Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 113 (2022) 570–575

www.elsevier.com/locate/procedia

ISEM XXI

Development of an OCT system for measuring machining defects on a texturing laser machine

Florian CHAYS[a], Harley STOECKLI[a], Stéphane BOURQUIN[a], Nicola GIANDOMENICO[a] *

[a]*HEPIA, haute école du paysage, d'ingénierie et d'architecture de Genève, Member of the HES-SO University of Applied Sciences and Arts Western Switzerland (HES-SO), Rue de la Prairie 4, CH 1202 Geneva, Switzerland*

* Corresponding author. Tel. Teams: +41 (0)22 558 63 04; *E-mail address:* nicola.giandomenico@hesge.ch

Abstract

During the process of parts produced by texturing laser machine, the dimensional verifications are done manually. For a specified kind of laser, the machining pass may remove approximately few hundred nanometers of material to a maximum depth of 150µm after several sequences.
If one could perform at least one measure after each laser pass, the machine will be able to correct by itself the defects and the flatness of the machined area.
This research has the aim of detecting, measuring, and correcting in real time defects that may occur. To realize the feedback process, which is an innovation in that area, we have coupled an optical measurement system to the laser machining head.
Such a system, developed by HEPIA, is an OCT (Optical Coherence Tomography) adapted for this specific application. Automatic verification will allow instant rectification of texturing defects bringing time saved of the produced parts.

Keywords: Texturing laser machine; Optical Coherence Tomography; Laser closed loop; realtime defect correction

1. Introduction

This feasibility research study was proposed by a manufacturer of texturing laser machines with the purpose to detect and correct in real time, or directly after machining, the random defects that may appear during a laser texturing operation.

The texturing machining method is used to create complex patterns on the surface of various materials to imitate typical surfaces such as wood, carbon or to obtain specific optical properties (Fig.1).

When texturing a workpiece with a laser, defects can occur sporadically. These defects are today detected by removing the finished part from the machine and checking it manually. It is time-consuming and expensive to redo the process until one achieves the desired accuracy. Furthermore, these defects cannot currently be predicted, as they are caused by instability of the laser source as well as environmental disturbances or machine accuracies, which are difficult to control at the considered scale of precision.

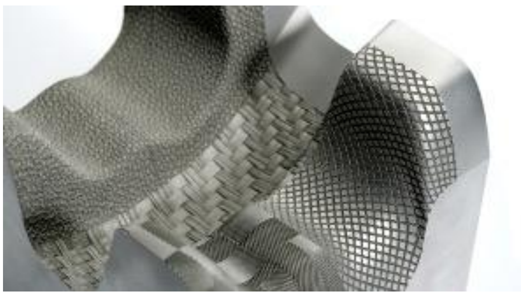

Fig. 1. Example of a piece textured by laser

This project aims to couple an optical measurement system to the laser machining head to measure the surface condition of

10.1016/j.procir.2022.09.176

the part continuously, or after each pass. This would enable implemented feedback during machining to correct directly, avoiding the need to move the part for measuring purpose.

Nomenclature :

OCT	Optical coherence tomography
FFT	Fast Fourier Transform
FD-OCT	Fourier Domain OCT
TD-OCT	Temporal Domain OCT
SLD	Super Luminescent Diode
MATLAB	Programming and numeric computing platform
DAC	Digital to analogue converter
GALVO	Galvanometer mirror
ARDUINO	Open-source electronic platform
SPI	Serial Peripheral Interface
PCIe	Peripheral Component Interconnect express

Optical coherence tomography (OCT) is a widely used optical imaging technique for the dimensional measurement of objects (or organs such as the eye) in cross-section. Indeed, a single transversal point OCT measurement allows to know the depth in different layers of materials if their refractive indices are not identical but known.

In the case of a machined metal part, there is no beam penetration into the object, so we obtain a single depth value corresponding to the distance of the surface of the part from a reference arm (topography).

OCT systems are based on a broadband light source coupled into a Michelson interferometer. Two main configurations are generally deployed:

- Temporal Domain OCT (TD-OCT), where the depth scan of the measurement is based on the mechanical movement of a reference mirror. This system was the precursor in the field of OCT, however the mechanical movement of the mirror limited the speed and the sensibility of the measurement.

- Spectral OCT (Fourier Domain OCT, FD-OCT), which uses the same configuration as the TD-OCT system, but where the reference mirror is kept fixed, and the photodetector is replaced by a spectrometer to spatially separate the different wavelengths from the source (Fig.2). An inverse Fourier transform (k-domain) of the acquired spectrum is required to recover the measured depth information. This technique has the advantage of acquiring a complete depth reflection profile of the sample by simply reading the photodetector line of the spectrometer. This method is generally preferred to TD-OCT for its speed and better measurement sensitivity, but the computation time required (inverse, resampling, Fourier transform) can still limit the image acquisition time.

The theoretical axial minimum resolution Δz_{min} (in depth, units are nm) for an OCT system depends on the center frequency as well as the bandwidth of the light source [1]:

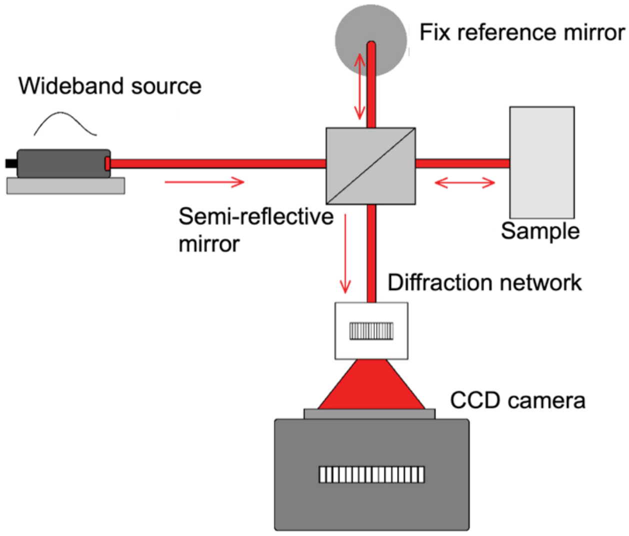

Fig. 2. Principle of the FD-OCT method in the frequency domain

$$\Delta z_{min} = \frac{2\cdot\ln 2}{\pi}\cdot\frac{\lambda_0^2}{\Delta\lambda} \qquad \{1\}$$

where λ_0 is the central wavelength (units nm) of the source and $\Delta\lambda$ the bandwidth at mid-height.

For better resolution, it is therefore preferable to work with a light source of shorter wavelength and broader spectral bandwidth.

However, in our case the central wavelength of the measuring light source will be chosen close to the machining laser one, in order that both beams endure identical geometrical and chromatic aberrations. In this way, the location of both focus spots on the sample match. This point is crucial to assure realtime machining correction of the sample.

It should also be noted that the maximum theoretical resolution can only be achieved if all the elements in the optical system (lenses, fibers, couplers, spectrometer, etc.) do not truncate the bandwidth of the source and if the chromatic dispersion generated by the elements located into the two arms of the interferometer is compensated.

The measurement range Z_{max} also depends on the central wavelength and bandwidth of the source, as does the axial resolution. However, the number of measuring elements N of the spectrometer (number of pixels of the spectrometer camera) also comes into account:

$$z_{max} = \frac{N\cdot\lambda_0^2}{2\cdot\Delta\lambda} \qquad \{2\}$$

With:
λ_0: the central wavelength of the source
$\Delta\lambda$: the bandwidth at half height
N: number of measuring elements of the spectrometer

On the other hand, it can be noticed that for a fixed N, a better resolution will lead to decrease the measurement's depth range.

1.1. Key values and objectives

This chapter summarizes all the data, both in terms of the dimensions to be measured on the machined parts and the characteristics of the machining laser.

- Characteristics to be measured on the workpiece:

The final pattern on the workpiece is made in several passes over small, precisely spaced primary surface features to hide the "point-to-point" appearance of the laser as much as possible. Each pass removes approximately 100 to 200 nm of material, with a maximum texturing depth of 150 µm.

Ideally, the measurement resolution requested should be in the micrometer range or less, and the final roughness of the part would also be interesting information to obtain. According to the machine manufacturer, it is possible to carry out a measurement after each pass (or even several passes). However, it is not necessary to make a direct measurement after each laser pulse, which reduces the constraints on the speed of the measurement/machining mode change.

Since the manufacturer currently uses mostly 1064 and 1030 nm lasers and we have a 1064 nm laser available for on-site testing at HEPIA, we have chosen, in agreement with them, to base this study on a 1064 nm laser. Since the machining and measurement beam must pass through the same optics, the measurement system will also be designed around this wavelength to limit chromatic aberrations.

After an initial study, it also turned out that it would have been more expensive to build the optical measurement bench at 532 nm, given the small number of sources available on the market at this wavelength. The feasibility of a 532 nm laser would therefore still have to be studied, especially in terms of total cost.

2. State of the art

The first study, "Inline coherent imaging of laser micromachining" [2] is based on the testing of two different sources, one at 1320 ± 35 nm and the other at 805 ± 25 nm, with the aim of achieving a low-cost continuous feedback measurement system. The final resolution obtained is of the order of 10 µm for each of the sources and in both cases the total cost is estimated to be less than $10,000.

Although the resolution obtained not reach our objective of 3µm, this study already demonstrates the feasibility of a feedback OCT measurement system coupled to a machining laser.

The second study, "Inline process metrology system for the control of laser structuring processes" [3], addresses the same principle, but this time with a 1017 ± 50 nm source.

The theoretical axial resolution is of 4.6 µm, closer to our specifications. But in addition, the article [3] mentions the use of a Gaussian algorithm that would allow to further decrease the resolution with a standard deviation of the distance measurements of the order of 220 nm.

In these two papers, the authors chose to overlap the measurement optical circuit on the machining optical circuit using a dichroic mirror, as shown in the figure below:

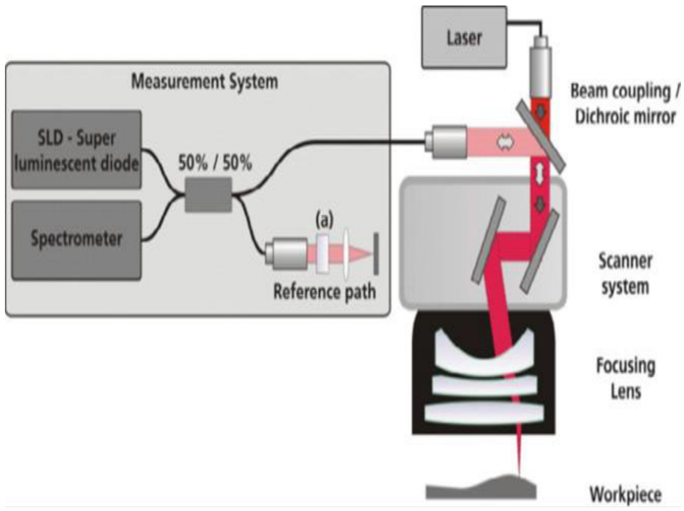

Fig. 3. Picture from the article "Inline process metrology system for the control of laser structuring" [3]

The use of a dichroic mirror, by definition, requires that the laser source and the measurement source have different wavelengths in order to be separated. The problem is that the F-theta lens (focusing lens) used to focus the laser on the workpiece is designed for the wavelength of the machining laser, so the wavelength of the measurement beam will suffer aberrations. According to the authors ([2] and [3]), some of these aberrations can be compensated, but a calibration might be necessary and complex. The more off-axis a measurement is made, the larger the aberrations become. Unfortunately, only the lateral resolution at the center is indicated in the article, so it is not possible to know the real impact of these aberrations on the measurement if one moves away from the optical axis.

In conclusion: our approach differs from these two systems by using a measurement source that have the same wavelength of the machining source. This has the advantages of reducing measurement aberrations to a minimum (we measure exactly where the machining laser struck) and doing away the dichroic mirror.

3. The OCT prototypes

3.1. Principle

The basic principle retained is the FD-OCT, but the implementation is different from those described in the state of the art. Indeed, the optical measurement circuit is classical but the implementation in the laser machining circuit is different, the aim being to get rid of the dichroic mirror in order to use a measurement source whose central wavelength is very close to the machining laser wavelength. Thus, we limit the optical aberrations on the measurement circuit due to the F-Theta lens.

To do this, the idea is to replace the dichroic mirror by a rotating disc composed of alternating reflective (measurement process phase) and transparent (machining process phase) sectors, according to the diagrams below:

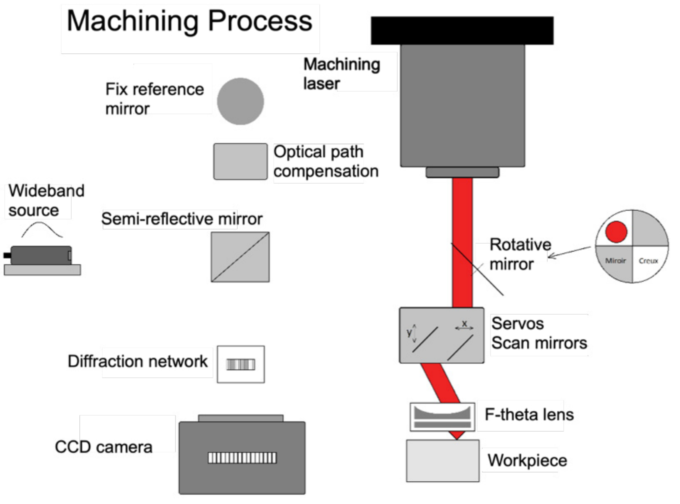

Fig. 4. Normal machining process

Once the machining has been completed (Fig.4), the rotating mirror swings out and the measuring phase can begin (Fig.5).

In the measurement process, the wideband source with the same wavelength as the machining laser source generates the beam that follows the same path through the mirrors and F-theta lens

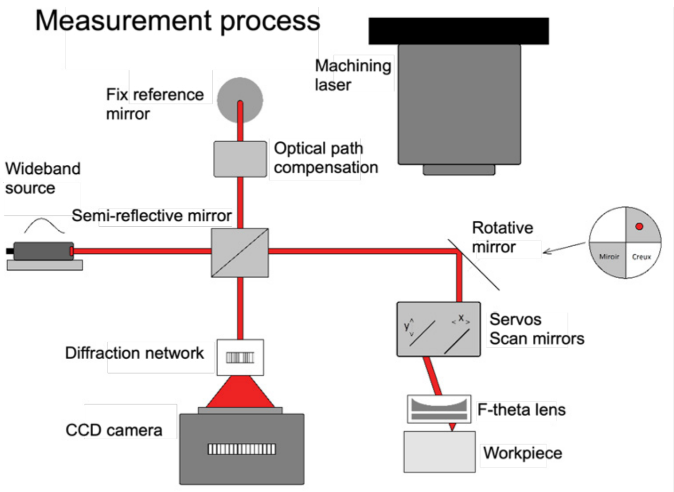

Fig. 5. Measurement process

The relationships between the different subsystems, in this case the light emitted by the source, the acquisition of the spectrum and the scanning of the surface, are coordinated by a MATLAB script and organized according to the diagram in Fig.6.

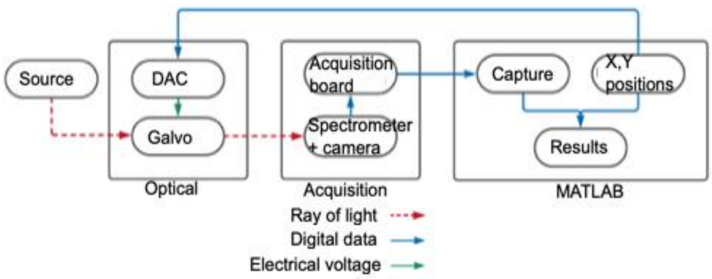

Fig. 6. Functional diagram of the prototype

The X/Y positions are determined by the MATLAB script and transmitted to the digital to analog converter DAC, which converts it into electrical voltage for driving the galvanometers. The light beam is thus deflected and passes through the device before being acquired by the camera. The image obtained is transmitted via an acquisition board to the MATLAB script which calculates the measured distance. The values are then stored in a matrix where the elements correspond to the X/Y positions.

3.2. The optical source

- Super luminescent diode (SLD):

Manufacturer Exalos / Model EXS210007-01, Wavelength λ: 1070 ± 45 nm, Optical power: 10 mW
Source driver EBD5020

As a reminder, the target is in the micrometer range. However, in the case where the workpiece is mainly reflective, it is possible to improve this resolution. According to the study [3], it would be possible to reach a sub-micrometer resolution, after digital processing, with a theoretical resolution source of 4.6 µm.

An electronic board has been developed during the project and it is added to the one supplied by Exalos to power the source. An Arduino Nano allows the power supply to be controlled from a PC rather than with the potentiometers.

3.3. The acquisition (spectrometer, camera, acquisition board)

A spectrometer model with an integrated InGaAs camera was chosen. The camera offers a high acquisition speed that will probably not be used 100%, so optimization is also possible here after the feasibility study.

- Spectrometer:

Manufacturer Wasatch Photonics / Model Cobra 1300, Wavelengths: 950 - 1450 nm

- Camera integrated in the spectrometer:

Manufacturer SENSORS UNLIMITED / Model GL2048R

- Acquisition card:

Manufacturer National Instruments / Model PCIe-1433

3.4. F-theta lens

It is interesting to note that during scanning, the angle of reflection is non-zero, which would imply a non-negligible or even total loss of power of the reflected beam if no lens was associated with it. The F-Theta lens compensates for this effect by paralleling the output beam, thus allowing an identical angle of incidence at all points on the surface to be scanned.

As this is an optical system based on an interferometer coupled to a wideband source, attention must be paid to the chromatic dispersion that occurs in the different elements and this must be compensated for by inserting the same optical components in both arms of the interferometer.

- F-theta lens:

Manufacturer Thorlabs / Model LSM02-BB, Bandwidth: 810-890 nm and 1000-1100 nm, Effective Focal Length: 18 mm

3.5. Software

As previously mentioned, the code was compiled on MATLAB, this choice being based on its computational capacity, the large number of libraries available and the possibility of creating graphical interfaces.

The script is composed of two subsystems: acquisition and analysis.

The acquisition includes the scanning of the surface, the transfer of the camera data and a graphical interface, while the analysis is limited to the mathematical operations allowing the extraction of a distance from the camera data.

- Beam position:

Establishing SPI communication between MATLAB and the DAC required the use of an Arduino Uno. This solution was chosen for its simplicity of implementation but suffers from a rather low data rate. As the scanning will be carried out by the machining laser, this is this is not prohibitive.

- Acquisition:

Since the PCIe-1433 acquisition card communicates directly with MATLAB via the Image Acquisition Toolbox, the acquired data are stored in a vector as soon as the beam position is reached.

- Data Analysis:

This is the most critical point, both in terms of speed of execution and the accuracy of the calculations to be performed. Indeed, the data acquired in the previous point corresponds to the interference spectrum in the spatial domain, called λ, and must be converted into the k-domain, before undergoing a Fourier transform.

The transition to the k-domain is done by means of an inverse law, which implies that the sampling is no longer linear and that the number of decimals is decisive (the 64-bit version of MATLAB is therefore reassuring). A resampling is necessary, by means of a linear interpolation, to be able to carry out the Fourier transform.

The spectrogram obtained essentially shows 3 peaks: the DC component and a pair, corresponding respectively to the Gaussian and to the frequency of oscillations on the latter.

3.6. Results display

To obtain the reflection profile of the piece under test, some signal processing steps must be applied:

- The discrete wavelength spectrum acquired by the spectrometer is first converted into the wave number space (k)
- The "inverse" operation performed in the previous step results in a non-linear distribution of points in k-space. A resampling of the signal is necessary to recover a linear distribution of these points
- The application of the Fourier transform on the k points gives access to the depth reflection profile of the piece.

4. Exploratory tests

To enable the concept to be validated, the laser manufacturer has supplied a sample containing laser-machined steps of varying heights (0.5 µm, 2 µm and 5 µm).

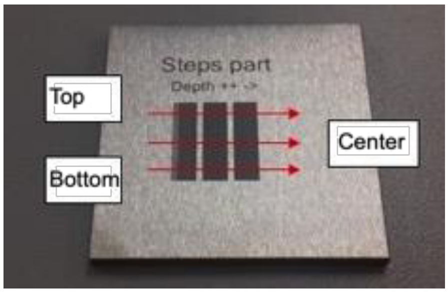

Fig. 7. Test piece machined by laser texturing

The OCT setup is shown in the Fig.8. A MATLAB script has been written to scan and display the results as a three-dimensional profile.

An instability in the communication between the camera and the script was observed and limits the number of successive acquisitions. It was therefore not possible to perform a global scan with the best possible resolution. In this case, while the theoretical maximum spatial resolution is 200 nm, a step size of 1.5 µm over a surface of 100 µm was chosen, i.e. 4096 measurement points.

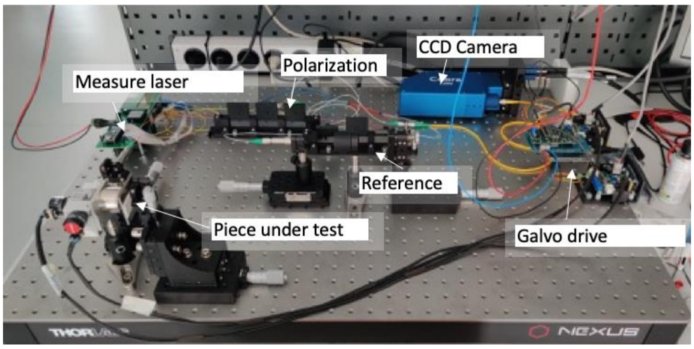

Fig. 8. OCT setup

The result of the scan is shown in Fig.9. The 5 µm step is clearly visible, the slope being due to the low spatial resolution. Note that the outliers have been filtered out, but some noisy values remain. Scans were also made of the smaller steps without any convincing results, as these do not appear on the profile. This is normal because the theoretical resolution for the setup used is higher than the steps we would like to measure. Digital processing and better spatial resolution could improve the results.

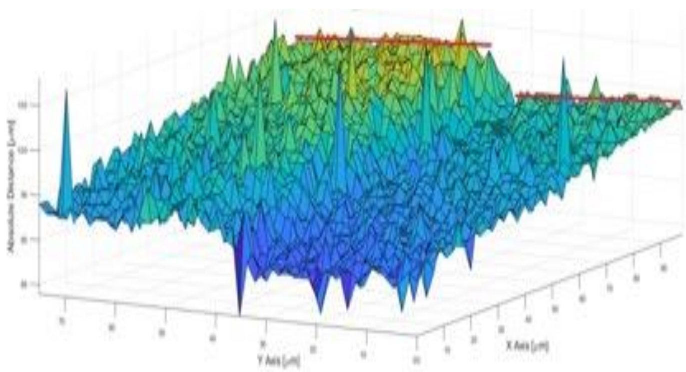

Fig. 9. Scanned profile of the 5 µm step of the sample, red lines indicate the level difference

4.1. Improvement outlook

The presence of noise makes it necessary to complete the concept to ensure the validity of the measurements. To this end, several areas of improvement are intended:

- Optical setup:

One of the fundamental elements that should be improved is the return beam of the reference path reflected by a mirror. As a result, its intensity is greater than the reflective sample beam. This imbalance limits the intensity of the light source and thus reduces the signal-to-noise ratio.

By means of a filter in the reference path, the intensities of the return beams can be rebalanced, allowing the intensity of the source to be increased and thus improving the detection sensitivity of the system.

In addition, some of the observed noise may be caused by vibrations in the optomechanical supports and the cross-scanning system. However, as the system will have to be integrated into the machining head, this is primarily an issue to be developed in the final implementation.

- Digital processing:

Some of the noise cannot be filtered out in an analogue way and there is no other option than to use digital processing to filter the measurements to obtain the desired result.

At first glance, multiplying and averaging the acquisitions is the simplest and cheapest way to remove noise, at the cost of a slightly longer measurement time. The interest lies in the simplicity of the calculation and can be applied to the measurements or to the result of the calculation.

On the other hand, the digital aspect also makes it possible to integrate a detection and control logic. For example, if the measured distance seems to be wrong, it is possible to order a second check or even to alert an operator.

- Acquisition:

The spectrum obtained is composed of 2048 points, whereas other cameras can reach 8192 points. This means that for the same wavelength band, the vector contains 4 times more data and the Fourier transform in the k-domain will be more precise, which makes it possible to extend the depth of investigation.

On the other hand, the possibility of improving the sensitivity of the camera also improves the accuracy of the measurements.

However, these improvements should be considered as a last resort, i.e. when the previous ones have been applied and the result is still not satisfactory.

- Phase detection:

In the current state of development, the calculation is based solely on the frequency of the fast spectrum ripples in the λ domain. However, it has been observed that by moving the sample, the ripples move as their frequency changes.

Therefore, by taking the phase of these ripples into consideration, it may be possible to calculate a distance with better resolution.

However, for this method to be applicable, the signal must be stable and as free of noise as possible. This is therefore the final improvement of such a device

Conclusions

The solution proposed in this project is innovative and different from previous research. We can conclude that the objectives have been achieved and that it has aroused great interest from the industry.

This prototype has validated the concept and its application in the laser texturing practiced. The targeted resolution of 5 µm was achieved and is very promising, given that part flatness defects can be as small as several tens of microns.

The limitations of the system observed are being studied and seem to be improvable without committing to major changes in the prototype.

In this study, we did not carry out the feedback that would allow the measurements taken on the part to be sent back to the machine, so that the latter could redo a machining pass to correct the defects observed. This step, which requires a strong interaction with the manufacturer, was not part of the objective of this project but could be envisaged in a possible future project.

5. Acknowledgements

This research and development have been supported by the HES-SO (University of Applied Sciences and Arts Western Switzerland).

The authors would like to express their cordial gratitude for their help and involvement to the members of the HEPIA/inSTI institute team.

References

[1] Tomlins, Pete & Wang, Ruikang. Theory, developments and applications of optical coherence tomography. Journal of Physics : Applied Physics. 38. 2519-2535. 10.1088/0022-3727/38/15/002, 2005

[2] Webster, Paul & Yu, Karen & Leung, Ben & Wright, Logan & Mortimer, Kevin & Fraser, James. Inline coherent imaging of laser micromachining. International Symposium on Optomechatronic Technologies. ISOT 2010. 10.1109/ISOT.2010.5687305, 2010

[3] Schmitt, Robert & Mallmann, Guilherme & Pothen, Mario & Winands, Kai. Inline Process Metrology System for the Control of Laser Surface Structuring Processes. Physics Procedia. 39. 814–822. 10.1016, 2012

[4] R. Leitgeb, C. K. Hitzenberger, and A. F. Fercher, Performance of Fourier domain vs. Time domain optical coherence tomography. Optics Express Vol. 11, Issue 8, pp. 889-894, 2003

[5] Ruikang K. Wang, V. Tuchin. Optical Coherence Tomography: Light Scattering and Imaging Enhancement. Handbook of Coherent-Domain Optical Methods pp 665-742, 2012

[6] Paul J. L. Webster, Logan G. Wright, Kevin D. Mortimer, Ben Y. Leung, Joe X. Z. Yu, and James M. Fraser. Automatic real-time guidance of laser machining with inline coherent imaging. AIP Conference Proceedings 1464, 492, 2012

[7] R. Lausten and P. Balling. On-the-fly depth profiling during ablation with ultrashort laser pulses: A tool for accurate micromachining and laser surgery. Appl. Phys. Lett. 79, 884–886, 2001

[8] A. F. Fercher, W. Drexler, C. K. Hitzenberger, and T. Lasser. Optical coherence tomography principles and applications. Rep. Prog. Phys. 66, 239–303, 2003

[9] Thorlabs, Optical Coherence Tomography Imaging Systems, Thorlabs Product Catalogue V20, 2010, pp. 1353–1393