which makes it easier to exchange sensors from different manufacturers and to use different measuring principles.

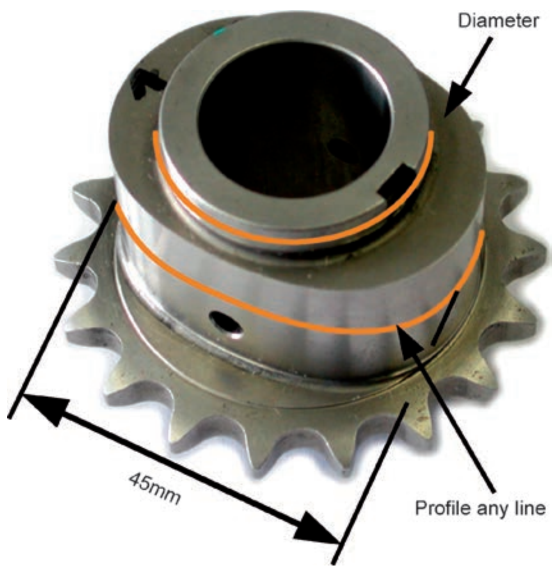

Fig. 5. Pump component, typical measuring tasks.

Table 1
Uncertainty budget for typical measuring tasks

Uncertainty contributors	Diameter (μm)	*C*-angle (°)	Profile (μm)
Repeatability, u_r	0.1	0.003	0.4
Sensor linearity, u_{lin_s}	0.2	–	0.2
Axis linearity, u_{lin_CGM}	0.2	0.001	0.2
Perpendicularity, $Z\ u_p$	0.7	–	0.3
Temperature, u_T	2.1	–	1.1
Calibration, u_{cal}	0.3	0.005	1.0
Bias, D_{sys}	0.4	0.005	0.9
Combined standard uncertainty, u_c	2.3	0.006	1.6
Expanded uncertainty (k = 2), U	5	0.02	4

4. Experimentals and results

4.1. Typical workpiece as a test artefact

Measuring uncertainty always depends on measuring tasks [10]. For that reason, before the year 1999 a typical measuring task was defined and the details of the measuring process specified as standards [11] in order to be able to compare the efficiency of 3D CMMs. Standardisation is not as advanced as far as grinding machines are concerned. In order to estimate the efficiency of the measuring head when used with a grinding machine, concrete measuring tasks on a typical workpiece – a pump component (Fig. 5) – were defined.

4.2. Measuring uncertainty budget

An assessment was made of the measuring uncertainty of these tasks. The contributing factors listed in Table 1 were taken in consideration. Individual contributor factors were determined by means of tests. Repeat measurements were made to determine repeatability (u_r). This measurement data was also used to identify systematic deviation (D_{sys}). CGMs axis linearity (u_{lin_CGM}) and sensor linearity (u_{lin_s}) were taken from the manufacturer's specifications. Perpendicularity of the CGMs Z-axis (u_p) can be manually adjusted. Typical perpendicularity as used by CGM users was identified in tests; this was taken as the standard uncertainty value. Temperature causes thermal expansion of the workpiece and deformation of the whole grinding machine. The CGM was not cooled. Ambient fluctuations were around 1 °C. To assess the effect of temperature, position measurements were taken over a longer period of time using a laser interferometer. This data was used to determine the temperature effect (u_T), with a 30-min interval being observed between two calibration procedures. Workpieces machined on the grinding machine and feedback to a high-precision CMM (u_{cal}) were used for the experiments.

$$u_c = \sqrt{{u_r}^2 + u_{lin\_s}^2 + u_{lin\_CGM}^2 + u_p^2 + u_T^2 + u_{cal}^2} \quad (1)$$

$$U = ku_c + |D_{sys}| \quad (2)$$

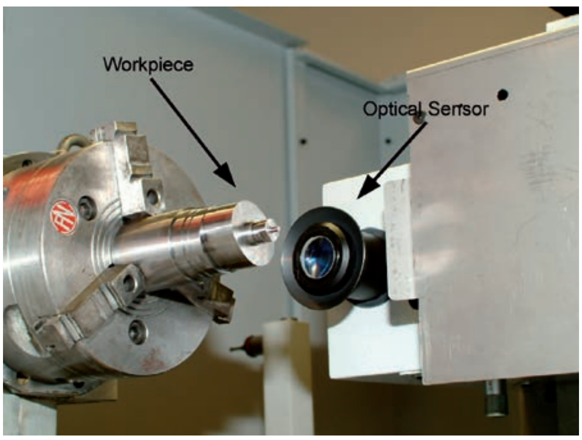

Fig. 6. Cylindrical grinding machine with integrated optical sensor and workpiece.

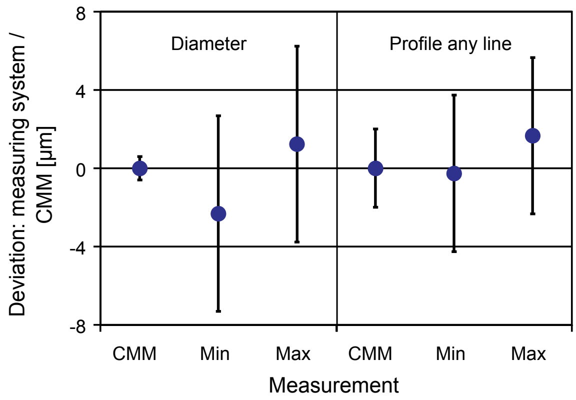

Fig. 7. Comparison between measuring results of the measuring system and the CMM.

Individual contributing factors were summarised with the aid of the law of error propagation (1) and expanded uncertainty (2) was calculated.

4.3. Experimental results

The whole sensor system was integrated in a high-precision grinding machine [12] and tested in the experimental grinding shop of the manufacturer (Fig. 6).

Various measurements were carried out to document the efficiency of the measuring head and the whole system (CGM and sensor). Circular grinder measurements were compared with measurements by a high-precision CMM. Diameter measurements of dimensions between 3 mm and 47 mm were carried out. Elliptical non-circular contours with a maximum radius of 22 mm and a minimum radius of 17 mm were also measured. Measurements were taken within 0.5 h. Diametrical deviation D between measurements taken with the measuring head and the CMM was between $D = -2.3$ μm and $D = +1.2$ μm. The difference between profile measurements on the circular grinder and those on the CMM was between $P = -0.3$ μm and $P = +1.6$ μm. In Fig. 7 extreme values in diameter measurements and profile measurements are shown; in addition, the measurement uncertainty for these features is given.

Uncertainty ranges for diameter and profile measurements with the new measuring system not only overlap the CMM uncertainty range but also include it. Thus, these experimental measurements confirm assumptions and calculations for the uncertainty budget (Table 1).

5. Conclusions

It has been shown that it is possible and useful to use optical sensors in grinding machines for grinding non-circular contours, although it is not possible to measure directly during grinding. Measuring in the grinding machine before or during a break of grinding, offers many advantages. With new possibilities to monitor the grinding process, this kind of metrology leads to added value for the whole manufacturing process. It becomes productive metrology [13]. It is not only possible to detect contour errors and to discard workpieces that are out of tolerance. It is also possible to gain new information and knowledge about the grinding process from the measuring result and to interact and improve the process by optimising feed rate and rotating speed. Even understanding about the limits of CGM dynamics can be improved. For example, grinding non-circular contours can cause very high accelerations which make excessive demands on path control. Measuring the contours after grinding makes it possible to detect overshoots, which can be reduced by optimising path control parameters.

The degree of measurement uncertainty when measuring diameter is adequate for measuring workpiece blanks. Determining relative position using $U_{C\text{-angle}} = 0.02°$ ($k = 2$) is extremely good.

This means that setting-up time and machining time can be shortened. Furthermore, measurement uncertainly in the micrometer range is achieved when measuring profiles with the grinding machine—greater precision in this range can only be achieved using high-precision CMMs. Here the workpiece must be unclamped and may have to be reclamped in position. This is all very time-consuming and reclamping with the precision required is often not possible.

The measuring head is currently at the prototype stage. A considerable proportion of the uncertainty budget is due to temperature drift within the grinding machine. In addition, the artefact used for the calibration procedure and its traceability plays a substantial role. Systematic deviations are subject to further research.

The sensor does not differentiate between the surface of the workpiece and the surface of the cooling liquid. This leads to systematic deviations between 1 μm and 4 μm, depending on the coolant film. Further work is being done on reducing or compensating for this contributing factor.

In recent years there has been great momentum in the field of optical sensors. Other physical effects and combinations of known principles of measurement will be used for new sensors systems. The standardisation of interfaces will enable new optical distance sensors to be integrated; here the risks will be calculable and the procedure less and less time consuming [14].

Acknowledgement

The authors wish to thank CTI, the Swiss Confederation's innovation promotion agency at the Federal Department of Economic Affairs, for financial support.

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