Key Figures for Reviewing the Dimensional Accuracy of Polymer Optical Waveguides in Modular Sensor Networks

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Summary: Structural health monitoring in mechanical engineering is a topic of recent research projects. Especially the monitoring of production processes is used to obtain valid data on how product quality can be optimized. Within the Collaborative Research Centre 653 a photonic based sensor network is used for monitoring of production processes. For future applications the required energy to drive remote sensor systems shall be supplied by optical means only as well as transmitting the signals for sensor control and data exchange. Therefore, the transmission losses of the optical waveguides have to be minimized. Transmission losses of optical waveguides can be divided into intrinsic and extrinsic losses. This paper will introduce the key figures for evaluating the dimensional accuracy of optical waveguides caused by the production process (extrinsic losses). The goal is to ensure a quality of the geometrical characteristics within the production process, resulting in minimized transmission losses.

Keywords: Optical, Sensor, Network

1. Motivation

Developing parts which exhibit a physical breakup of device and related information is the vision of the CRC 653 ‘Gentelligent Components in their Lifecycle – Utilisation of Inheritable Component Information in Production Engineering’ [1]. More than 15 different research projects are focusing on different techniques of writing and reading information in the surface zone of mechanically stressed devices, on new sensor concepts to measure load during the time of device production and lifecycle as well as communication strategies for data exchange between different components and at component level.

For the communication at component level a new production process, the dispensing of polymer optical waveguides was developed. In order to establish photonic based sensor networks in machine tools for the monitoring of production processes, one aspect of current research is the optimization of dispensed optical waveguides towards a parallel signal and energy transmission. To achieve these research goals, the optical waveguides have to have a high transmission rate. The transmission rate is influenced by the optical polymer itself as well as by the production process, related to the dimensional accuracy [2]. By optimizing the dimensional accuracy of the dispensed waveguides transmission losses will be reduced. This paper will introduce the key figures for reviewing the dimensional accuracy of optical waveguides.

2. Methodology

2.1. Application of Gentelligent Technologies

One of the essential objectives within the framework of the CRC 653 is to apply new methods and techniques for storing, reading, writing, communicating and utilising data within defined scenarios in order to demonstrate the feasibility of gentelligent production. A sensitive milling machine, for example consisting of a z-axis with integrated micro sensors [3] and optical waveguides, will ensure the monitoring of process forces. The manufactured metal component uses an integrated hybrid waveguide, consisting of an RFID transponder and an optical link for energy transmission [4], to inherently store process step data needed to guide the part through the production area as well as ensure communication between different components. Further information such as identification numbers will be stored magnetically [5] within the milling tool. Such technologies warrant that the whole production process is monitored.

A future aspect of the CRC is to combine process information with applied load data coming from the lifecycle of the component. Strategies for intelligent maintenance and effective reconstruction of next generation parts are objectives of the CRC.

2.2. Dispensing of Polymer Optical Waveguides

The main motivation for this sub-project within the CRC 653 is the development of a production process which ensures communication at component level. The aim is to implement a new process assuring the manufacturing of data links on 3D shaped metallic components. Later on, these data links will be evaluated to ensure parallel signal and energy transmission at component level for powering self-sufficient micro sensors. Currently, no method for optimizing the overall characteristics of integrated waveguides and consequently the production process is known. First of all, if the attenuation is measured with sources, receivers and environmental conditions close to practical use, the obtained results will be useful for optical system design only [6]. For process development reasons, a different characterization standard for measuring optical attenuation is needed. Therefore, the length-dependent attenuation by varying different types of excitation is measured [7]. Secondly, by evaluating different process parameters like dispensing pressure or the distance of the dispensing needle to the substrate an optimization of geometrical characteristics will be ensured. By introducing key figures for quantifying the differences in geometrical waveguides characteristics time consuming experiments will be reduced.

It takes three stages to produce a step-index waveguide. By use of a time-pressure dispensing system, the optical polymer with a low refractive index is applied to the metallic component. Figure 1 illustrates the stages of manufacturing a step-index waveguide within a trench structure. This first layer will be the optical cladding of the waveguide. Afterwards, a second optical polymer with a higher refractive index is dispensed onto the first cladding layer. Finally, the structure is covered with the optical cladding. After every stage of production, the optical polymer has to be cured by UV-irradiation. Typical lengths of dispensed waveguides are in the cm range. The adjustable cross section of the trench may vary between 0.3 mm and 1.0 mm [8].

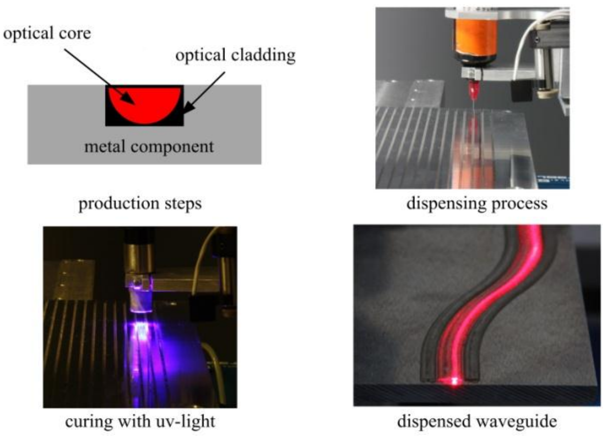

Figure 1. Process technology of manufacturing dispensed optical waveguides.

3. Definition of Key Figures

3.1. Evaluation of the cross sectional area of polymer optical waveguides

For reviewing the dimensional accuracy of a waveguide over its internal length, the relative standard deviation of the cross sectional area (RS_{csa}) is calculated (Eq. 1) for a defined number of increments. Each of these increments then marks the beginning of a new segment such that the number of segments equals the number of increments. For each segment the surface area $A_{profile}$ is calculated by using equation 2. Variable z marks the profile height and Δx the step size of the profile width (cf. chapter 4).

$$RScsa = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(A_{profile} - \bar{A}_{profile}\right)^2}}{\frac{1}{n}\sum_{i=1}^{n} A_{profile}} \cdot 100 \qquad (1)$$

$$A_{profile} = \left(z_i \cdot \Delta x\right) + \left(z_{i+1} - z_i\right) \cdot \frac{\Delta x}{2} \qquad (2)$$

The smaller the differences in surface area, the better the dimensional accuracy of the waveguide, resulting in a minimal value for RS_{csa}. Besides the dimensional accuracy, the cross sectional shape may influence the transmission characteristics as well.

3.2. Evaluation of the cross sectional shape of polymer optical waveguides

Due to the physics of light propagation in an optical waveguide, the light is transmitted or refracted at the surface boundary between optical core and cladding. The direction of propagation depends on the geometry of this interface and the inclination angle, leading to different optical path lengths. Figure 2 plots a real profile of a dispensed waveguide (red line) and 3 profiles with different deviations from a semi-circle.

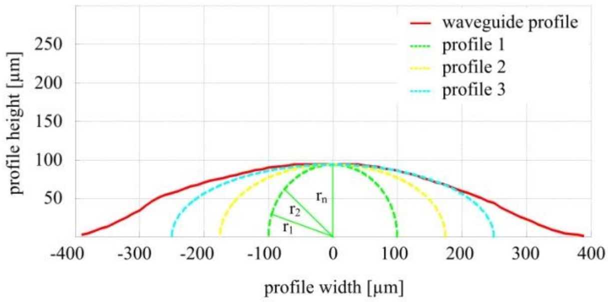

Figure 2. Comparison of different cross sectional shapes .

The relative standard deviation RS_{rad} of the profile radius of each cross section is calculated by equations 3, 4 and 5. For each cross section the radius r_i is calculated (Eq. 5). The relative standard deviation for one cross section $r_{profile}$ (Eq. 4) of these radii will be clearly indicative of whether this profile is close to a semi-circle or not.

$$RSrad = \frac{1}{n}\sum_{i=1}^{n} r_{profile} \qquad (3)$$

$$r_{profile} = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(r_i - \bar{r}\right)^2}}{\frac{1}{n}\sum_{i=1}^{n} r_i} \cdot 100 \qquad (4)$$

$$r_i = \vec{r}_i = \begin{pmatrix} x_1 - x_1 \\ z_i - z_1 \end{pmatrix} \qquad (5)$$

The RS_{rad} calculated for the profiles illustrated in figure 2 are 0 % for profile 1, 19.1 % for profile 2, 28.9 % for profile 3 and 42.2 % for the waveguide profile. These results show that the defined key figure is able to distinguish between different cross-sectional shapes with reference to a semi-circle.

4. Experimental Results

In a first trial, the quality of the defined key figures was evaluated. It involved the variation of 3 production parameters as well as the surface characteristics of the aluminium substrate by varying the surface roughness. Each substrate under the test was exposed to 3 different traverse speeds. For each traverse speed, the dispensing pressure and the distance of the dispensing needle from the substrate were varied at 5 steps (cf. Fig. 5). After the production process, the waveguides were prepared for analysing the geometrical characteristics. The Institute of Micro Production Technology covered the waveguides by sputtering 50 nm of chrome. Because of the high transparency of the optical polymer and the high reflectivity of the aluminium substrate, this step was necessary to enable the measurement of the waveguides by using a confocal point sensor. Figure 3 illustrates the results of calculating RScsa and RSrad of an example waveguide.

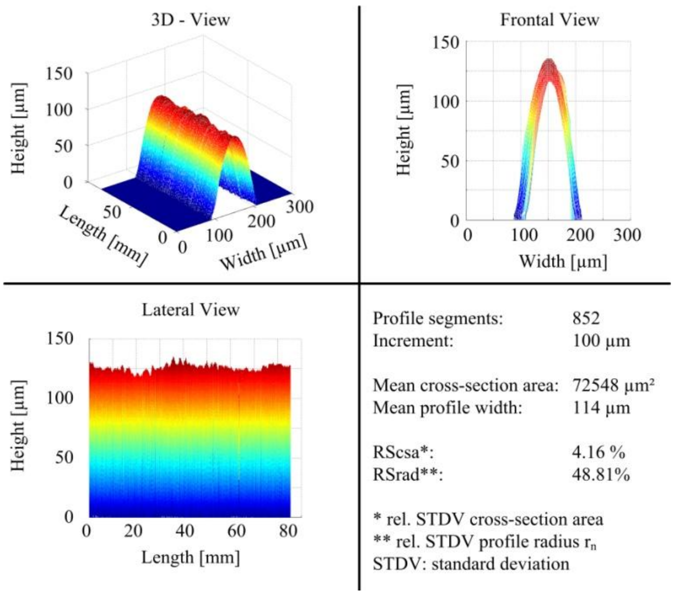

Figure 3. Evaluation of a dispensed optical waveguide (optical core only) by using key figures RScsa and RSrad.

The waveguide's (optical core only) internal length is 8.5 cm. For the purposes of optically measuring the geometrical characteristics, the step size in x-direction (width of the waveguide) was set to 10 µm and the step size in y-direction (length of the waveguide) was set to 100 µm. Resulting in a matrix with the height information (z-variable) for each measurement point in the x- and y-directions, RScsa and RSrad were calculated as described in chapter 3.

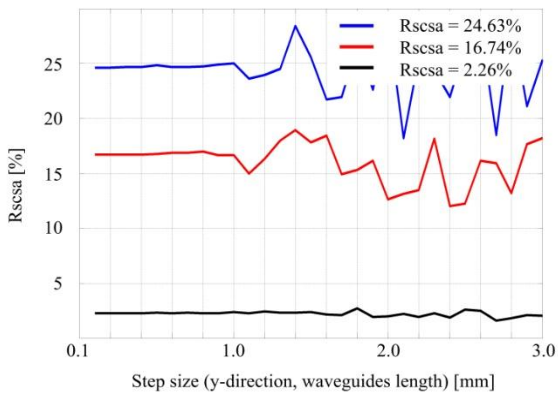

Figure 4. Results calculating RScsa for different step sizes.

Figure 4 shows the results calculating RScsa for different step sizes. The influence on how the step size changes the calculated RScsa is shown. Future measurements of the geometrical characteristics by means of confocal point sensors will do with a step size of 1.0 mm. Last but not least, Figure 5 shows examples of how different process parameters influence RScsa results. This example shows, the main impact on dispensed waveguides geometrical characteristics has the dispensing pressure.

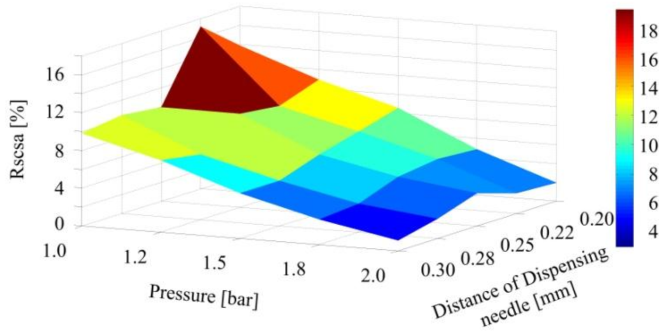

Figure 5. Suggests that dimensional accuracy is mainly influenced by the dispensing pressure.

5. Conclusion

The defined key figures can be applied to evaluating the dimensional accuracy of dispensed optical waveguides. First experimental results show the potential of the key figures to quantify small changes in the geometrical characteristics of optical waveguides in order to obtain a feedback from the production process. Future research will demand statistical verification of these key figures. Furthermore, the simulation of optical attenuation will be correlated with attenuation measurements.

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