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MACHINE INTEGRATED TELECENTRIC SURFACE METROLOGY IN LASER STRUCTURING SYSTEMS

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Abstract: The laser structuring is an innovative technology used in a broad spectrum of industrial branches. There is however a market trend to smaller and more accurate micro structures, which demands a higher level of precision and efficiency. In this terms, an inline inspection is necessary, in order to improve the process through a closed-loop control and early defect detection. Within this paper an optical measurement system for inline inspection of micro and macro surface structures is described. Measurements on standards and technical surfaces are presented, which underline the potential of this technique for inline surface inspection of laser structured surfaces.

Keywords: inline metrology, frequency-domain optical coherence tomography, surface inspection, laser structuring.

1. INTRODUCTION

The functionalization of surfaces based on laser machining is an innovative technology used in a broad spectrum of industrial branches. Its main advantage against other machining processes is the high process flexibility achieved. This technique permits the structuring of different work pieces (different form and complexity) with the same machine tool configuration. Application examples can be found to minimize air resistance, reduce operating noise, optimize the manufacturing of tools and moulds [1] and minimize friction losses on innovative products [2].

There is however a market trend towards the improvement of the overall process quality and automation as well as towards smaller micro structures. The fulfillment of these demands are at present limited by the absent of a sufficiently described overall process model as well as the absent of a robust and accurate inline process monitoring technique.

On the one hand the missing process model leads to a the time consuming effort to initialize the laser structuring of new products. This procedure depends on the applied material composition, product form and surface roughness. If the process behavior is unknown for a determined workpiece, laser parameters and suitable machining strategies have to be identified in a trial and error testing before the real machining process can be set-up. In this context reference geometries need to be laser structured and analyzed outside of the machine tool until a suitable parameter set is found. On the other hand the absent of a process control based on the real machined surface causes a high degree of inefficiency. This is explained by the inability of the machine to identify process defects during the machining procedure, leading to an increased possibility of rejected parts with a high degree of added value.

For solving this task with a high level of compatibility and integration, an optical distance measurement technique based on the frequency domain optical coherence tomography (FD-OCT) is presented. The described telecentric measurement through the laser machining optics enable a fast and highly accurate surface inspection in machine coordinates before, during and after the structuring process. Based on this process monitoring a machining control can be set-up, leading to a fully automated process adjustment and manufacture procedure.

2. STATE OF THE ART

2.1. Laser structuring process

The laser structuring technology utilizes thermal mechanisms to machine a part, which are induced throw the absorption of high amounts of light. The physical interaction of laser radiation and matter is therefore a crucial point in this process. Its efficiency is associated to laser and material properties, as applied wavelength, focus radius, angle of incidence, laser pulse repetition frequency, material light absorption, surface roughness and metal temperature [1]. Typical working wavelengths for the machining of metals and its alloys are 1064 nm (infra-red light) or 532 nm (green light). The guidance of the laser beam throw the part's surface is accomplished in most systems using a rastering system or a laser scanner [3]. This configuration uses computer numerically controlled galvanometer mirrors to deflect and a f-theta objective to focus the laser beam over a structuring area. This lens is wavelength optimized to focus the chief ray of the laser beam normal to the scanning field regardless of the scan angle, as well as to make the traveled distance of the laser spot on the focal plan directly proportional to the scan angle [4].

2.2. Laser structuring process monitoring

Inline process monitoring solutions for laser based structuring systems currently being developed in the academy or in the industry show technical limitations. The technologies available present in part low accuracy, no depth information or are not able to measure directly in machine coordinates. In [5] an approach using conoscopic holography is used. This technique is not able to measure directly in machine coordinates, inserting transformation errors and measurement displacement. In [6] a technology based on the acquisition of process generated optical emissions is presented for the monitoring of the selective laser melting process. A similar approach can be also applied on laser structuring systems. This technique is not able to deliver any direct depth information, just being able to monitor the amount of energy absorbed in the machining procedure.

3. SOLUTION CONCEPT

The solution concept for the machine integrated FD-OCT measurement system was designed based on the rastering system machine layout (Fig. 1). As measurement system an optical distance measurement technique based on the frequency domain optical coherence tomography (FD-OCT) was used. The system integration is accomplished through an optical element as beam splitter.

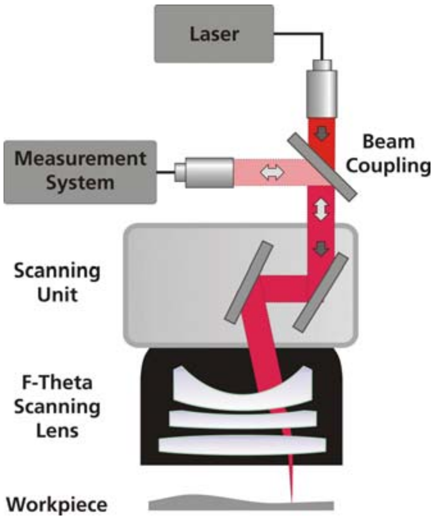

Fig. 1: Solution concept

3.1. frequency domain optical coherence tomography (FD-OCT)

The FD-OCT is a measurement technique based on the low-coherence interferometry, using for it a broadband light source, as a superluminescent diode (SLD), which has a low temporal coherence. Differently from normal low-coherence interferometers, which use a piezo element to move through the measurement range and find the maximum interference point, in the Fourier domain technique the depth information is gained by analyzing the spectrum of the acquired inter-ferogram. The calculation of the Fourier transformation of the spectrum provides a back reflection profile as a function of the depth. Depth information is obtained by the different interference profiles from different path lengths in both arms (reference and measuring arms), where the higher the path difference between reference and measuring arm, the higher the resulting interference frequency signals (Fig. 2).

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 (a_R as the reflection amplitude of the coefficient reference arm and a(z) as the backscattering coefficient of the object signal, with regard to the offset z_0) [7].

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

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 pathlength between the specimen and the reference arm.

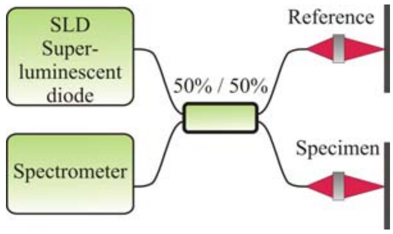

Fig. 2: FD-OCT Set-up composed of a low-coherence light source (SLD), a fiber based coupler, a reference and a specimen arm and a spectrometer for the signal acquisition and processing.

By finding the maximum amplitude peak at the spectrum's fourier transformation, the absolute optical path difference relative to the reference arm can be detected.

The maximum measuring depth, Z_{max}, of a FD-OCT system is described by: [8]

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

where λ_0 is the central wavelength, $\Delta\lambda$ is the bandwidth, n is the sample's refractive index and N is the number of elements of the spectrometer detector.

The axial resolution of a FD-OCT is described by: [8]

$$AR_{FD-OCT} = l_c/2 \approx 0.44\,\lambda_0^2/\Delta\lambda \quad (3)$$

For the measurement of single distance measurements (a single back reflection) the axial resolution can be increased to a sub-micrometrical resolution by the usage of signal processing techniques, as the fitting of a parable.

3.2. Measurement system prototype

The measurement system set-up was designed with the aim to minimize optical aberration caused by the scanning lens. At the same time the system should be able to couple laser and measurement beam using an edge filter or dichroic beam. Therefore the possible measurement wavelength range was defined to be close to the machining laser wavelength (1064 nm), between 900 nm and 1060 nm.

The spectrometer for the interference signal acquisition was developed with a measuring range of 107 nm, which can be adjusted in the absolute frequency range from 900 to 1100 nm depending on the light source to be used (Fig. 3).

As a detector an indium gallium arsenide (InGaAs) line camera was used. Standard silicon based detectors present quantum efficiencies of less than 20% for the applied wavelength range against values between 60%-80% for InGaAs (1,7 µm) based detectors [9]. The light source used in the measurement system is a superluminescent diode with central wavelength at 1017 nm and wavelength range of 101 nm. The light source's max. optical power is 10 mW.

The theoretical measuring range (maximum depth scan) of the developed FD-OCT using the presented SLD light source was calculated using equation 2 to be of 1,31 mm. The available measurement range was evaluated using a precision linear translation table. The results showed a maximum distance measurement of 1,25 mm using a specimen of aluminum with a technical surface, which simulates the workpieces used for the laser structuring. The theoretical axial resolution of the system calculated based on equation 3 is 4,58 µm. The usage of a gauss fitting algorithm to find the modulation frequency after the fourier transformation of the acquired light spectrum, increases the axial resolution by calculating a sub-pixel accurate curve maximum. Based on this technique an increased axial resolution could be achieved. The standard deviation of the distance measurement values acquired in the center of the scanner field was of 218 nm. A detailed analysis of the measurement system is presented in [10].

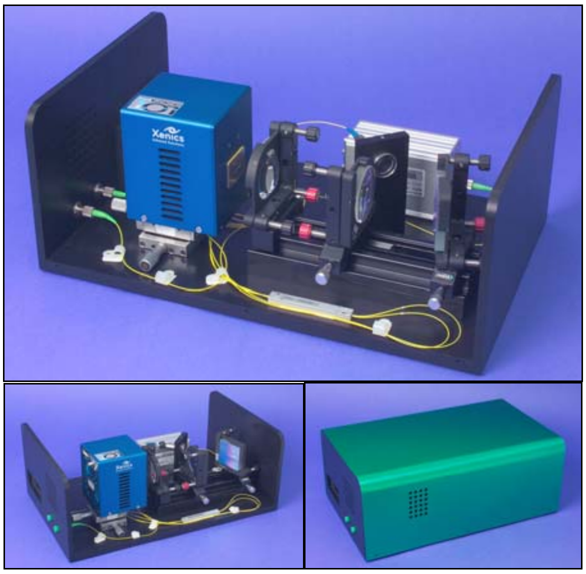

Fig. 3: Measurement system based on fourier domain low coherence tomography.

3.3. Beam coupling

The concept chosen for the integration of the developed FD-OCT in a laser structuring machine is based on an optical filter or a dichroic beam splitter used as an optical coupler. The coupling is accomplished by using this optical element in the reflective area for the measurement wavelengths and in the transmissive area for the structuring laser wavelength.

A very important requirement on this system is the laser beam's transmission efficiency. The laser beam coupling performance will be directly connected to the machine process energy efficiency as well as to the overall heat development on the coupling system. In order to warrant a robust system without long time deviations and without energy loses an optical element with a transmission of near to 100% needs to be chosen.

Another important system requirement is a highly accurate beam alignment. A misalignment between laser and measurement beam will lead to a displacement between the laser and the measurement spot, causing a mismatch / uncertainty in the measurement results.

The developed coupling system meets the described demands and enables a system integration by an unique machine hardware change. The insertion of a coupling optical element in the laser beam path with a determined angle (45° for a dichroic beam splitter or a wavelength dependent angle for an optical filter) fulfills the complete integration. The component disposal for the beam coupling can be seen in the prototype setup presented in Fig. 4.

The coupling efficiency of the concept was evaluated using an optical edge filter for the wavelength 1064 nm. By changing the angle of the edge filter, the edge frequency between reflection and transmission is displaced. By an angle of 23° the edge frequency is adjusted in such a way, that the filter reflects the wavelength bandwidth of the measuring system and transmits the wavelength of the laser beam (Fig. 4). An overall coupling efficiency of over 95% for the laser beam and over 93% for the measurement beam was evaluated in laboratory tests. These results validate the concept for the machine integration.

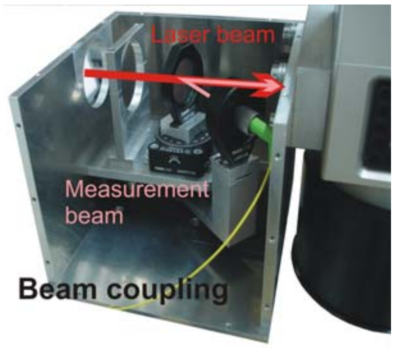

Fig. 4: System prototype with detailed view of the beam coupling unit (Laser and Measurement beam coupling)

3.4. F-Theta scanning lens

As presented in Fig. 1 a typical scanning system used in laser structuring systems is composed mostly of a scanning unity based on galvanometric moved mirrors and a f-theta scanning objective.

The scanning objective used in the presented system prototype was a telecentric F-theta scanning lens. This lens is wavelength optimized through the insertion of different optical elements, which add a targeted optical distortion in the lens system. The aim of this optimization is to create a focal plane for the laser beam, as well as to create a direct proportional relation between scanning angle and laser spot position [4].

The designed optical system of a F-theta lens causes optical aberration in wavelengths other than the machining laser wavelength. This aberration introduces systematic errors to the measurement results, such as a distortion of the focal plane through changes in the optical path and deformation of the measurement spot. The distortion can be seen in the measurement results as slight deviations of the real object form or a small increase of the measurement uncertainty in the boarder of the scanning field.

The specific optical dispersion in the f-theta lens' central optical path for the measurement wavelength was evaluated in a laboratory test. The evaluated dispersion could be compensated on the measurement system by the usage of a special designed glass rod, which was inserted on the system's reference path.

4. SYSTEM PROTYPE

In order to evaluate the proposed inline measurement technique previously to a machine integration, a system prototype was constructed. For the deflection of the laser and measurement beam a galvanometer based scanning unit of the company SCANLAB AG was used. A telecentric F-theta objective with focal distance of 80 mm was applied for focusing both beams on the structuring plane (Fig. 5). The combination of both optical elements enables a scanning working field of 30 mm x 30 mm. As machining laser a nano second pulsed fiber laser with central wavelength at 1064 nm was used. The positioning of the laser structuring and measurement head is executed by means of a precision positioning table. The controlling of the scanner and laser unit is executed by a specially developed piece of software. A laser security compliant housing completes the prototype.

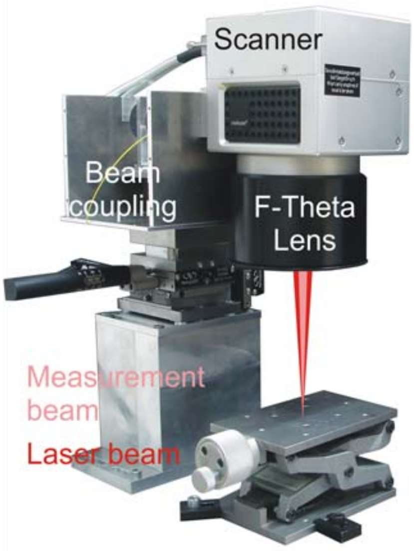

Fig. 5: System prototype

5. RESULTS

The evaluation of the system prototype was carried out through a series of test measurements in flatness and step standards, as well as in rough surfaces (Fig. 6).

By measuring a flatness and a step standard the amount of optical aberration introduced by the telecentric F-theta objective could be investigated. Alterations in the optical path length of the measuring beam affects the surface form inspection and need to be characterized.

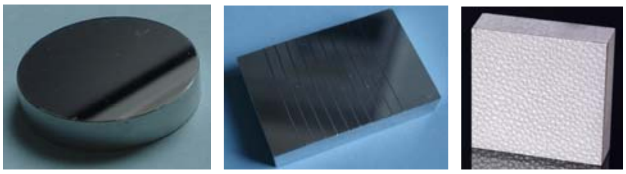

Fig. 6: Test objects – flatness standard, step standard and a laser textured letter structure

The measurement of the flatness standard shows a slight distorted plane (Fig. 7). For a measurement area of 30 mm x 30 mm a parabolic distortion could be detected in x and y directions. After the extraction of the plane inclination a max. deformation of 108 µm in the x axis and of 115 µm in the y axis was measured. This measurement distortion is caused by an optical dispersion on the measurement beam in dependency of the scanning angle. A correction of this effect can be achieved by a system calibration based on a measurement of a reference surface. Another approach is using the simulation of the optical system, in order to determine the amount of form error caused by the f-theta objetive.

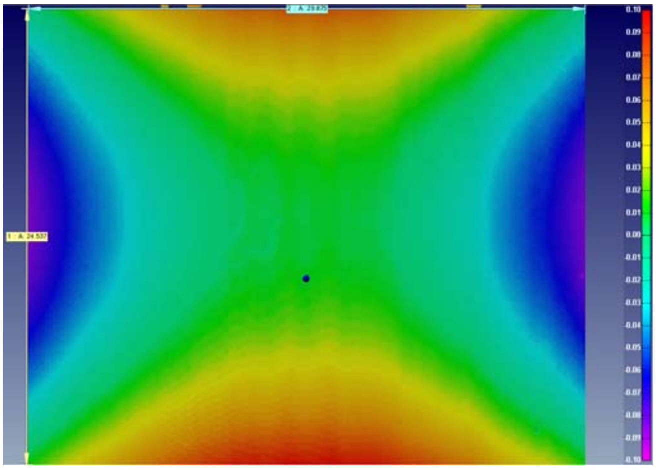

Fig. 7: Surface measurement of a flatness standard

To evaluate a possible non-linearity also in dependency of the scanning angle a step standard was measured (Fig. 8). An overall non-linearity on the same baseline of the deformation was measured.

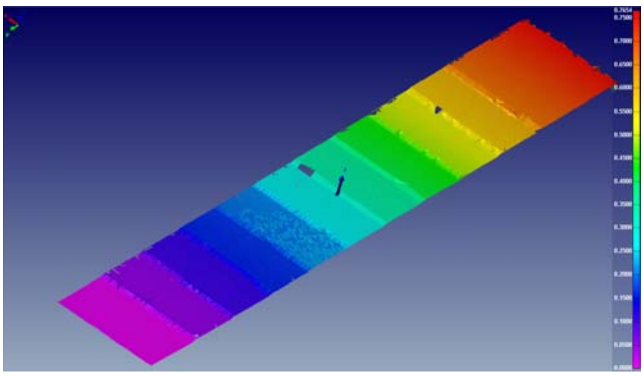

Fig. 8: Surface measurement of a step standard

The prototype system was also tested with rough and structured surfaces. For a first evaluation a euro coin was used. The measurement result show a robust measurement of the surface (Fig. 9).

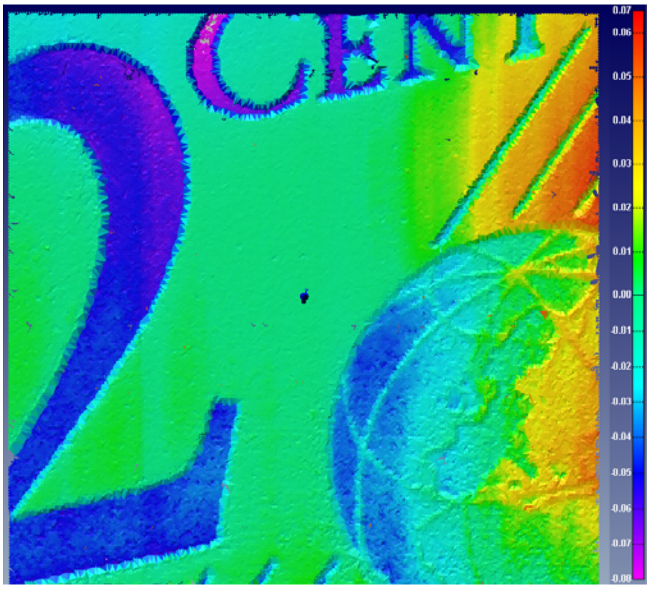

Fig. 9: Surface measurement of a 2 cent euro coin (measurement scale in mm)

Regarding the application of laser structuring systems in the manufacturing of tools and moulds [1], a laser machined letter structure was analyzed and acquired (Fig. 10). The resulting measured surface demonstrates the robustness of the system on the inspection of complex surfaces.

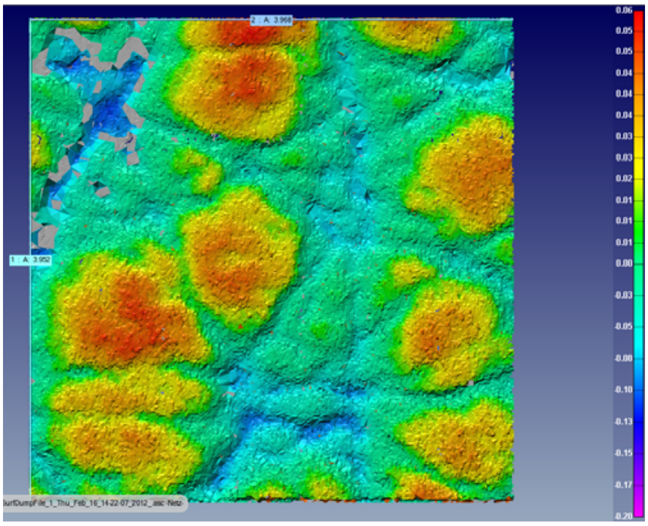

Fig. 10: Surface measurement of a laser textured letter structure (measurement scale in mm)

6. CONCLUSION

Within this paper an optical measurement system for inline surface inspection of micro and macro surface structures with sub-micron accuracy was described. Measurements on standards and technical surfaces are presented, which validates the potential of this technique for a telecentric surface inspection on laser structuring machines.

Future investigations, specially in the optical simulation of the system, will be carried out in order to determine the optical aberration on the measurement wavelengths. Based on this results the total form error on the measurement values can be defined. Further on a calibration concept will be defined and implemented.

In a second step the usage of the measurement system to set-up a closed loop control of the process will be investigated. An automatic process parameter adjustment as well as a machining feedback control are aimed.

8. ACKNOWLEDGEMENTS

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