Chromatic confocal sensor for in-process measurement during lathing

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There is a growing interest in monitoring systems to evaluate the quality relevant features as close as possible to the machining, thereby reduce the time lack between production and measurement. By the establishment of a quick feedback loop the reject due to defects can be minimized because errors in the production process can be detected with close temporal proximity to the machining. However, for implementation of optical sensors near the machining process new concepts and designs are needed to achieve a robust and miniaturized sensor probe. Chromatic confocal microscopy is a promising approach to obtain measurements near the production due to the fact that the height of a point can be determined with a single shot. For this reason a miniaturized design of a chromatic confocal sensor based on gradient index lenses is presented. The modeling and optical design is presented and a layout of a sensor is developed using a diffractive optical element for the axial chromatic split of the light. In a further step considerations of the fabrication process are summarized and first results are presented.

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NOMENCLATURE

DOE = Diffractive Optical Element

GRIN = Gradient Index

1. Introduction

For a reliable production control of the quality of the produced goods is necessary. Till this day it is still common to obtain quality control in standards laboratory by measuring all relevant parameters on control samples. The drawback of this spot checking is, that if a error in production occurs a high amount of reject will be produced before the problem is detected. Therefore the aim is to reduce the time between measurement and feedback. At best, the measurement could be obtained directly during or at least directly after machining but still in the machining process [1].

For the control of quality relevant features there are in general two approaches that are already state of the art: tactile measurement systems e. g. coordinate measurement systems, and optical measurement systems. However these sensors are usually not able to operate in the production environment. For this reason in this investigation a concept for a optical sensor will be presented that can be used in production environment.

Therefore a short review of optical measurement systems will be given to come to a conclusion which principle offers the highest potential to solve this problem. For the chosen principle the modeling and design of a miniaturized sensor will be presented that will be suitable for an integration of a lathing tool. To close this investigation the fabrication process of the sensor will be presented and some critical aspects concerning the manufacturing will be discussed.

2. Considerations regarding the lathing process

The aim of this contribution is to develop a sensor that can be integrated into a lathing tool. The critical aspect is to develop an optical sensor that is able to obtain a reliable measurement even in the production environment [2]. To come to a conclusion which sensor system can be used and what accuracies can be achieved, a consideration of the production process has to be obtained. In this contribution the lathing process is chosen as an example of a machining process.



Fig. 1: Schematic integration of an optical sensor into a lathing tool

As machining occurs in general not in controlled environment, there is temperature variation present at the shop floor. In addition there are mechanical vibrations existing. Both factors lead to a disturbance in the measurement signal.

Another main reason for failures in the in-line measurement during machining with optical sensors is given by the contamination of cooling liquid or metal chips on the surface. Especially liquid on the surface has due to the differing refractive index, an effect to the measurement result because the optical path difference (OPD) will change [3].

In lathing there is the big advantage that the tool is stationary and the machined part is turning. For the integration of an optical sensor near the servicing point it is sufficient to implement the sensor somewhere in the tool holder. For the measurement the turning axis of the production machine can be used to gather data of the outline of the produced good.

3. Considerations regarding the selection of the optical measurement principle

The measurement task is to gather quality relevant data of an object in the lathing machine while lathing occurs. Given that the rotating axis can be used for the measurement it is sufficient to have a point detector. By measuring while turning a line of the object surface is measured. Due to the feed of the turning tool it is possible to obtain a measurement of the whole surface of the product in the lathing machine. With that it is important to select a sensor principle that can measure a height profile at one point in one shot. Another demand is that the measurement principle should allow miniaturization of the sensor because of the often encountered limitation of space near the machining tool. Following the classification of optical sensors from [4] there are three different classes: triangulation systems, focus systems and interferometric systems.

- **Triangulations systems** (e. g. laser triangulation, fringe projection, deflectometry,...) allow a calculation of the surface topography by evaluating a given structured light pattern used for illumination. Due to the triangulation angle the detected pattern is varying from the generated pattern and is a function of the surface topography.
- Focus systems (e. g. autofocus sensor, confocal microscopy,...) determine the object position by searching the best focus for each object point.
- Interferometric systems (e. g. laser interferometry, white light interferometry,...) evaluate an interference pattern that is

generated by an interaction of coherent light from a reference surface and from the object.

Due to the requirement for the given task, a point sensor with a high possibility for miniaturization is needed. Hence triangulation systems may have a drawback because they need two pupils (one for illumination, one for imaging) with a certain triangulation angle. Interferometric systems need a reference and an object wave for the detection of the topography. With that the setup of the system is more complex than other principles. Therefore they might not be as robust as the other principles. Consequently focus systems show due to their simple and robust set up and their ability for miniaturization a good possibility for the integration into the lathing process.

In focus systems chromatic confocal microscopy has a unique status. Due to the evaluation of a broadband signal it is possible to detect the height position of a point with one shot [5, 6]. This is obtained by using a broadband light source. The optical design is obtained in a way that a wavelength depending axial shift of the focal plane for each wavelength is generated (see Fig. 2). With a confocal filtering using a pinhole and a detection of the light using a spectrometer, the wavelength depending intensity is recorded. With an evaluation of the detected spectrum a determination of the height position is obtained.



Fig. 2: Schematic signal recording in chromatic confocal microscopy a) longer wavelength: Light focused in front of the object b) design wavelength: Light focused at the object c) shorter wavelength: light focused behind the object

4. Optical Design of the Sensor system

For the implementation of an optical sensor near the machining tool it is necessary have a robust principle that has the potential for a high miniaturization. Considering the short review of optical measurement principles given in chapter 3, chromatic confocal microscopy seems to be a promising approach. With it a one-shot measurement is possible and it allows a miniaturized, simple and robust design of a sensor. Therefore the design of a chromatic confocal point sensor will be presented, that is suitable for implementation into the production environment near a lathing tool.

The first task is to develop a concept to obtain a miniaturized design. Therefore the preferred possibility is to use gradient index (GRIN) lenses. The basic principle is that a material with an inhomogeneous refractive index is used [7]. Due to the continuously increasing refractive index in a glass rod an arched light path is generated and with that a lens effect is obtained. For this reason it is possible to design optical systems with small dimensions (i.e. a diameter of afew millimeters and a length of a few tens of millimeters).

To obtain the axial shift of the focal plane for each wavelength it is common to use the chromatic aberrations that are induced by each glass. If not corrected, these aberrations have the desired effect to generate a different focus position for each wavelength. The drawback of this approach is, that a certain amount of glass is needed to generate a sufficient focus shift over the bandwidth of the light source. Another possibility to realize a high axial measurement range, is to enforce the axial chromatic split by the use of a diffractive optical element (DOE).

In Fig. 3 the layout of the proposed sensor is displayed. To get a high axial measurement range the chromatic axial split is obtained with a diffractive optical element (DOE). With that it is possible to use a light source with a bandwith of 60 nm to realize a axial measurement range of 300 microns. As light source a fiber coupled superluminescence diode is used. The single-mode fiber can be assumed as a point light source. On the return path it is used as the confocal pinhole. With a GRIN lens, the light is collimated and a DOE is used to focus the light to the object and to obtain the chromatic axial split. In Table 1 all relevant data of the designed chromatic confocal sensor are summarized.

Bandwith	800-860 nm
Numerical Apertur	0.17
Airy spot radius	2.9 µm
Depth measurement range	≈300 µm
Sensor diameter	2 mm
Sensor length	≈15 mm

Table 1: Specifications of the chromatic confocal sensor



Fig. 3: Layout of an chromatic confocal sensor based on GRIN lenses and DOE

The optical sensor design is obtained using ZEMAX. For the design the parameters of the DOE serve as a degree of freedom. The obtained design and the performance is shown in Fig. 4. The point sensor has a diffraction limited imaging with an airy spot of 2,9 μ m and a wavefront flatness of $\lambda/30$. The needed phase map of the DOE is shown in Fig. 4 c) to generate a diffraction of the 1. order to get the desired effect for the element.





Fig. 4: Design of the chromatic confocal sensor a) Sensor layout b) Spot diagramm of the middle wavelength c) Wavefront map of the middle wavelength d) Phase plot of the DOE

The DOE is the critical element in this design and needs some special considerations. For the fabrication it is easier and more reliable to produce a binary approximation of the ideal sawtooth phase grating. For the diffractive element it has to be considered, that there are different diffraction orders. The diffraction efficiency for these orders can be calculated for a binary grating with [8, 9]

$$\eta_q = \operatorname{sinc}^2\left(\frac{q}{2^N}\right) \frac{\operatorname{sinc}^2\left(q - \frac{\Phi_0}{2\pi}\right)}{\operatorname{sinc}^2\left(\frac{q - \frac{\Phi_0}{2\pi}}{2^N}\right)}$$

where q is the diffraction order, N the discrete level of the binary grating, and Φ_0 the peak-to-peak thickness variation. With a peak-to-peak phase difference of 2π this formula simplifies to:

$$\eta_q = \operatorname{sinc}^2 \left(\frac{q}{2^N}\right) \frac{\operatorname{sinc}^2(q-1)}{\operatorname{sinc}^2 \left(\frac{q-1}{2^N}\right)}$$

The numerator of the ratio of the two sinc functions is zero for all integers of N except for:

$$q = p2^{N} + 1$$

With that, the diffraction efficiency simplifies to:

$$\eta_{(p2^{N}+1)} = \operatorname{sinc}^{2}\left(p + \frac{1}{2^{N}}\right)$$

With this equation the nonzero diffractions efficiency can be calculated, these are plotted in Fig. 5. The first diffraction order is given for p=0. It is obvious that with a rising approximations all diffractions order are almost vanishing apart from the first. This is the one used for the optical design. With that it has to be guaranteed that the other orders are small compared to the first order. It means that at least an approximation level of N=2 has to be choosen. In that case an efficiency of \approx 80 % is achieved for the first diffraction order and the -1, which is the order that has the highest contribution in the case of N=2, has an efficiency of less than 10%.



Fig. 5: Diffraction efficiencies of all non-zero diffraction orders of a grating with a stepped approximation to an ideal sawtooth grating.

5. Fabrication of the chromatic confocal sensor

The main challenge in the fabrication process is to write the DOE to the front surface of the GRIN lens. Due to the small diameter of these elements it is not trivial to obtain that task. The GRIN lens is generated by a laser writing process of the structure into photo resist. For this task a custom laser direct writing system CLWS300M [10] at the Institut für Technische Optik (ITO) is used (see Fig. 6).



Fig. 6: Laser plotter for laser direct writing into photoresist developed at the ITO

For the fabrication, the GRIN lens is assembled in a specially designed chuck. With it, it is possible to level the front surface of the GRIN lens with the surface of the chuck. Only if that is guaranteed, it is possible to obtain spin-coating of the photo resist. This chuck is then assembled in the laser plotter to write the desired DOE phase structure. Afterwards, the element is developed in a chemical process. In Fig. 7 the diffractive structure generated in the photo resist is displayed.

With the DOE written to the GRIN lens, the chromatic confocal sensor needs to be assembled. Therefore a single mode fiber mounted in a glass ferrule is joint and glued to the GRIN lens. To protect the sensor from the production environment it is necessary to assemble a cover glass at the front.



Fig. 7: Laserstructured photoresist at the front surface of a GRIN lens

6. Conclusion

In this approach a design of a chromatic confocal sensor was presented that can be implemented into the production environment of a lathing process. The optical design was obtained based on GRIN elements to get a miniaturized design of the sensor. By designing the DOE as a focusing element on the front surface of the GRIN lens, the axial chromatic split is obtained and a diffraction limited spot is achieved.

Furthermore, the first considerations and results of the fabrication of the DOE to the GRIN lens were presented. As the next step, the integration of the designed sensor has to be obtained.

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