WP2

D2.1 - Development of the first generation inline measurement system

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INTRODUCTION

ADALAM Context

Workpackage context

The main objective of this work package is to design and implement a complete solution for an inline topography measurement and analysis for monitoring before, during and after the laser micro machining. The following approach integrates a high-resolution optical distance measurement system in the beam path of the laser micro machine, enabling an in-line measurement of the current state of the machined micro- and macro-structures directly in machine coordinates. Based on this device an automatic and adaptive process will be enabled. The following solution uses a low coherence spectral interferometer in a Michelson-type set-up, with a measurement path through the scanning optical system and an external reference path.

One of the biggest challenges herewith are the very high axial and lateral tolerances of the process. Especially the required lateral tolerances under 10 µm demands special developments on the measurement system and on the machine optical system.

Moreover the high shape and feature variation of the workpieces to be manufactured represents a further challenge especially in regards to the numerical aperture of the optical system as well as to the measurement data processing and analysis.

Finally the overall optical effects of the scanning optics (scanning mirror and objective) represent a challenge for the measurement system regarding effects on the optical path, measurement spot diameter, laser and measurement beam coaxiality. Especially the internal dispersion properties of a telecentric scanning lens cause a wavelength and field angle dependent change in the measurement beam's focal length and beam waist diameter. Furthermore the optical path of the measurement beam is distorted by the optical aberration of the optical system. This effect is in addition position dependent, leading to a position dependent optical path.

These effects need to be characterized and compensated in the measurement system unit and integration / coupling unit. The sensing unit will rely heavily on the use of adaptive optical elements. An attractive feature of adaptive optics is that it can alleviate the extreme requirements on the scanning objective and can be tuned to the specific objective used in a setup after a calibration step.

In order to fulfill the main objective and cope with the related challenges four work areas / specific objectives were defined and subdivided on working groups, which are lead and executed by partners regarding their expertise. The work areas / specific objectives are as follows:

- Design and implementation of an **optical high-precision distance measurement system** optimized for the USP laser characteristics (high power and ultra short pulse duration), machine optical system and process axial and lateral tolerances;
- Concept and design of an optimized **scanning objective** with enhanced numerical aperture and lateral accuracy (reduced laser and measurement spots) as well as reduced focal depth and chromatic aberration regarding the measurement beam wavelength;
- Design and implementation of an **active alignment unit** for beam coupling and sensor integration based on adaptive optics;
- Design and Implementation of an **automatic point cloud analysis software** for feature detection and characterization for the generation of qualified information, which is feed back to the machine for process adaptation and control.

- Design and implementation of **evaluation and calibration methodology** to ensure high fidelity and reliable data. This work will be done in close collaboration with WP4.

As a second solution to comply in particular with the required lateral resolution, a high numerical aperture (NA) sensing head will be developed and attached to the machine scanning unit not using the optics of the scanning head. The measurement system device will address both sensing paths based on an optical switch (see picture in section 1), being able therefore to measure through the processing optics as well as through the high NA sensing head. This solution has the advantage of offering additional versatility to the machining head when measuring smaller structures, which are not measureable by the main sensing head.

Task context

In this task the first generation of the inline measurement system will be designed and developed. This first prototype will be the based for the investigation and development of the adaptive laser micromachining system of WP3.

This first system will be based on the existing prototype developed in IPT for the usage in nanosecond pulsed lasers and their scanning optics. For this purpose, the prototype will be improved to compensate the optical aberrations of the current state of the art scanning optics for USP lasers as well as the reflection wavelength dependencies of the scanning mirrors coatings for USP lasers.

THEORY BACKGROUND

Spectral domain low coherence interferometry

Measurement principle

As described by Schmitt et al., 2013, the measurement system used is based on the spectral domain low coherence interferometry (SD-LCI). Differently from normal low-coherence interferometers, which use a piezo element to find the maximum interference point, in the SD-LCI the depth information is gained by analyzing the spectrum of the acquired interferogram. The calculation of the Fourier transformation of the acquired spectrum provides a back reflection profile as a function of the depth. For the generation of the interference pattern a measurement and a reference path are used, where the optical path difference between these arms is detected. The higher the optical path difference between reference and measuring arm, the higher the resulting interference modulation. A standard SD-LCI setup is presented in Fig. 1.

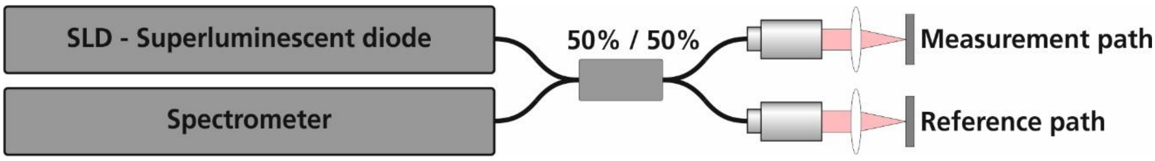

Figure 1. As described by Schmitt et al., 2013, spectral domain low coherence interferometry (SD-LCI) Set-up

According to Brezinski, 2006, the total interference signal I(k) is given by the spectral intensity distribution of the light source (G(k)) times the square of the sum of the two back reflected signals (aR as the reflection amplitude of the coefficient reference arm and a(z) as the backscattering coefficient of the object, with regard to the offset z0), where k is the optical wavenumber (see (1)).

$$I(k) = G(k)\left|a_R \exp(i2kr) + \int_{z_0}^{\infty} a(z)\exp\{i2kn(z)(r+z)dz\}\right| \quad (1)$$

where n is the refractive index, 2r is the path length in the reference arm, 2(r+z) is the path length in the object arm and 2z the difference in path length between both arms. By finding the maximum amplitude at the spectrum's Fourier transformation, the absolute optical path difference can be detected.

The measurement range is determined as the region, where the system is capable of detecting a back-reflection from a specimen. Tomlings et al., 2005, describe the maximum measuring depth (Zmax) as follows:

$$Z_{\max} = \left(\lambda_0^2 / 4n\Delta\lambda\right)N \quad (2)$$

where λ0 is the central wavelength, Δλ is the bandwidth (FWHM - full width at half maximum), n is the sample's refractive index and N is the number of detector units covered by the light source's spectrum.

The axial resolution is defined by the coherence length of the used light source. Therefore the high axial resolution is implemented independently of the beam-focusing conditions. In other words, this parameter is independent of the used imaging optic.

For a light source with a Gaussian spectral intensity distribution, Brezinski, 2006, describes the axial resolution as follows:

$$AR = l_c/2 \approx 0.44\,\lambda_0^2/\Delta\lambda \tag{3}$$

For the measurement of single distance (a single back reflection) the axial resolution can be increased to a sub-micrometric resolution by the usage of signal processing techniques, such as gauss fit. SD-LCI systems use superluminescent diodes as low coherent light sources. These sources are available in numerous configurations with central wavelengths from 650 until 2,100 nm, with different output power levels and spectral bandwidths. This warrants a large flexibility on the design of SD-LCI systems, enabling the optimization on the final application, processing head's optical system and specimen.

Literature

1. Schmitt, R., Pfeifer, T., Mallmann, G., 2013, Machine integrated telecentric surface metrology in laser structuring systems, Acta Imeko Vol. 2 Nr. 2, p. 73-77
2. Brezinski, M., 2006, Optical coherence tomography – Principles and Applications, Elsevier, pp. 130-134.
3. Tomlins, P. H., Wang, R. K., 2005, Theory, development and applications of optical coherence tomography, Journal of Physics D: Applied Physics 38, p. 2519–2535.

PREVIOUS SOLUTION CONCEPT – FRAUNHOFER IPT

In-line Measurement System

The following information and results are based on the work presented at Schmitt et al., 2013.

Spectrometer

The used diffraction grating is optimized for the wavelength of 1000 nm and has a large blaze angle of 36° 52’ as well as a high groove density per millimeter (GR50-1210 - ruled diffraction grating with 1200 lines per millimeter). Both characteristics lead to a high wavelength splitting and consequently to a compact spectrometer design. The first element on the imaging system is an achromatic lens, more specifically a AC508-150-B lens, an achromatic doublet, from Thorlabs, with a focus of 150 mm and a a diameter of 2". The second element is a meniscus lens, more specifically a LE1076-B lens from Thorlabs, with a focus of 100 mm, a diameter of 2".

Detector

Considering the challenges involved within production environment as well as on the workpiece reflection conditions, a highly robust measuring system operation and consequently a highly sensitive detector are demanded. For this purpose the best quantum efficiency within the available detector technologies was chosen for the line detector, an InGaAs-based set-up. In this context a line camera from the company Xenics (XLIN 1.7-512) was applied. This model exhibits a detection range of 900 - 1700 nm, a pixel pitch of 25 µm and a height of 500 µm. The camera includes also a Peltier cooling element for a reduction of dark current and improvement of the image quality.

Light source – Superluminescent diode

Due to the wavelength limitations of the laser scanning lens just a SLD product series from the company Superlum with central wavelength between 1000 - 1020nm is able to meet the light source specifications. The SLD type SLD-52-HP offers in this context the widest spectral bandwidth associated with a high optical output power. These properties are as well positive regarding the overall system robustness under rough and oxidized surface reflection patterns. This source was selected for the further system development, exhibiting a final configuration with a central wavelength at 1017 nm, a spectral bandwidth of 101 nm and an optical output power of 10 mW.

Prototype

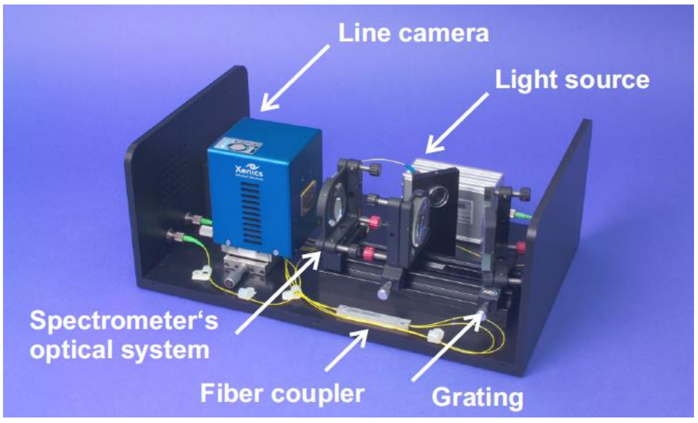

Figure 2. Prototype of the high precision in-line measurement system

Literature

4. Schmitt, R., Mallmann, G., 2013, High-precision inline measuring technology for laser structuring systems, Apprimus, p. 23-30

Concept and design of the complete measurement solution

Solution concept

The first generation measurement system will be further on based on a spectrometer for the interferogram acquisition. The system will be however updated in its concept. As a matter of update on the polarization sensitivity in the system configuration and assembly, the grating type will be changed. Transmission gratings present a higher polarization insensitivity in comparison to reflective gratings. This characteristic leads to an increase on the system robustness, when considering the optical fiber related polarization changes before the x-coupler and the reference / measurement paths. The used superluminescent diode will also be changed for a model at 980 ± 50 nm. This update focuses on an optimal beam coupling using special components for ultra short pulsed lasers with high pulse energy.

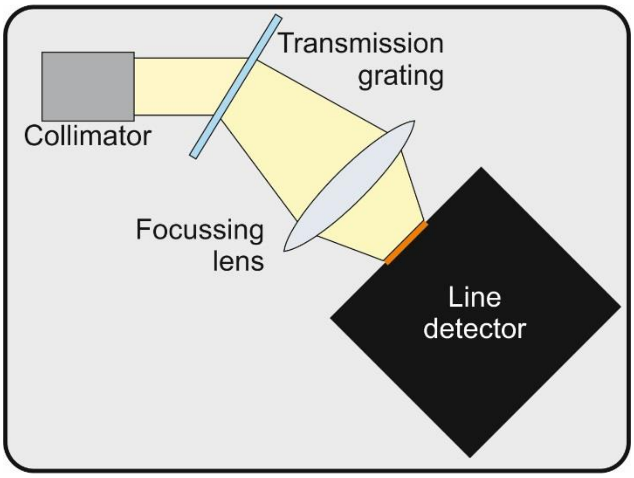

Figure 3. First ADALAM measurement system concept

Prototype system

Simulation

The chosen spectrometer design is based on the usage of a transmission grating (as mentioned) and 2 identical pairs of lenses. The lens system images the different wavelengths on the line detector based on InGaAs. This system is composed by a positive and a negative achromatic lens followed by the same achromatic lens in a different sequence. This set-up focuses on a compact construction of the spectrometer, however maintaining a small spot at the line detector.

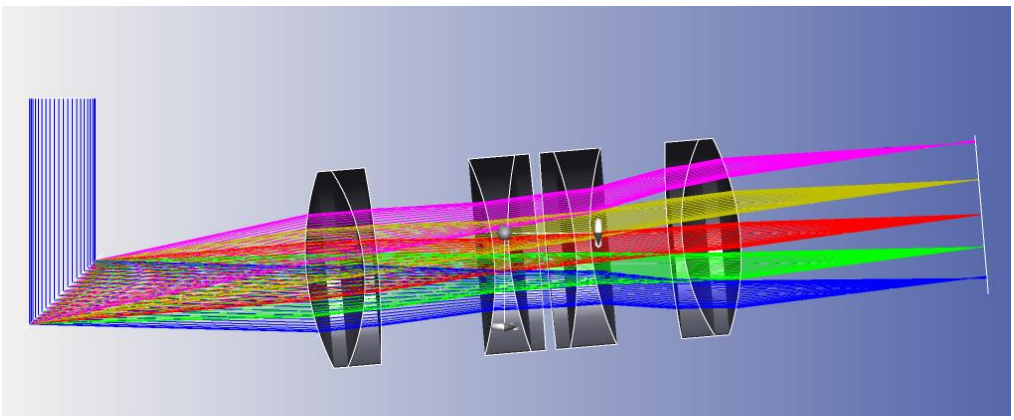

Figure 4. First ADALAM spectrometer simulated design

Hardware prototype

The measurement system prototype has a housing made of aluminium. This material helps to dissipate the dammed heat within the box due to the camera work.

The box has an interface for the camera image transfer, camera link, and for the power supply as well as a fibre connector.

Figure 5. First ADALAM spectrometer prototype

Evaluation and calibration of the measuring system

With the aim of ensure that the system acquires high fidelity data with the demanded accuracy for dimensional quality control in the micron range, a new methodology will be defined.

Taking in consideration the current state of the art related to the calibration methods for optical system, new patterns or artifacts will be designed. Geometries and space distribution will be selected according to the working volume and accuracy. Figure 6 shows two examples of artifacts, based on spheres (left) and based on prisms (right), depending on the main measures or properties of the measuring system the appropriate one is selected.

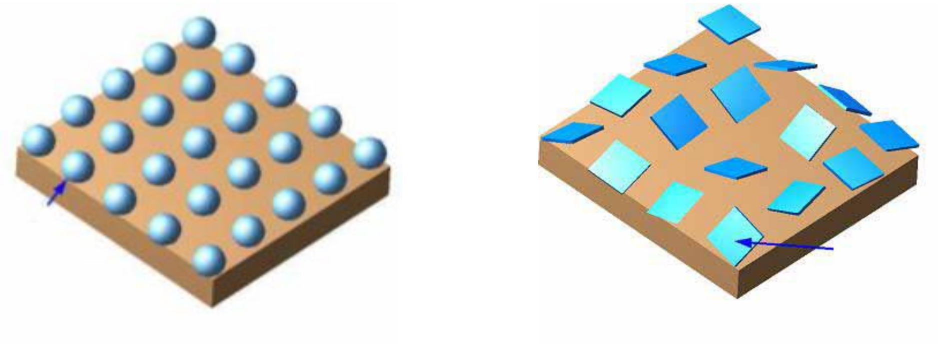

Figure 6. Examples of artifacts based on spheres (left) and prisms (right)

Thus, by the exploitation acquired by the measure of geometries and distances of these artifacts, it will be possible to generate a complete characterization of the measuring system. The identification and quantification of deviations and errors will allow to correct and properly set up the system to be exploited by the laser machine for adaptive machining.

Data management

Once it is ensured that data acquired by the system are reliable and free of deviation and offsets, they will generate point clouds, high fidelity digital representation of the physical part surface. This will be then used for digital geometry extraction, providing quantitative information concerning the micromachining features quality.

Geometry extraction will be carried out due to two main factors:

1. Reliable data acquisition: Achieved by calibrated measuring system.
2. Certified algorithms: In this way, final results will be free of errors coming from data processing software. DATAPIXEL will used algorithms already certified by PTB (Physikalisch-Technische Bundesanstalt).

An example of this data processing is shown in Figure 7, a color mapping resulting from the comparison between a master drill and other samples of the same batch is presented.

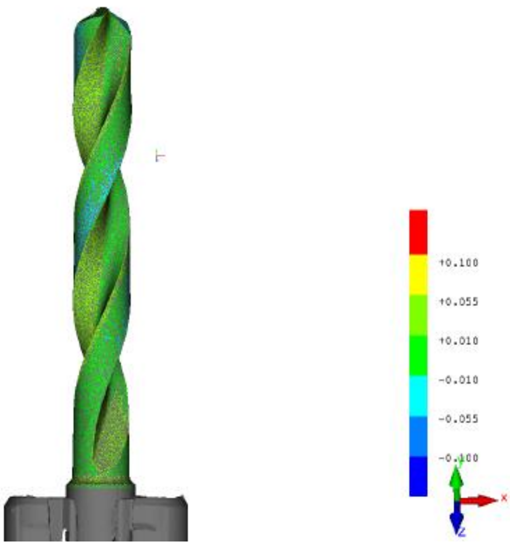

Figure 7. Example of a drill's point cloud comparison to its target shape (Sandvik Coromant)

NEXT STEPS

Once this first prototype is developed the next steps will be the following:

- The integration of this prototype in a laser micro processing machine from Lightmotif and the adaptation of the supporting units (specially, reference path and coupling unit).
- Based on the fully integrated system, a series of testing experiments will be carried out, focusing on the system's usage for the machine automation and control.
- Design and implementation of the second generation system and its units (Task 2.3, 2.4., 2.5., 2.6., 2.7.).
- From the experience of the data acquisition and the geometries to be extracted depending on the use cases, the point cloud analysis will be totally automated in terms of geometries measurement, reporting and communication with other tools.
- After the evaluation of the quality of the data acquired, this system will also be exploited for evaluation and calibration of the machining system. It will be used to scan the certified dimensional artifacts to monitor the accuracy of the location machinery.

All these tasks are aligned with the WP2 and WP3 structure, the main goal is to have a second version of the measuring system by M20. Then, it will be completely evaluated and characterized by M24.