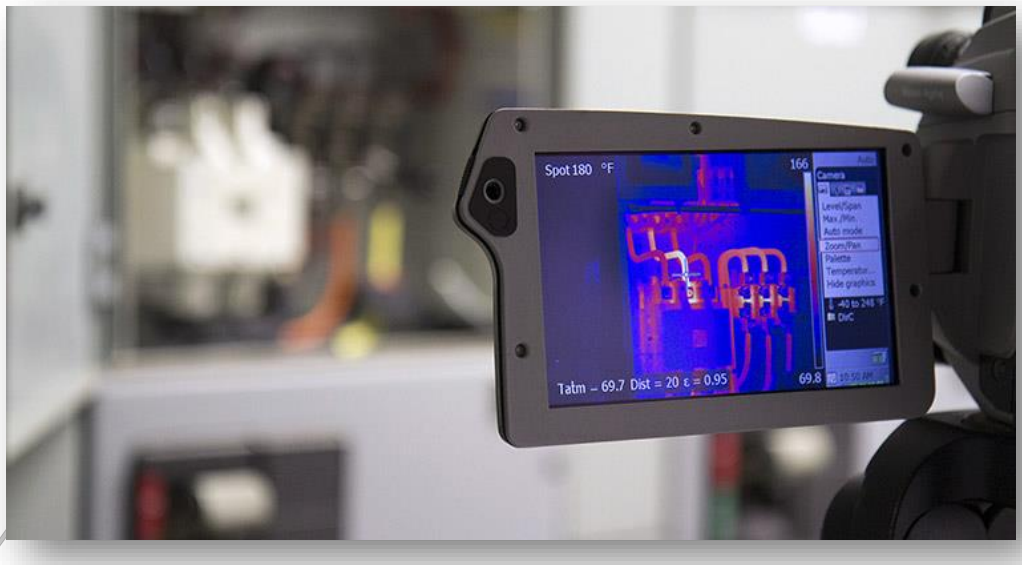
Internship report

Elaboration of a lock-in thermography measuring device for the investigation of thin hard chrome layers

Achbah, Fatima-Zahra
2A MECATRONIQUE



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A report submitted in the partial fulfillment of the requirements for the validation of the second year work placement

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Thank you all! It was such a pleasure to do this internship.

Résumé

Le présent document est la synthèse de mon travail effectué dans le cadre du stage de ma deuxième année à l'Ensiame. Ce stage a eu lieu à ITW e. V. Chemnitz, Chemnitz saxe Allemagne.

Le but de ce projet de 2 ans est de faire la conception et la réalisation d'un dispositif d'essai et d'une méthode de caractérisation non destructive de revêtements électrolytiques (chrome dur) résistants à l'usure et à la corrosion de composants fonctionnels.

La solution R & D est basée sur une comparaison de la réponse du signal d'une thermographie en phase pulsée ou d'une thermographie Lock-in modulée en fréquence et le développement d'un modèle pour décrire la microporosité ou la microfissuration des couches de chrome dur. La microporosité est représentée par une fraction volumique stochastique avec un espacement de réseau typique. Les perturbations sont constituées d'éléments à différencier (pores ronds, fissures cylindriques, coniques), qui présentent une caractéristique thermophysique altérée par rapport au matériau de base (chrome). Ceci conduit à des phénomènes de conduction de chaleur instationnaires avec un changement caractéristique du temps de diffusion d'une onde photothermique excitée de l'extérieur.

Mots-Clés

Thermographie Lock-in, imagerie thermique, fissure et pores, LED, thermographie infrarouge, caractérisation non destructive.

Abstract

This report is the summary of the work I have done during my 2nd-year internship. The internship took place at the ITW e. V. Chemnitz Germany, and I was assigned to work on a two-year project.

The project is about the conception and executing of a testing device and method for nondestructive characterization of wear and corrosion resistant, electroplated coatings (hard chrome) of functional components.

The course of this internship was first to understand the Lock-In thermography technic since it is a highly relevant method in nondestructive testing. Then do experiments using the IR camera and try to characterize the cracks and pores of the chrome layer with pulse phase thermography since at the end of the project there will be a comparison testing using the two methods.

Keywords

Lock-in thermography, Chrome, Thermal imaging, Crack and pores, LED, Infrared thermography, nondestructive characterization.

FIGURES AND TABLES INDEX

List of acronyms

LIT: Lock in thermography.

PPT: Pulsed-Phase thermography.

ND: Nondestructive.

NDT: Nondestructive testing.

IR Thermography: Infrared thermography.

ROI: Region of interest.

FFT: Fast Fourier transformation.

Contents

General introduction

The second-year internship is an opportunity to discover the world of work in a company or an administration. It is also an opportunity for the engineering student to put into practice his know-how, his knowledge and all his skills in very subtle major such as mechatronics.

The hard chrome plating plays a vital role in the industry because it doesn't oxidize and has the capacity withstand extremes of temperature and climate. It is likewise simple to administer to and has an ultra-brilliant, specular completion, all of which make it a perfect material for industrial components such as pistons. In the industry we have to ensure the quality of the chrome plating to protect and to improve the production and from here comes the critical role of NDT since the quality of chrome plating hides in a microscopic level.

The aim of the R & D internship is the development of a testing device and a method for nondestructive characterization wear-resistant and corrosion-resistant, hard chrome coatings of functional components. Precisely planning, constructing and commissioning of a LIT measuring device for the investigation of thin hard chrome layers.

This report describes most of the work done during this project. It has four chapters. The first will present the host organization and the general context of this project. The second will shed light on the difficulties and the criteria for success. The third chapter will discuss the progress of the project after detailing the decomposition of tasks. The fourth will unveil the practical part of the project and the experiments that had been held. And the last one will present the general conclusions of the work that has been done

Chapter I

General context of the internship

1. Context of the internship

1.1. Company overview presentation:

1.1.1. ITW e. V. Chemnitz:

The Institute for Innovative Technologies ITW e. V. Chemnitz was founded in 1992 as a private non-profit research and development institution. The active business of ITW e.V. Chemnitz started in 1993 with seven employees. The number of employees quickly reached 20 employees, mostly engineers, and scientists.

ITW established capacities for the development of mechatronic components, optical measuring, and testing technology as well as automation technology. Competence in 3D digitization, 3D measurement technology, integrated image processing systems in conjunction with robust software solutions, form the basis for innovative solutions in measurement and test engineering, knowledge-based evaluation and process control for automation and quality assurance.

Collaboration with various industries and the internal cooperation of the departments of the ITW bring about synergy effects, which have made the institute a robust and reliable innovative partner for commercial enterprises. Through close collaboration with small and medium-sized companies, the institute was able to establish itself in the Saxon research and development landscape. The number of employees grew to 33 employees by 2005. In 2004, total revenues of EUR 1.8 million were generated from research and development projects as well as from industrial orders.

The combination of publicly funded upstream development with clear user orientation and customer proximity has proven to be a competitive strength in the market for R & D services. This is evidenced by the so far 29 patent applications of the ITW and more than 40 member companies.

The location of the institute in the technology and business park Solaris on the Neefestrasse in the Chemnitz southwest offers an advantageous infrastructure and favorable transport links. The proximity to the other business parks and the new Chemnitz trade fair also has a positive effect. ITW occupies a total of 500 m² of office space and 300 m² of laboratory space at the institute's headquarters in the Solaristurm and the branch office Annaberger Straße.

1.1.2. Core Competencies

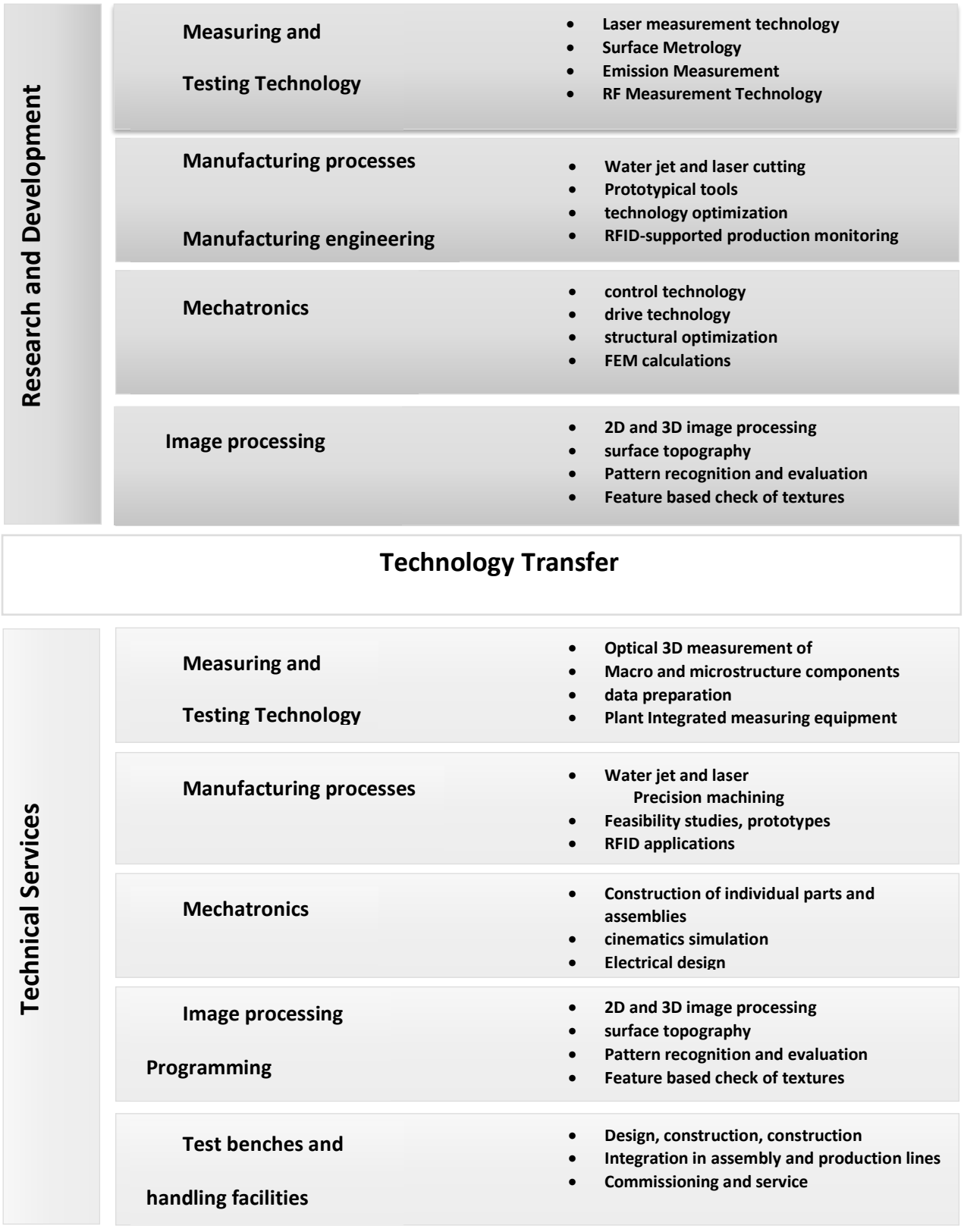

Figure 1 Self-presentation of the company

Figure 1 Shows the core competencies of ITW e. V. Chemnitz under the direction of Dipl.-Ing. Dietmar Scholze. In general there is two department: the industrial one and the R&D department. The project was conducted by the R&D department for that reason I was part of the **R&D** team, sector: **Mechanics and automation technology**. In this sector we find **Kristina Brottka, Michael Schramm, Stephan Schramm**.

1.2. Background and aim of this work

1.2.1. Chromium plating

Hard Chrome Plating is an electrolytic process utilizing a chromic acid based electrolyte. The part is made the cathode and, with the passage of a DC current via lead anodes, chromium metal builds on the component surface. A wide variety of parts can be coated; it requires only the proper fixturing, a large enough bath, sufficient lifting capacity, and adequate power sources. Hard Chrome Plating offers many attractive properties to the engineer. [1]

What are the benefits of hard chrome?

- It is ultra-hard;
- It gives superb substrate adhesion;
- It can be applied to a wide variety of substrates;
- It provides superb abrasion resistance:
- The deposition temperature is low;
- It can be applied to a wide range of geometries;
- It gives ultra-high metal-to-metal sliding wear resistance;
- It has a bright, attractive finish;
- It produces very low friction;
- The plating is stable and non-corrodible; [1]

Where is hard chrome used?

- Aerospace industry
- Automotive industry
- Forming technology
- Pressure rollers [1]

1.2.2 Presentation of the project

The hard-chrome process plays an essential role in the production of functional components. Although the industry sees hardly any economically and technologically viable alternatives, In April 2013, chromium trioxide was included in Annex XIV of Regulation (EC) No 1907/2006 (REACH Registration, Evaluation, and Authorization of Chemicals) of Substances of Very High Concern (SVHC Substances of Very High Concern). As a result, we can use chromium

trioxide from September 2017 only after authorization by the ECHA (European Chemicals Agency).

The metal layer that consists of pure chromium deposited in the galvanic process at the cathode (workpiece) is harmless. The problem is with the electrolyte. And thus the hexavalent chromium compounds become acutely toxic, carcinogenic, mutagenic, highly acidic and oxidizing.

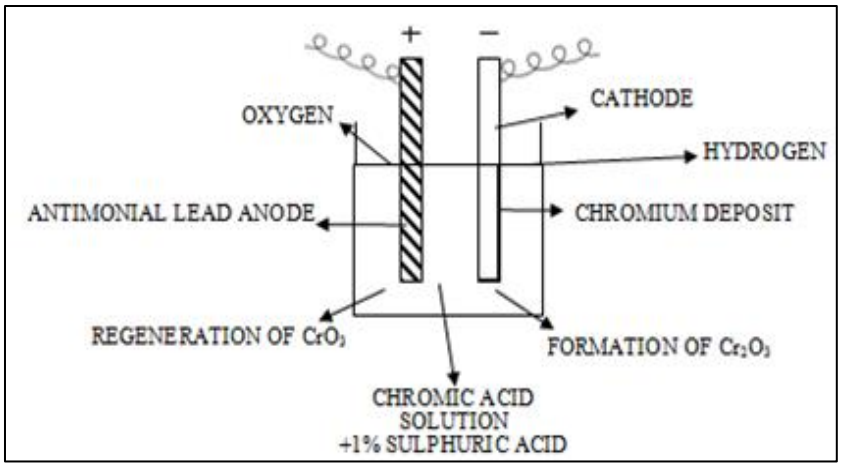

Figure 2: Hard chromium deposition

To find a substitution or a solution we need to investigate different chrome layers with varying thickness to find the best solution for chrome layering because as we said before, it is a crucial process to improve the quality of surfaces and protect industrial components.

Finding a solution for this problem is a common objective for many research-oriented companies such as Fraunhofer Institut IPA and ITW e.V. Chemnitz.

In ITW e.V Chemnitz the project's name is: " Prüfeinrichtung und Verfahren zur zerstörungsfreien Charakterisierung Verschleiß und korrosionsbeständiger, galvanotechnischer Beschichtungen (Hartchrom) funktionaler Bauteile." Its reference: MF 150174 and it is funded by the government. The project duration is **04/2016 - 03/2018**. The team working on the project is composed of Michael Schramm (Project manager), Stephan Schramm, Kristina Brottka. I joined them as a mechanical and automation engineering intern.

The procedure is in a **two-stage** process for the nondestructive characterization of hard chrome layers with physical calculations and evaluation algorithms. We have to generate a measurement and calibration. **In calibration**, we have to model and test the characteristics of the hard chrome layer. The basis is the destructive test on patterns of the hard chrome layer, the geometric measurement of their characteristic features such as a multilayer, layer thickness, Pores, cracks, etc. Their influence on the thermal conductivity of the surface to be tested (Thermal diffusivity) is simulated in a model depending on the porosity. The procedure for **measurement** begins with lock-in thermography to determine the thermal diffusivity of the macroscopic workpiece. The phase image evaluation from image sequences is carried out on the mesoscopic level (a representative volume of porosity). This is recalculated and compared with a model of the effective medium. The homogenization is to be used under the condition of adequate scale separation. It distributes stochastic modeling of the microscopic features (such as pores, cracks) in a description of an effective medium into the representative volume. The

examination of the hard chromium layer takes place in each case in comparison to the patterns from the amplitude and phase image or from the reconstruction in the simulation of the effective medium in its various classifications in a procedure for transmission to the mesoscopic level of lock-in thermography. The macroscopic workpiece is tested by assembling it from several test sites with different properties.

I was assigned to work on the lock-In thermography precisely choose the excitation source lock-in frequency and do the signal path and the test sequence. And depending on the means we have try to do the experiments. In addition, write Matlab codes that will help us calculate the FFT and the phase and amplitude images. My supervisor Brottka is working on Modeling and FEM simulation and assigned me to do a stochastic distribution of spherical pores in a chrome layer.

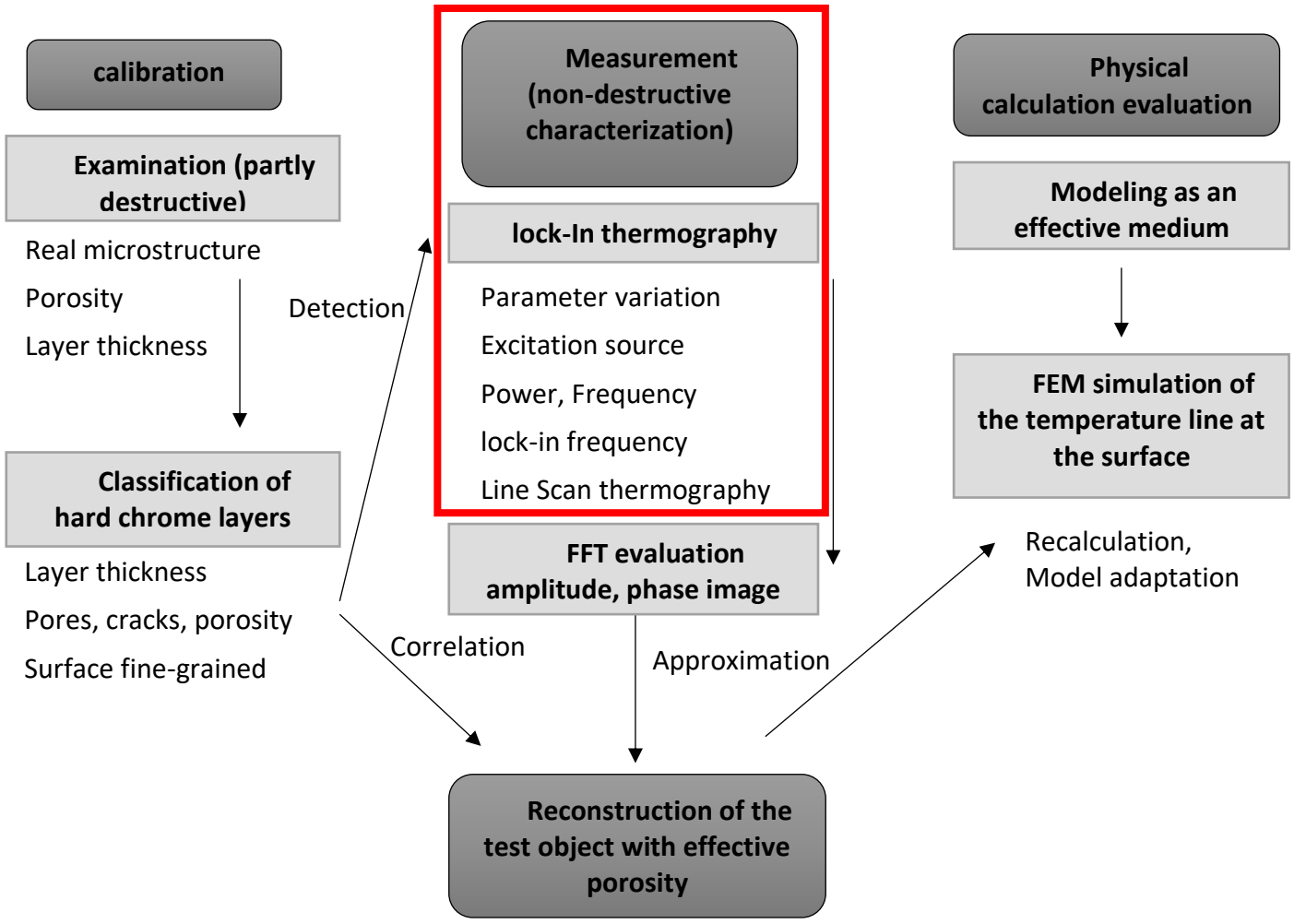

Figure 3: Process for non-destructive characterization of hard chromium layers

Before staring the plan that was proposed to me was the following: (**LOCK-IN THERMOGRAPHY METHOD**)

- Selection of the technical components of the measuring device

- Development of the signal path after detailing the test sequence
- Selection of an optical excitation source (diode laser, high - power LED)

- Commissioning the devices, parameterizing the devices and the software

- Parameterization of the signal processing: Lock - in amplifier
- Matlab code: FFT offline
- Adjustment of the high - end infrared Thermo-camera for experiments with different waveforms

- Carry out measurements on samples with different porosity

- Create a test plan
- Performing and recording measurements

- Development of the evaluation of the measurement results

- Comparison with simulation calculations (model data)
  → Write a Matlab code that generate an example of a chrome layer with spherical pores with a determined porosity.

Chapter II

Problematic and difficulties

2. Problematic and difficulties

2.1. Microscopic description of hard chrome layer:

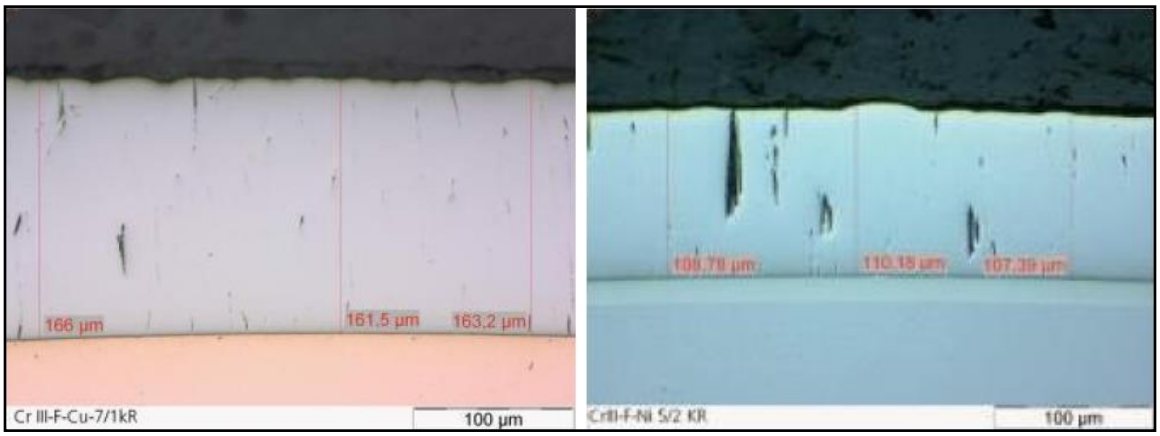

Figure 4: Microscopic image of a chrome layer showing different type of cracks

The hard chrome layer can range from several microns (µm) to hundreds of microns (millimeter thick). During the deposition of the chromium, the interim chromium hydride and the subsequent outgassing of the hydrogen causes stresses and cracks in the layer. The microscopic cracks have a positive effect on the tribological properties in the construction of hydro- and aerodynamic sliding pairings. They form small, communicating air cushions or oil reservoirs on the surface. At 300 to 800 cracks per centimeter, we can consider the hard chrome layer as microcracked. The so-called bright chrome, however, has little cracking (1 to 20 per cm) or is almost free of cracks. For quality assurance, many parameters of the hard chrome layer must be tested: thickness, homogeneity, porosity (besides a hydrophilic micro-surface may be desirable), crack number and typical crack length.

The microporosity is represented as a stochastic volume fraction with typical lattice spacing. The perturbations consist of elements to be differentiated (round pores, cylindrical, conical cracks), which have an altered thermophysical characteristic compared to the base material (chromium). This leads to unsteady heat conduction phenomena with a characteristic change in the diffusion time of an externally excited photothermal wave.

2.2. Project's chrome layer sample:

Figure 5: Experimental specimen

The specimen is a part of a cylinder or piston (for example) with a thin layer of chrome, and we are interested in detecting pores of this layer to calculate its porosity. The properties of chrome are listed in the following chart.

Specimen Properties	
Density (ρ)	7140 kg/m^3
Thermal conductivity (k)	91 W/(m.K)
Sp. heat capacity (Cp)	440 J/(kg.K)
Thermal diffusivity(α)	$28{,}966.10^{-6}\ m^2$/s

Figure 6: Properties of chrome

✓ Problem :

As can be seen in the last paragraph chrome layers are extremely thin, and the fact that its cracks and pours are even smaller makes it a bit of a challenge to detect them, for that reason, there is a significant probability of detecting waves reflected by the material instead of the chrome layer. Therefore we need an exhaustive study and simulation to know the different responses of the chrome and the metal underneath.

The other problem is the simulation its self is not an easy task as it seems. The chrome layer has a stochastic distribution of different shapes of pores and cracks which is correlated by additional microstructural investigations with the spatially averaged thermo-physical properties such as the local thermal conductivity or thermal conductivity of the layer. Thus giving a full-scale module of chrome layer is beyond the bounds of possibility.

This problem puts us in an unfavorable situation and makes it hard advancing in the project and makes us question the validity of the solutions. This is the technical problems. But in addition to that, there are no other R & D results or IP applications in the meantime, which prevent the successful implementation of the R & D project. The economic prospects for the exploitation of the solutions has not changed compared to the date of application.

The Project started **04-2016** but I started as an engineering intern **09-2017**, the following figure will showcase my work during the internship and the duration of each task.

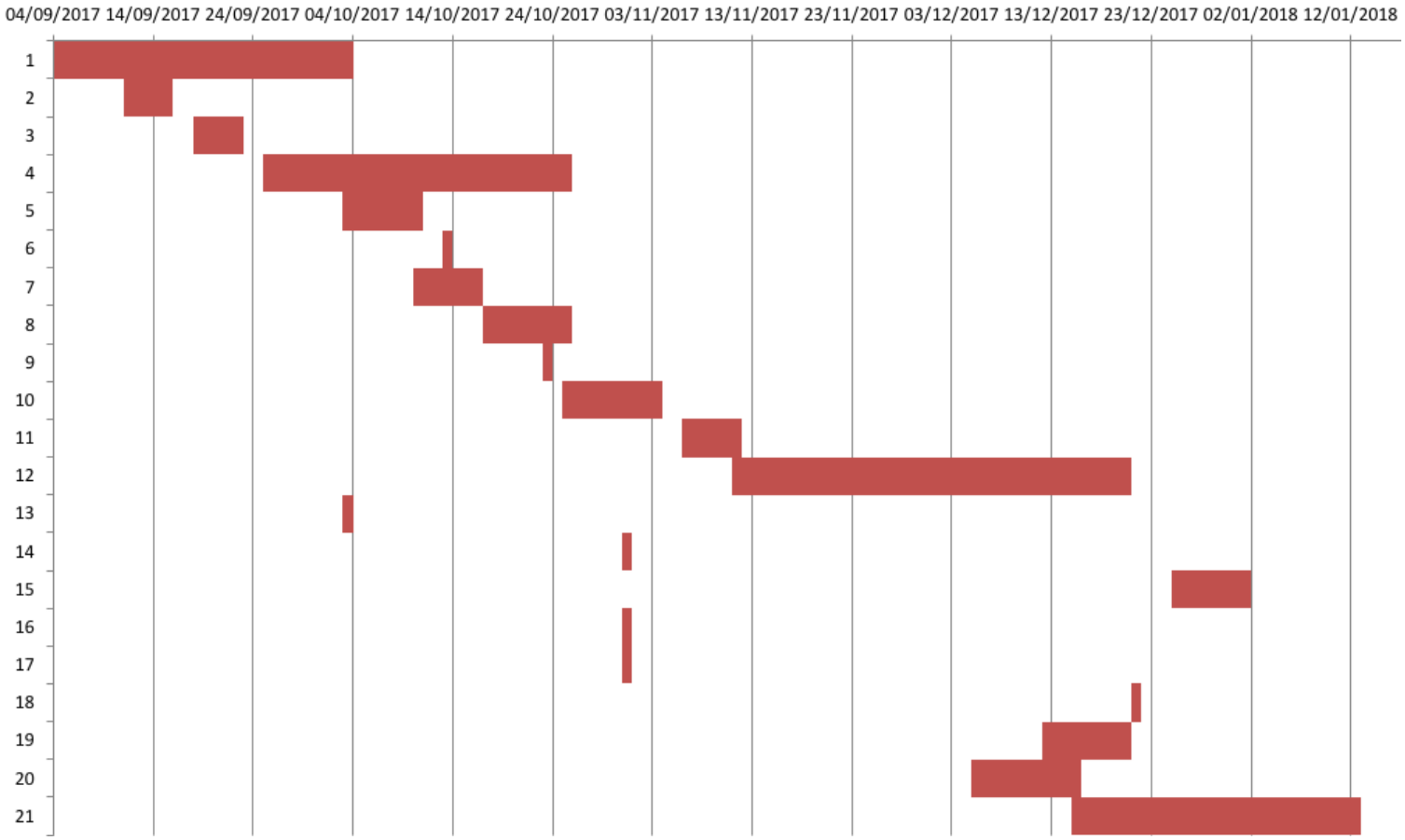

Figure 7: Gantt project

1: Understanding the topic
2: First encounter with the IR camera
3: Image processing with Matlab of the IR images
4: Development of the signal path
5: Write Matlab code of the chrome layer simulation
6: Travelled back to France (Residence permit regulation**)**
7: Selection of optical excitation source
8: Matlab code that extract the phase and amplitude image from data
9: Discover of the equipment
10: General researches to improve the results
11: Adjust IR camera, choose the frame rate
12: General researches to improve the results 2
13: Public holiday 1
14: Public holiday 2
15: Christmas Holiday
16: Connection TTL improvement
17: Synchronize the trigger with the recording
18: First presentation
19: Preparation for the first presentation
20: First draft of the report
21: Second draft of the report

Chapter III

Analysis and decomposition

3. Analysis and decomposition

3.1. IR Thermography as an NDT method:

ITW's R&D team suggests using an NDT (Annex) to investigate chrome layers. NDT is divided into several methods based on some different scientific principles such as electromagnetism, thermography, optics... Yet, we are only interested in IR thermography since the company had already the equipment that can help us carry out the project.

IR thermography is the technique of using an infrared camera to test these patterns which can then show the current condition of a device or composition of the material. [2]

Two approaches deploy IR thermography: passive and active. The following Figure present different type of IR thermography. For further information consult IR Thermography.

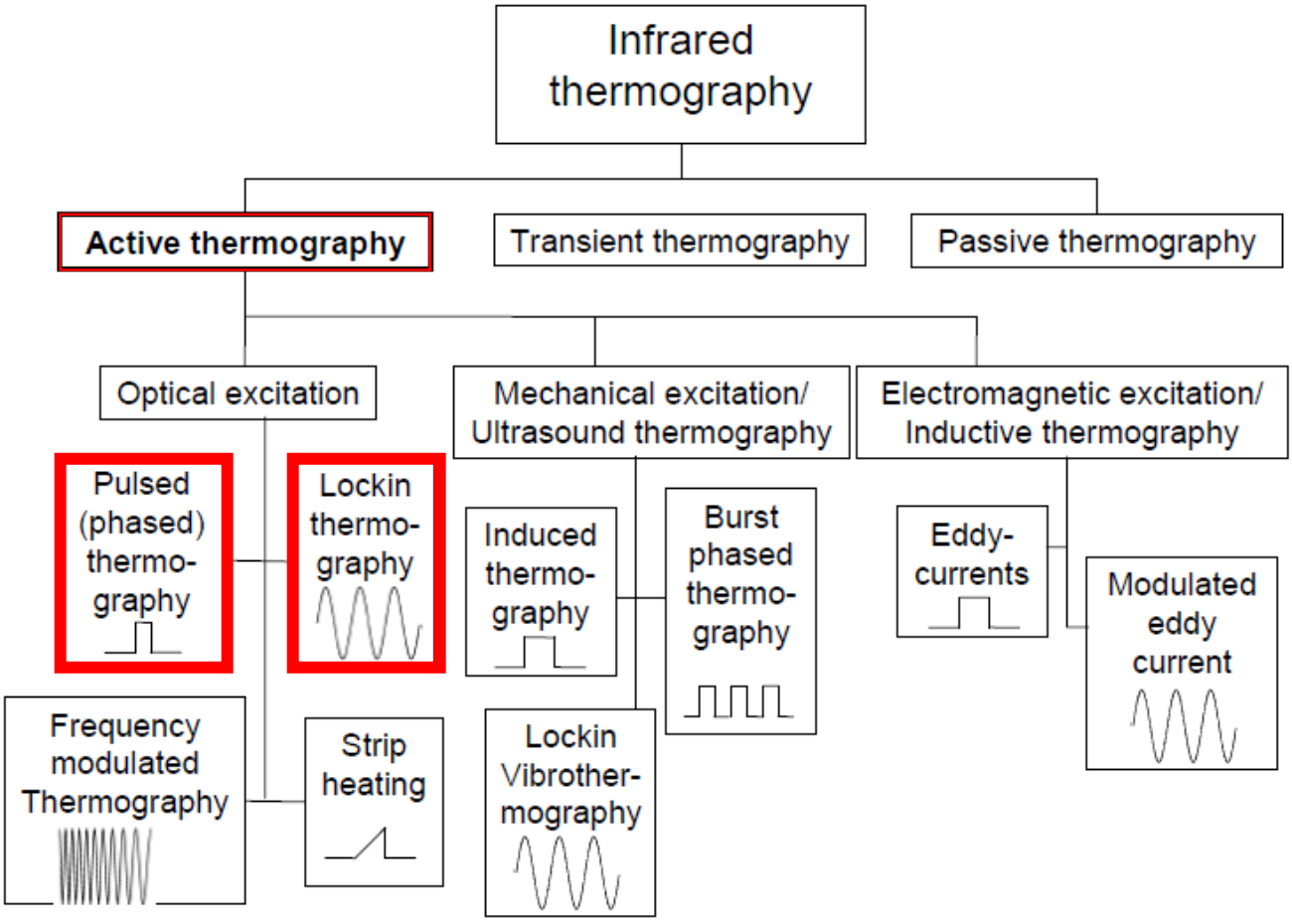

Figure 8: Transient thermal NDT approaches [2]

From those different technics we are using the LIT and PPT the decision was made by R&D team as an alternative to the ultrasonic techniques because it is expensive and also active infrared (IR) thermography techniques are gaining popularity because they are noncontact, nonintrusive, rapidly deployable and applicable to structures under harsh environments. PPT and LIT techniques are among the most widely accepted active IR thermography NDE techniques. [3].

3.2. Lock-In thermography as a NDT:

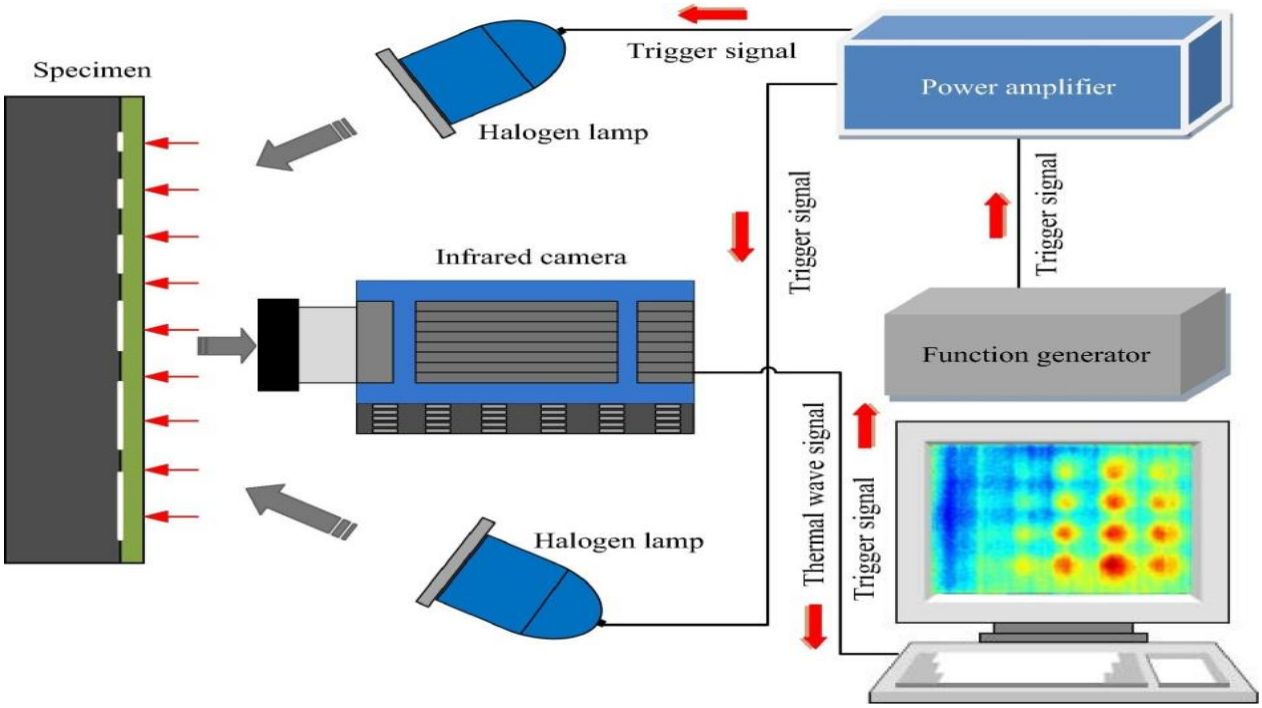

Figure 9:Lock-In thermography diagram [8]

3.2.1. The general principle of the technic:

The principle of LIT is all about the heating process, what we basically do is heating the specimen and thus chrome layer with a sinusoidal wave generated by a heating source, more specifically the periodical transfer of heat at the surface of a homogeneous semi-infinite material results in a thermal wave, which in one dimension is given by,

$$T_{z,t} = T_0 . e^{(\frac{-z}{\mu})} . e^{i(\omega t - \frac{z}{\mu})} = A(z) . e^{i(\omega t - \emptyset(z))} \quad (1)$$

where, T_0 [°C] is initial change in temperature produced by the heat source, ω [rad/s] is the modulation frequency, A(z) is the thermal amplitude,Ø(z) is the phase, f [Hz] is the frequency, λ [m] is thermal wavelength, z [m] is the depth, and μ [m] is thermal diffusion length. [4]
In brief what we need to do is the following: (For further details see Annex).

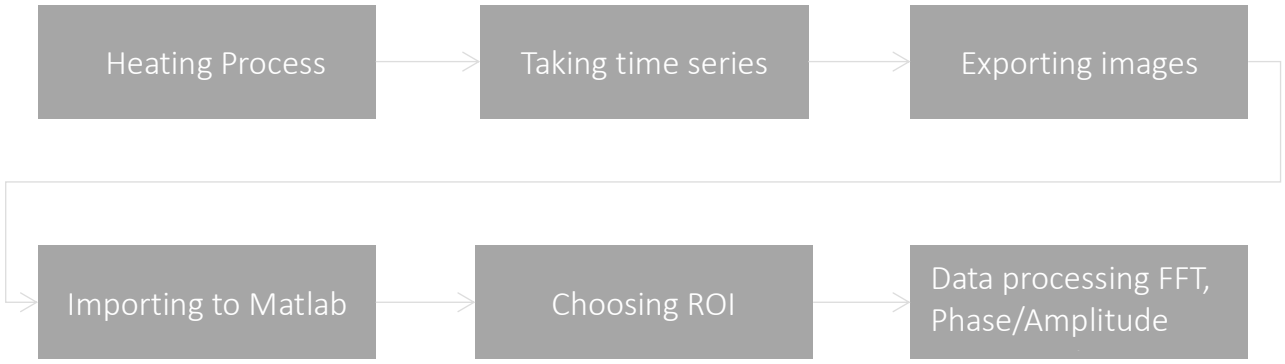

Figure 10: Test sequence offline processing

The importance of the LIT hides in utilizing a Lock-in amplifier.

3.2.2. The signal path

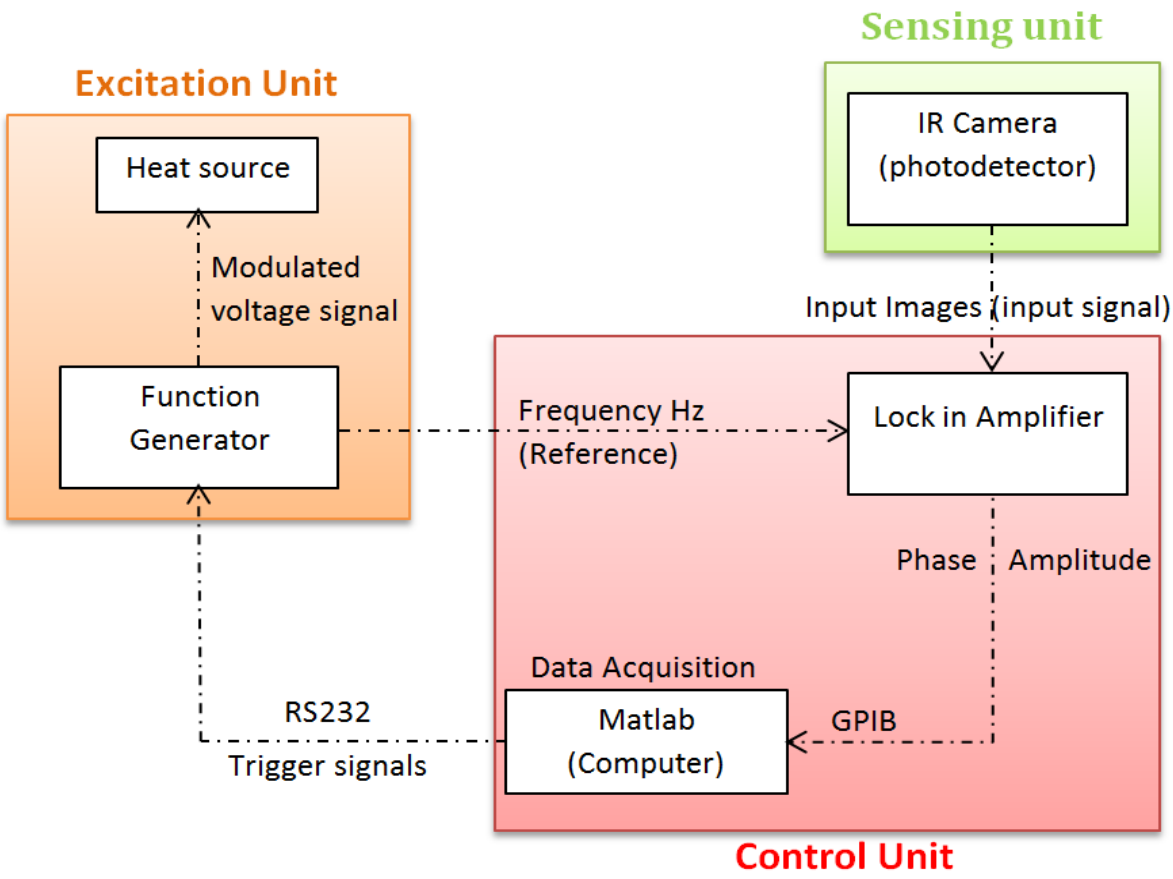

Figure 11: Signal path

After understanding the topic and LIT principle, I have detailed a signal path that would help me develop the project based on my theoretical learning. The signal path is composed of 3 units, and each unit has specific hardware and software connected by a different type of communications:

- ***Excitation Unit:***
    - **Heat source** such as LED, LASER, Halogen Lamp, Xenon lamp …

The choice of the heat source is based on the power of the heat source and its wavelength. For example, the halogen lamp is used for material with no profound defects. Laser and LED are the ones we use with a microscopic level of defect. [4]. But I choose Laser as a source of heat since it is more potent than the LED with a longer wavelength and it was proved its ability on detecting microscopic defects especially in the range of 5-10 µm.

    - **Function generator** such as AWG, …

For the function generator we need to calculate the frequency range.

The frequency-modulated excitation determines the penetration depth and thus the detectability in depth, size of the defect. The sampling interval of the photothermal waves for lock-in thermography controls the maximum frequency of the spectrum in the Fourier transformation. The sampling time defines the frequency resolution (bandwidth of the channel). That should amount to more than four, better ten periods. This results in low-frequency excitation (**0.1 to 0.9 Hz**) to significantly increase the measurement duration. More specifically we use the definition of thermal diffusion length:

$\mu = \sqrt{\frac{\alpha}{\pi . f}}$ **(2) .** where: $\boldsymbol{\alpha = \frac{k}{\rho . C_p} = 28,966 . 10^{-6}\ m^2/s}$ (2.2.) is the thermal diffusivity of chrome and f is the lock in frequency (in other terms wave's frequency). Equation **(2)** become : $\boldsymbol{f = \frac{\alpha}{\pi \mu^2}}$ and using a varying range of chrome layer with different thickness: **[100 µm … 300 µm]** and with using a Matlab code we have the following figure (Figure 10) that shows exactly what has been explained above.

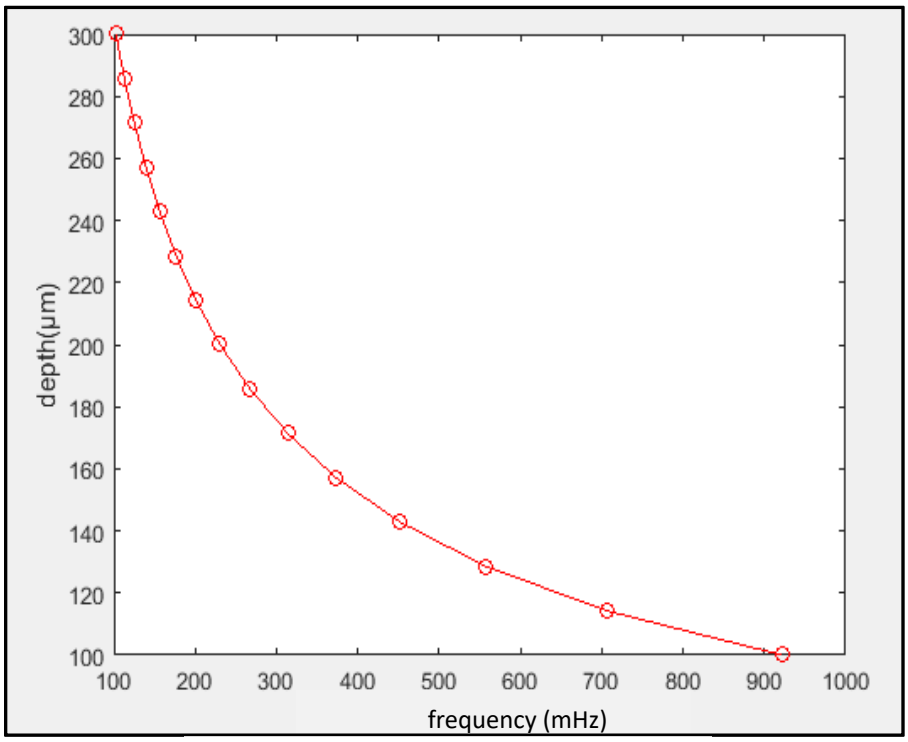

Figure 12: Depth with lock-In frequency

- ***Sensing Unit:***
  - The sensing unit has the IR detector and in best cases an IR camera. for The IR camera we need to precise the frame rate and the recording time. For the recording time, it is mainly based on the frequency and the characteristic of the chrome layer. For the frame rate, we calculated using the Nyquist criteria.
- ***Control Unit:***
  - **Lock in amplifier:** For the lock-In amplifier we need to choose the right frequency range but the work is mainly based on the phase/amplitude images.
  - **Computer** (Matlab for data processing and the software that comes with IR detector or IR camera).

Chapter IV

Application and development

4. Application and development

In this chapter I will describe the material. Then I will demonstrate the experiment conducted using these equipment. We were supposed to do the LIT based on the values and excitation source demonstrated in the previous chapter (The main objective of the internship). However, the material needed to do the LIT as described in the signal path are not available in the company for the time being.

4.1. Description of the means and material

4.1.1. InfraTec ImageIR 8300 Camera (640*512 PX):

Spectral Range	MWIR (**2,0…5,7**) µm
Detector Type	Cooled Indium Antimonide (InSb) -Focal Plane Array
Frame Rate	Full screen: **300 Hz** Field: **570 Hz** Quarter image: **1,0Hz** Line: **2,4 Hz**
Temperature Resolution	NETD @ **30 °C < 25 mK**; typical **20 mK**

Figure 13: InfraTec ImageIR camera and its characteristics

The InfraTec ImageIR 8300 Camera is a high-end IR camera. It has some outstanding characteristics that can help us conduct this project. The camera has three modules illustrated in the following figure that contain different sensors and detectors which help us do the active thermography such as PPT and LIT and of course the passive thermography. The R&D team in ITW e. V. Chemnitz doesn't know how to achieve the active thermography using the existed modules in the camera.

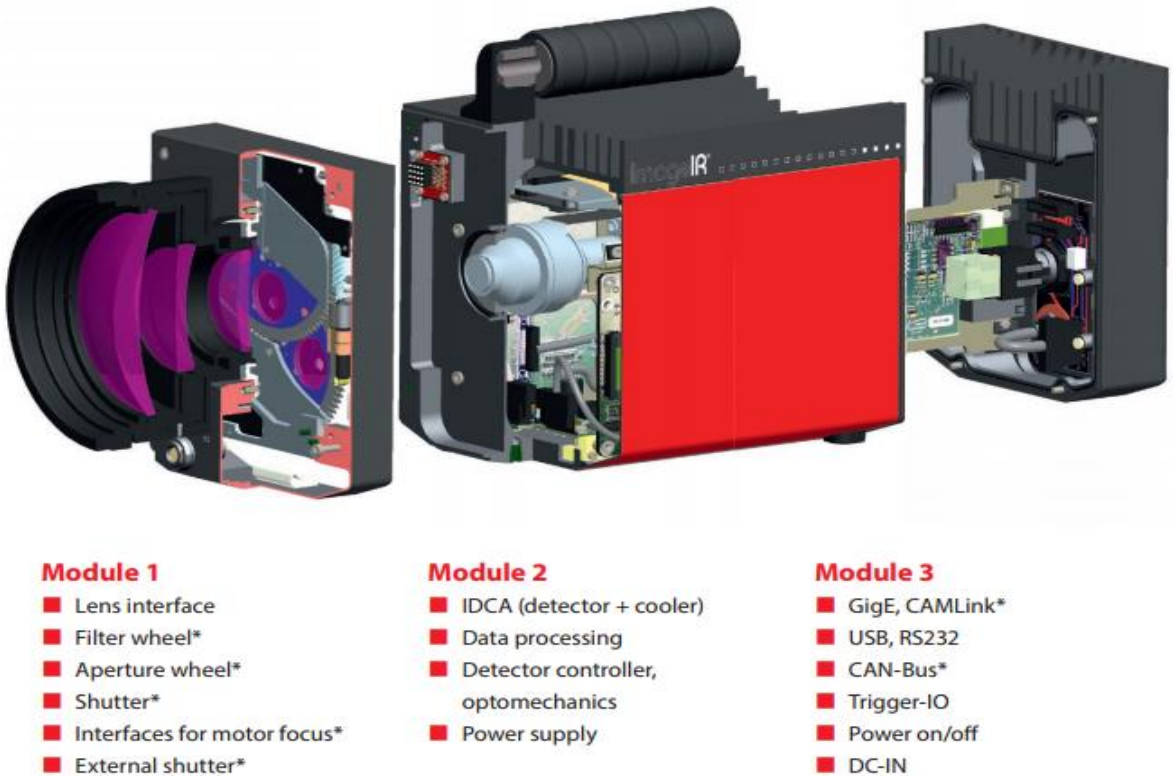

Figure 14: The modules of the IR camera [9]

4.1.2. The software IRBIS 3:

The camera is accompanied with the software IRBIS 3. The software helps us have all the information we may need from IR images to diagrams everything was done using only the software. We can also do the LIT and PPT using just the software without actually using Matlab.

We have been mainly interested in the two windows the **red** one and the **orange** one as you can see in the figure (Figure 13). Using the **red** menu helps us install the camera change the lock-in generator frequency and activate the trigger. The **orange** menu helps us choose the recording time. With these two windows, we manage to do the recording in a passive mode.

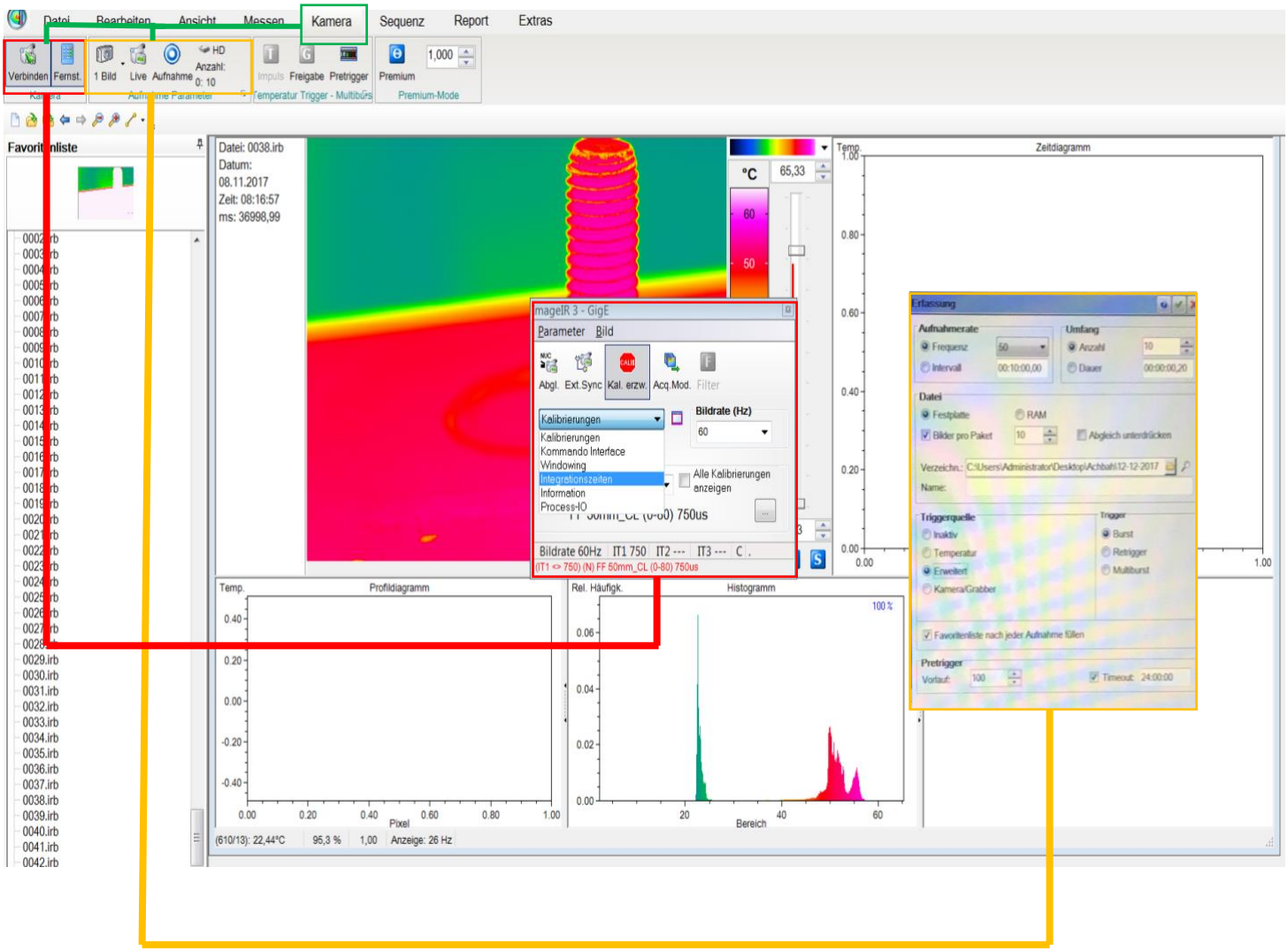

Figure 15: IRBIS menu, main window

4.1.3. PP602 lighting controller+ Lighting IR with Optics (940 nm):

To use the LED as a heating resource, we need the LED controller. For that reason I am going to emphasize its characteristics and talk from now on about it since the LED can only give us what we did using the controller. To generate the pulse we use InfraTec embedded trigger to give us a multi-burst pulse signal. The connection between the camera is important because we need to have a vice versa communication between camera's trigger and the activation of the recording and image taking.

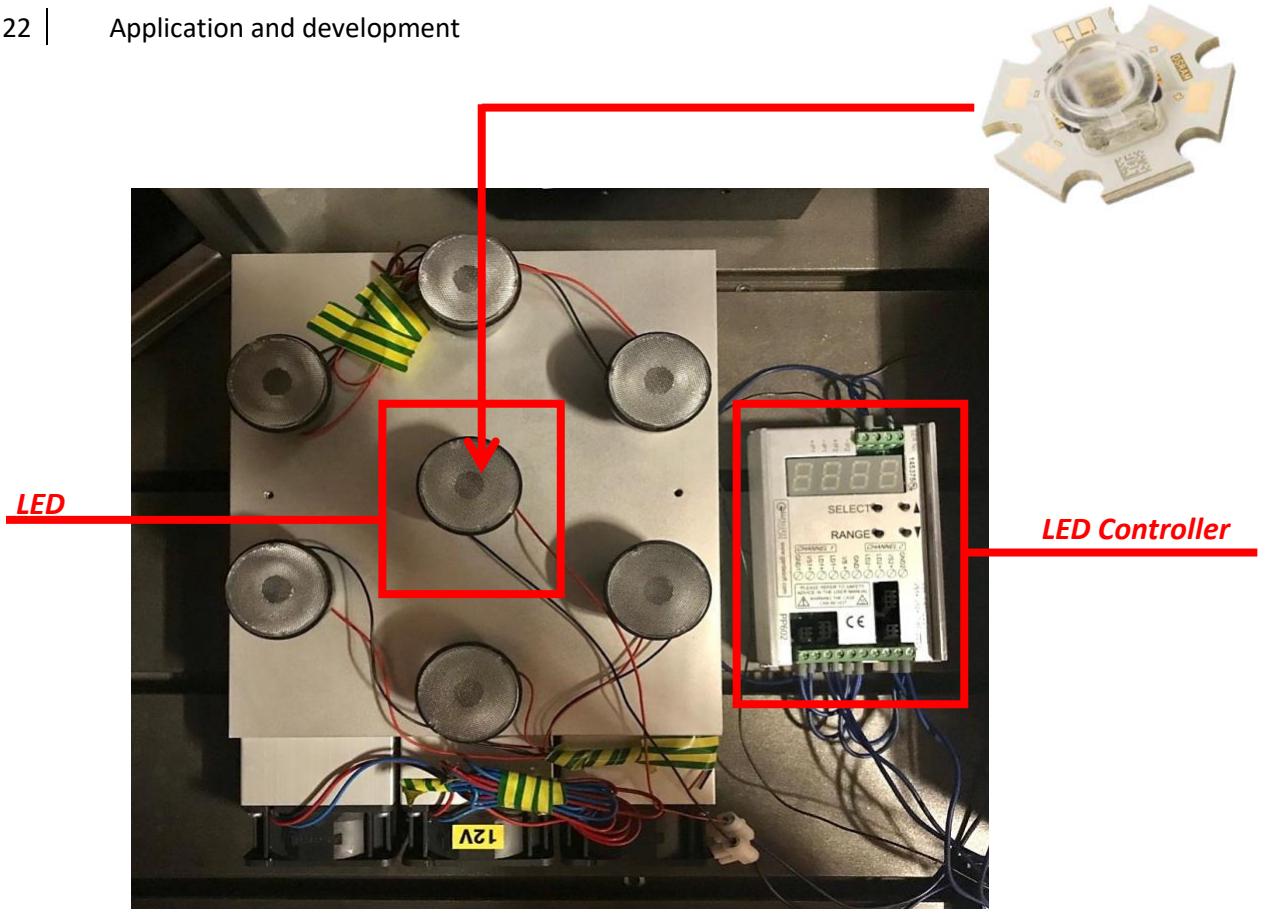

Figure 16: Lighting/ Heating set up

⇒ ***Conclusion:***

After the use and the reading of the documentation, it turned out that the IR camera is capable of doing the PPT just by using an internal trigger. But for the LIT we will still need a function generator that can generate a sinusoidal signal.

4.2. Connecting LED with camera's trigger:

The importance of this step lies in the importance of using a function generator.

The trigger is a rising edge TTL-Signal in the chosen frequency. We connect the camera to the lighting controller using a power supplier. Then the trigger signal is activated using the IRBIS software. We choose the lock-in generator frequency as stated in the section (3.2.2.). The figure 15 pictures the connection between the two. Current is limited to match the characteristics of the LED which are 1A for the current.

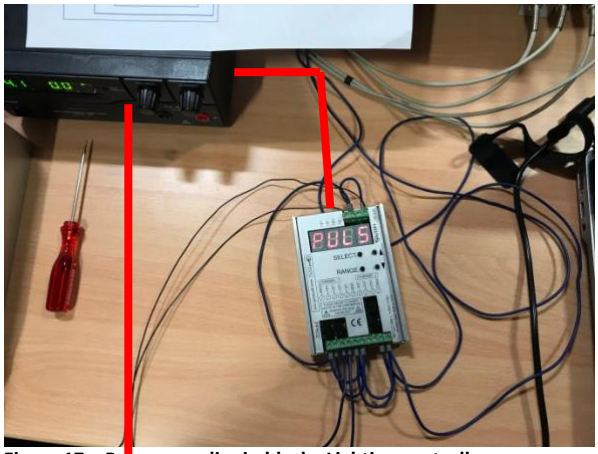

Figure 17: Power supplier in black+ Lighting controller

Figure 19: Behind of the camera

RS232

Figure 18: The connection between the camera and the Lighting controller

The lighting controller generates one pulse with a specific pulse width and delay. We get to change and choose the pulse width and the delay, but we cannot exceed **99ms**.

The following figure shows the three different parameters of each pulse.

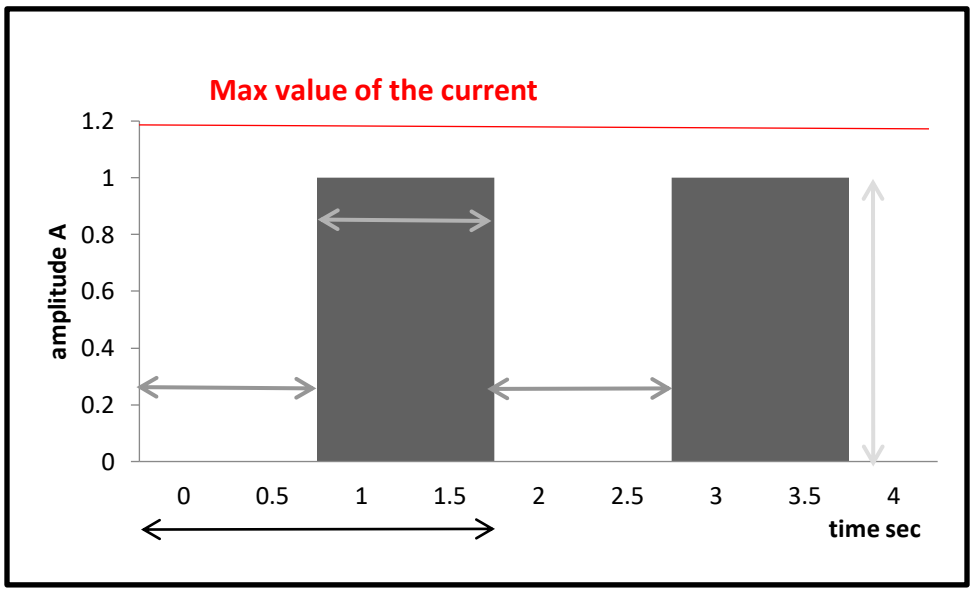

Figure 20: Pulse width and the delay

DEL: The delay. After triggering, we have to wait for an instance (delay)

PUL: The pulse width. The length of a pulse.

CUR: The pulsed current. The value that we want to have (in Ampere). It should be equal or smaller than the max value of the current.

The signal we use in this experiment is a square signal and not the sinusoidal one.

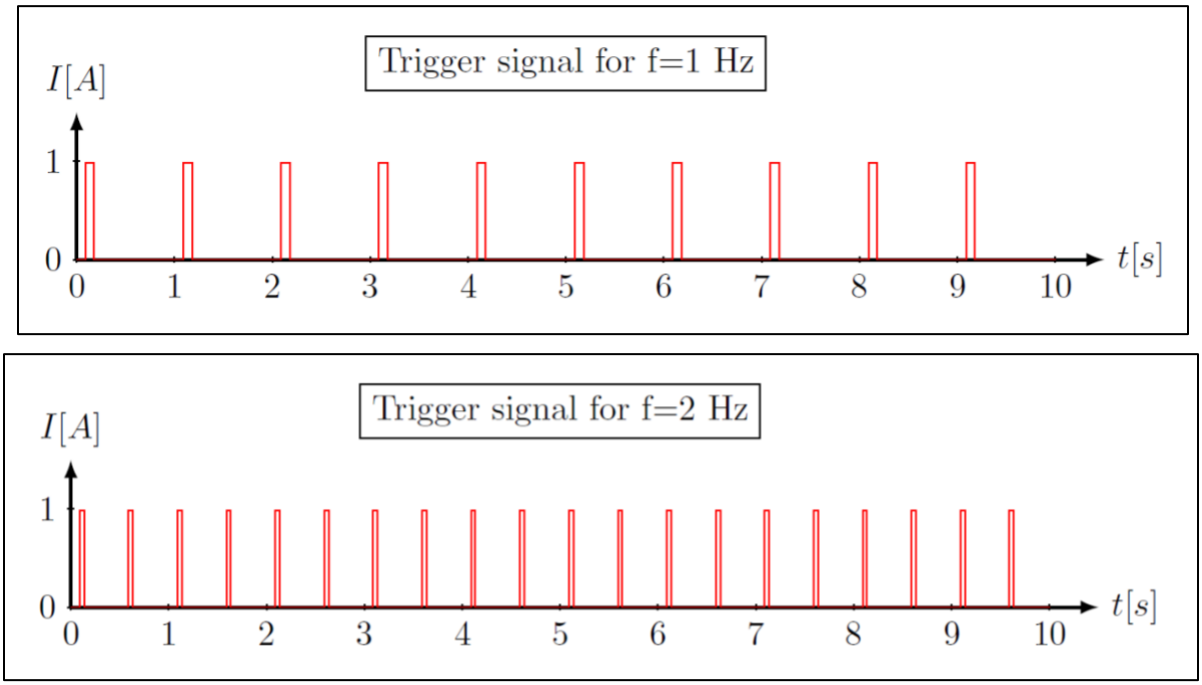

Figure 21: Trigger signal for f=1 and 2 Hz

The camera's trigger interface has 4 communication channels: Two out and two In. The lighting controller is connected to the OUT-1. After doing this step we get to control the LED from the software IRBIS. But what we need is the activation of the LED and thus having multi-burst must launch the recording and thus having a heating process while taking the time series. For that we need to have a TTL connection from the output of the lighting controller back to the camera. for that we connect the OUT-1 that come from the LED controller to IN-1 of the camera.

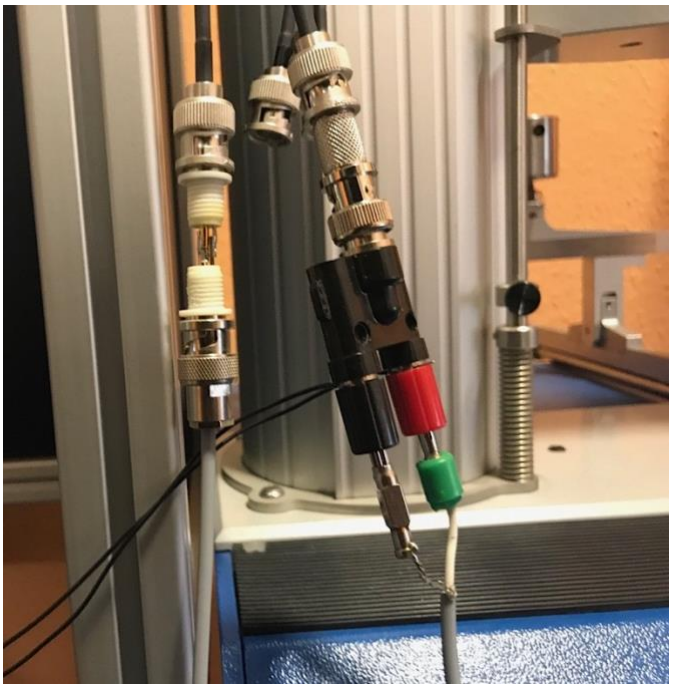

Figure 22: The TTL-Signal connection

4.3. Experimental set-up and data acquisition:

In this part we need to do the experiments and find out how the camera operates. What we were supposed to do was doing the lock-In thermography with chrome layers. We received the chrome layers from the laboratory late December. However we did not receive a lock-In amplifier and a sinusoidal function generator. Which explain why I discussed above a square signal. For that reason we will carry out measurements using first a black plastic to see the reaction of the camera and how it operates to pave the way for the team after receiving the equipment. What we supposed to do was using this range of frequencies calculated in the last chapter. Also what we were supposed to have is a phase image that shows the pores and cracks of the chrome layer.

4.3.1. Experimental set-up of the PPT:

For our set-up, we have the IR camera as IR detector, the LED and lighting controller and the specimen. First results were based on some black. That black sample helps us to understand how the set-up works and if we had succeeded in doing the PPT. Then we started working with the chrome.

The camera was set in that position to capture the waves reflected and emitted by the chrome layer which was 45° inclined. We fabricated a small support out of cardboard to have the best angle between the detection with the camera and the exposition to the radiation coming out of the LED. We use the cardboard to avoid any external heat changing.

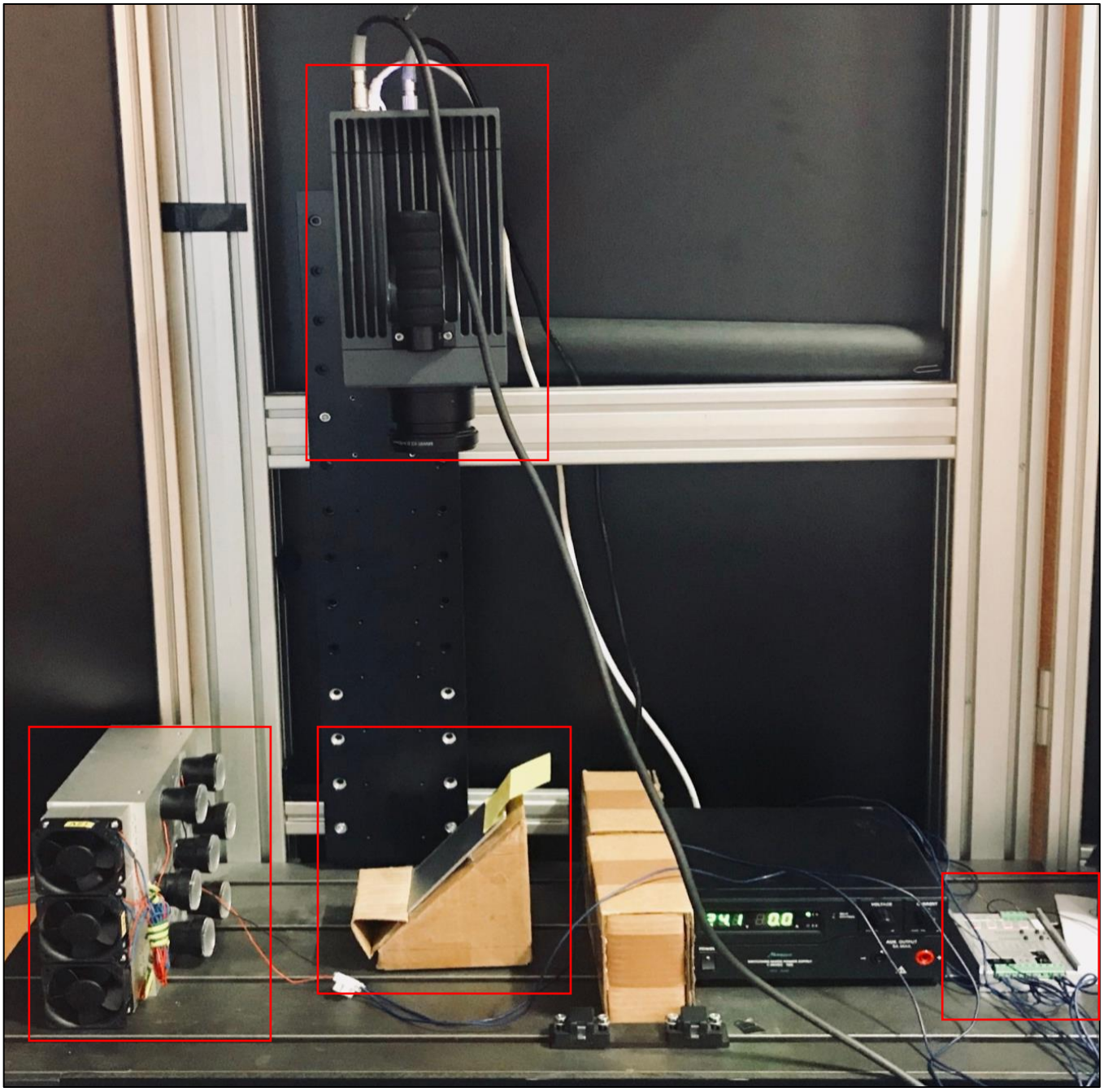

Figure 23: Experimental set-up

4.3.2. Recording and data processing:

We turn on the camera and set up all the parameters we have found after the theoretical research. We do different tests for different parameters:

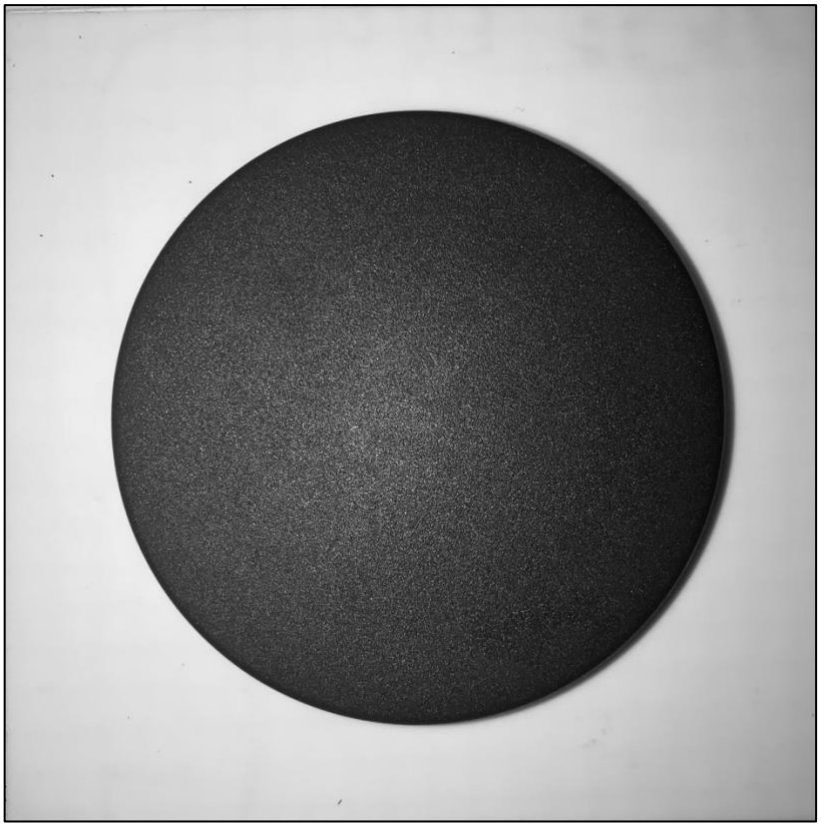

Figure 24: The used black plastic

Test object (1)	Frame rate[Hz]	Lock-In generator frequency [Hz]	Recording time	Interval [s]	Number of pictures
Black plastic	50	1	8min 20s	10	50
Black plastic	50	0,5	8min 20s	10	50
Black plastic	50	2	8min 20s	10	50
Black plastic	50	0,1	8min 20s	10	50
Black plastic	50	0,33	8min 20s	10	50

Figure 25: Test object 1

We used a black plastic in the first test to see in reality how the IR camera works and how it responds to different parameters and to avoid reflectivity of a standard metal material.

The results were the following:

From those results, we can say that the best frequency that can help us see some results and be able to interpret them are those from **experience 1** and **experience 3** which corresponds to **1 Hz** and **2Hz**. The reason is the fact that the LED is not powerful enough and thus we need some fast pulses to heating up the chrome sample. We can see on the figure some cooling in the different experiences. Unfortunately we still don't know what is the problem in this situation is it with the camera or with the LED.

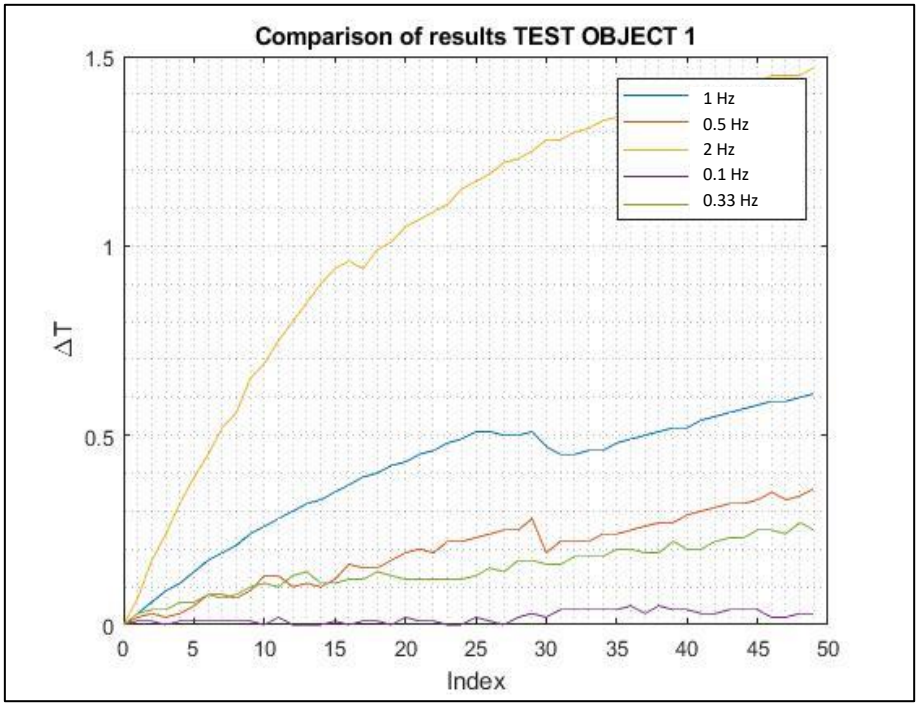

Figure 26: Test 1 with Black plastic results

After finishing with the black plastic and knowing the suitable frequencies that we are going to use we start experimenting with a chrome specimen. The chrome layer thicknesses were **0.02 mm**, **0.05mm** and **0.1 mm**.

The choice of the lock-in generator frequency is based on the **Nyquist criteria** which say: The lock-in frequency can be only varied in certain steps because we have some serious exponential limitation: $f_{lock-In} = f_{frame}/2$ for that reason and in the next test we change the interval from 10 s to 0.5 s for $f_{lock-In} = 1Hz$ and 0.25 s for $f_{lock-In} = 2Hz$.

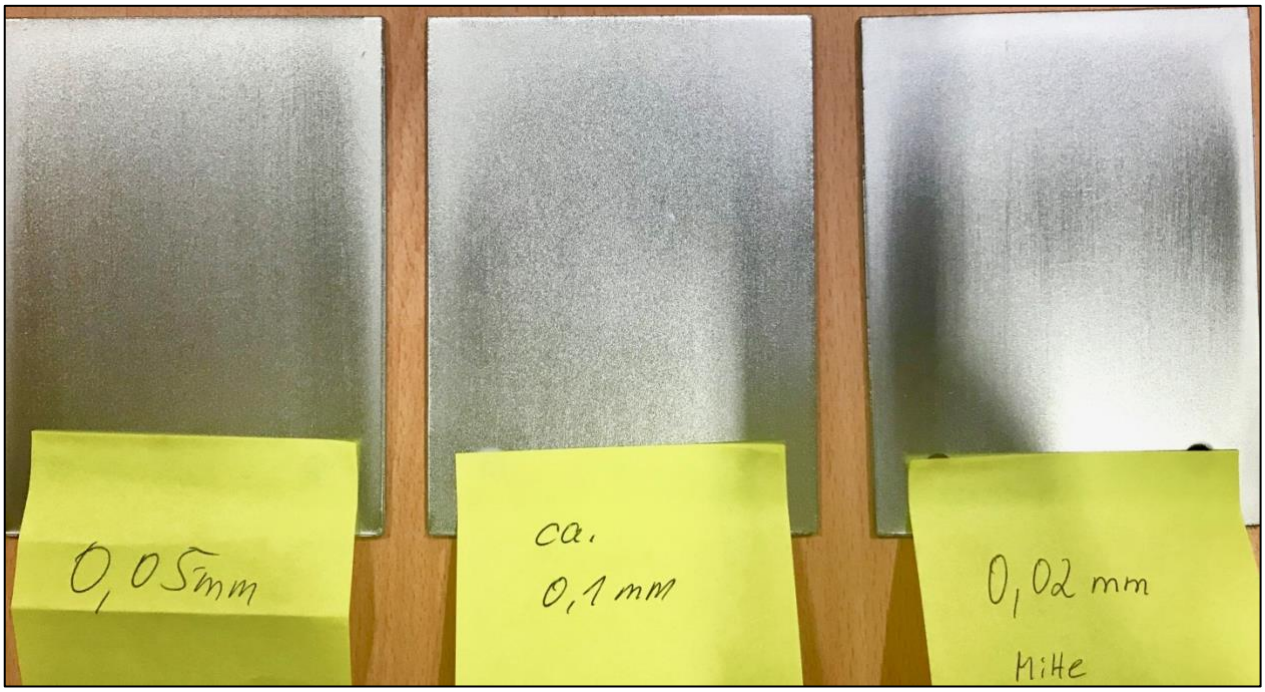

Figure 27: Different chrome samples

Test object (2)	Frame rate[Hz]	Lock-In generator frequency [Hz]	Recording time	Interval [s]	Number of pictures
Chrome 0.02 mm	50	1	8min 20s	10	50
Chrome 0.05mm	50	1	8min 20s	10	50
Chrome 0.1 mm	50	1	8min 20s	10	50
Chrome 0.02 mm	50	2	8min 20s	10	50
Chrome 0.05 mm	50	2	8min 20s	10	50
Chrome 0.1 mm	50	2	8min 20s	10	50

Figure 28: Test object 2 with two different frequencies

For the chrome layer, we experimented using the frequencies we discussed above. For now, we still just trying to get used to the camera and see what the results are. The following figures manifest the temperature changes during the time for each frequency of the trigger also known as the lock-in generator frequency.

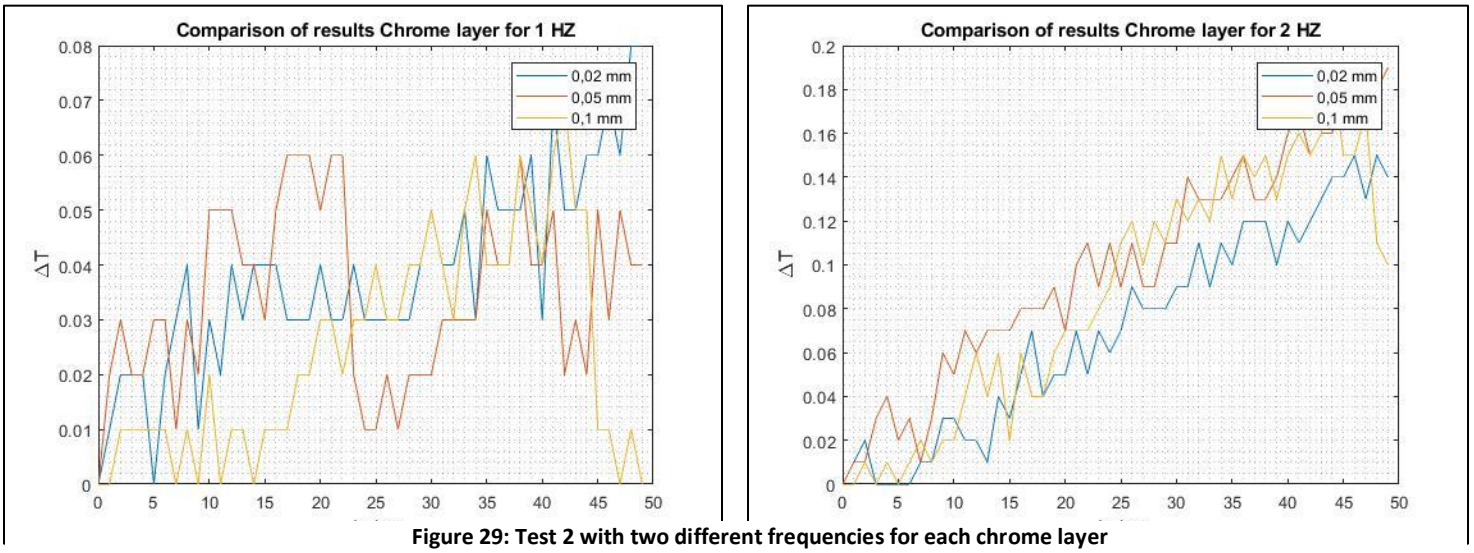

Figure 29: Test 2 with two different frequencies for each chrome layer

We see a heating up process, which is different for each layer thickness. First we do a fitting procedure with linear regression to test if this parameters are already sufficient to distinguish the different layers more experiments have to be done. I tested for repeatability with one frequency (we didn't have sufficient time for all the frequencies) and two specimens.

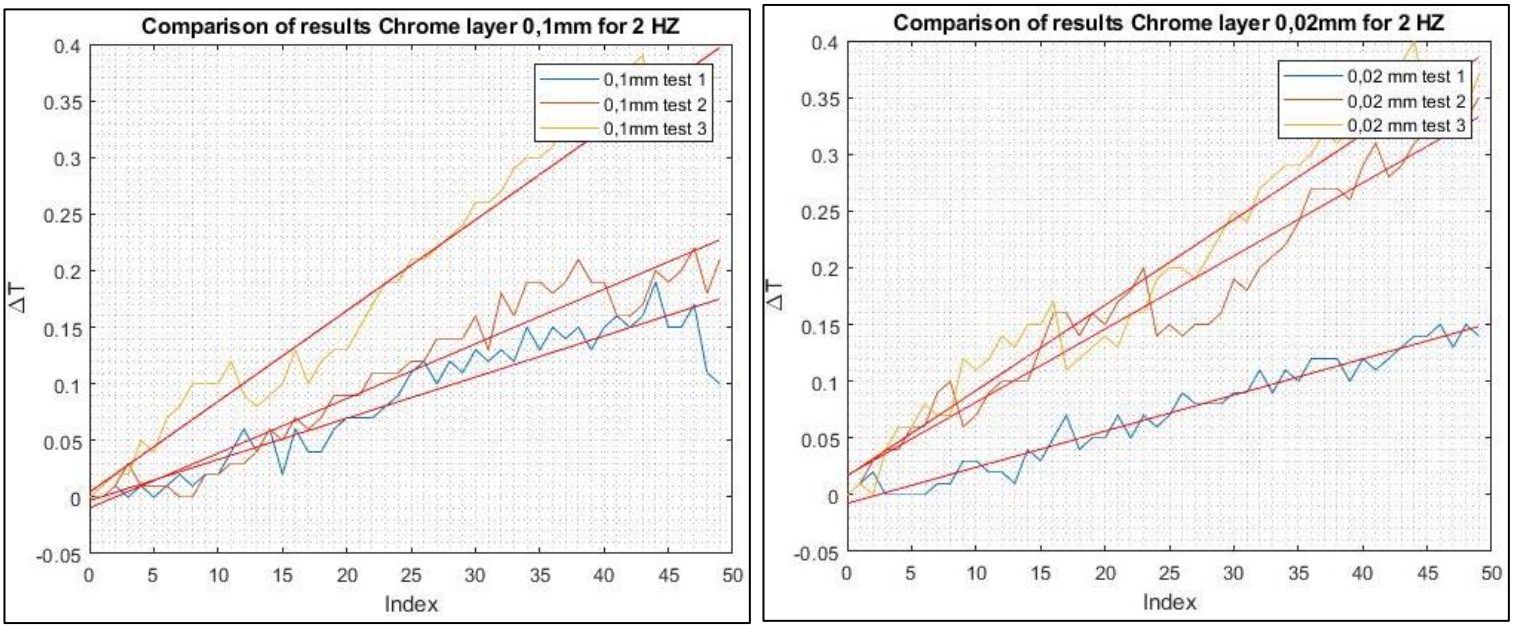

Figure 30: Comparability between the results of three tests for f=2 HZ

The regression parameters so far as you can see in figure 28 and in figure 29 don't show a good repeatability. (Regression type 1. Where $y = ax + b$).

Regression parameters for Chrome layer 0.1 mm for 2 Hz	
Test 1	a= 0.0036 ; b= -0.0031
Test 2	a=0.0048 ; b= -0.0096
Test 3	a=0.0080 ; b= 0.0044

Regression parameters for Chrome layer 0.02 mm for 2 Hz	
Test 1	a=0.0032; b= -0.0076
Test 2	a=0.0064; b=0.0172
Test 3	a=0.0075; b=0.0167

Figure 31: Regression's parameters

Consequently we changed the frame rate (interval) based on Nyquist Criteria. We did the same experiment and plot the thermic signal using one frequency for one specimen but this time with a frame rate of 4Hz (interval=0.25 s) and we had the following results (Figure 30). We still have the same step appearing after one third of measurement, this time I think it is caused by the camera, which maybe stops to activate the trigger while saving data and it is more obvious in this case since we have a lot of measurements (8 min 20s with an interval of 0.25 s). Thus the specimen cools down and then starts to heat up again after the triggering.

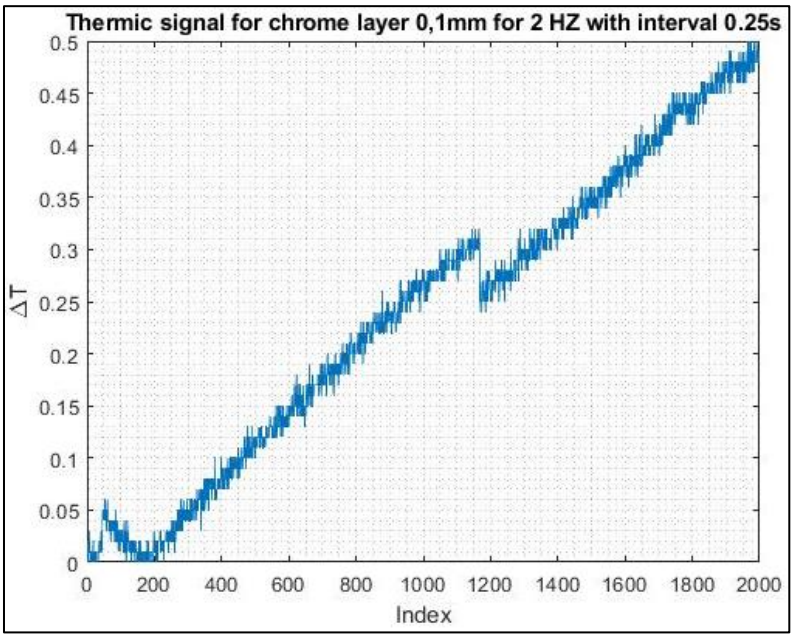

Figure 32: temperature profile for f=2 Hz and interval=0,25s

After the new measurement it appears that the new interval and frequency does show the wanted lock-in generator frequency and thus we have succeed at choosing the right lock-in frequency for the right frame rate.

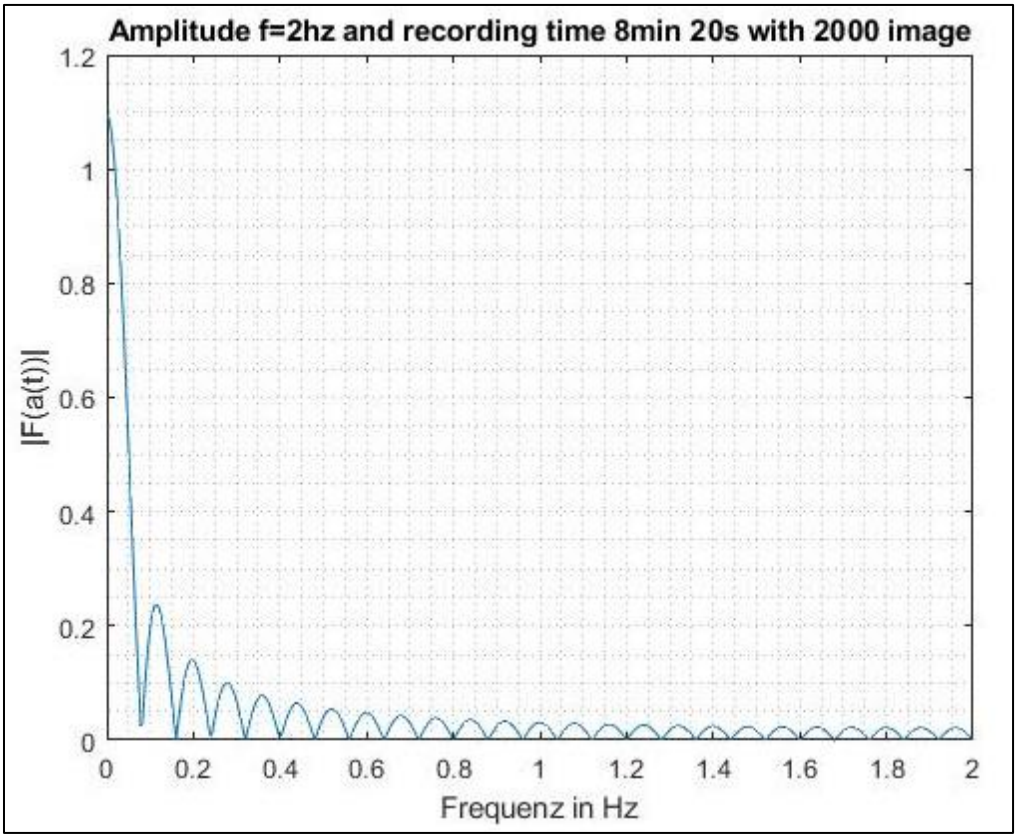

Figure 33: Amplitude and frequency generated by the FFT

Those results are based on a hand to hand calculation, which means we have to record the temperature with the camera and upload it to Matlab and then do the FFT. But the camera can do the phase and amplitude image too. It is hard to do it online [There is a difference between the online and offline measurements, the online is calculating the FFT and do the phase and amplitude image while recording. The offline FFT we have to wait until we finish recording and then do the hypothetical calculation]. The online is not obvious for now for that reason we only do the offline FFT. The next images are supposed to be the image amplitude images for phase shift 0° and 90° for the black plastic specimen. It was done using the software. Due to time limitation I didn't succeed at doing it with the chrome layer.

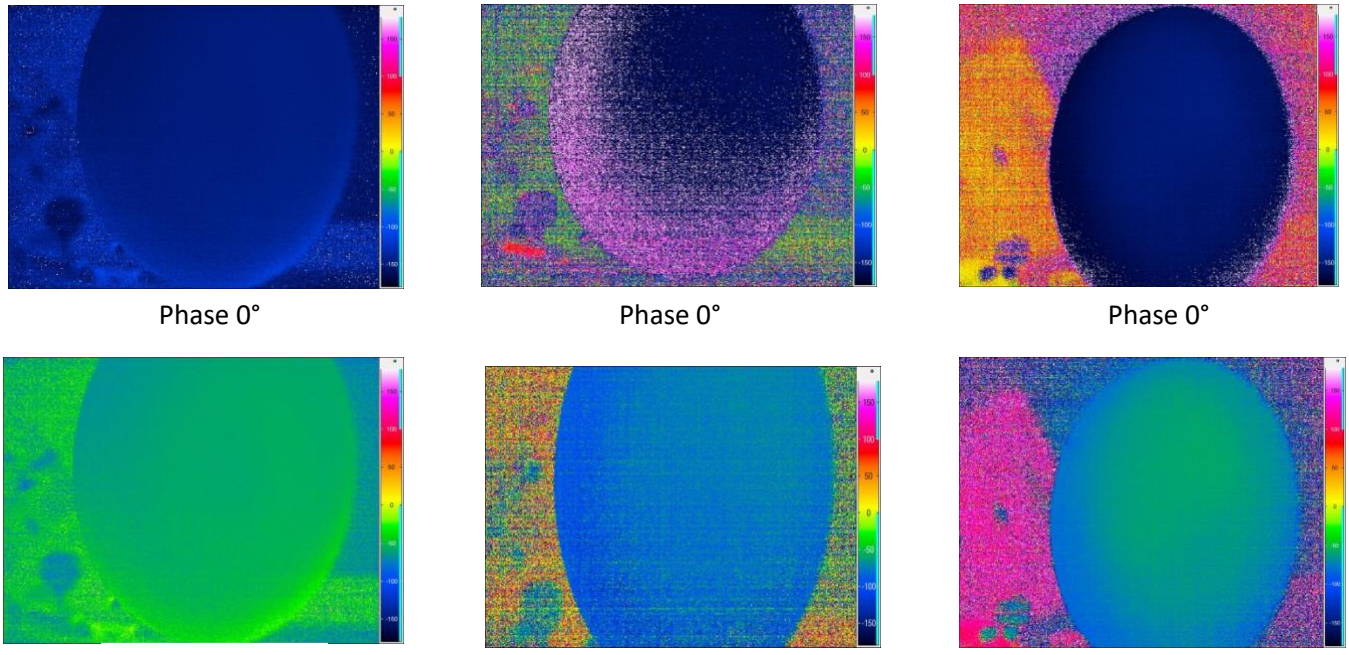

Figure 34: Phase image of black plastic generated by IRBIS as Offline results

As for now, the only thing we can notice is the difference between the images of the 0° and phase 90°. We still don't have a conclusion on that since the black plastic is homogeneous and have no cracks and pores, unlike the chrome layer.

⇒***Conclusion:***

To summarize, what we basically wanted to do is LIT (That what I signed up for) but we lack equipment and to top it off the company doesn't know how to use the camera nor the software to do THE ACTIVE THERMOGRAPHY and thus the LIT or PPT. For that reason what I worked while doing the measurements and the recording was to find how to do the active thermography. How to show the lock-in generator frequency chosen in the amplitude response and how to have 90° and 0° figures.

4.3. Chrome layer modeling:

The first attempt was to do the experiments using a chrome layer with a stochastic distribution and record the response. But at the same time, we need some known effects to make the comparison and to see how accurate our results are. As a result, we are doing at the same time the modeling of the chrome layer and then sending finite element model to the laboratory so at the end we can conclude. So far we haven't received the chrome layer from the modeling yet. My supervisor Brottka was the one working on the modeling and she asked me to write a Matlab code that generate a chrome layer with spherical pores. And then she will use this generated distribution in FEM software **COMSOL MULTIPHYSICS** to do the modeling and send the example to the laboratory.

We need many parameters to do the distribution:

- ✓ The number of the pores
- ✓ Volume of pores and thus r: radius of each pore
- ✓ Porosity

I wrote 3 function that generates the previous parameters based on other parameters:

- → The depth of the chrome layer that varies between 100µm and 300µm.
- → We assume that all pores have the same volume
- → We assume that all pores are spherical

The parameters all depend of each other. For that reason we create a median radius r_m = 5 µm, of the pore and a porosity. This median radius helps us have an estimate of the total number of pores. we use the following expression: $v = phi * Vt$ where **Phi** is the porosity and Vt the total volume of the chrome layer (a*b*depth).

$$v = \sum_{i}^{n} v_i = n * \frac{4\pi {r_m}^3}{3}$$

This expression gives us the total number n of pores that we should not exceed to maintain the fixed porosity that we need to have in our modulated chrome layer. So **n** is the total number of pores. now from this estimated n we calculate the volume. The most important part is the stochastic distribution of pores and cracks for that we use the function `normpdf` of Matlab to have the normal random distribution of the pores in our chrome layer of a certain depth.

The following figure shows exactly what have been describe above for the following values:

```
a=10; % mm
b=10; % mm
depth=0.3; %mm
phi=0.02; %porosity
rm=0.005; %mm ==> 5 µ
```

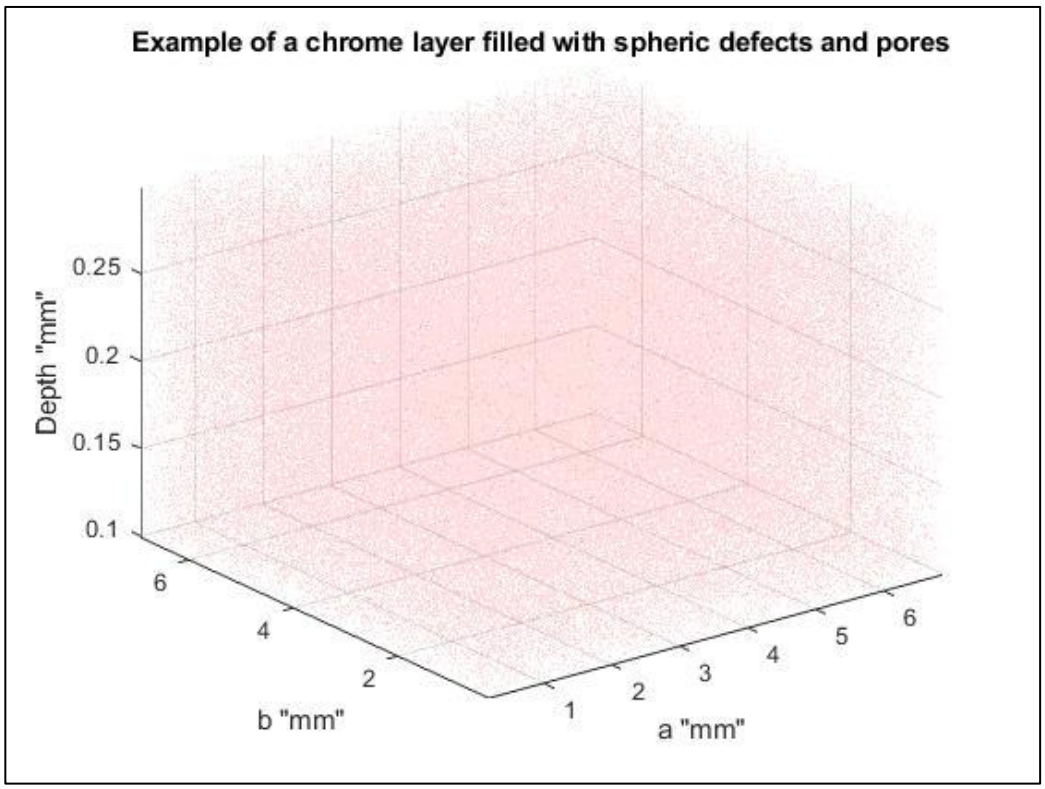

Figure 35: Chrome layer with stochastic spherical defects

The red dots are the pores generated by the function scatter of Matlab. Those red dots have a volume and a radius and the total number of them is n calculated above.

Conclusion and perspectives

To summarize, what the company asked me to do the first time was to understand the Lock-In thermography develop a test sequence and from it a signal path. From the signal path choose the excitation source and generate a Matlab code that calculates the FFT and thus the phase and amplitude image. The whole LIT is not possible if we don't have a sinusoidal function generator and a lock-in amplifier. The purpose of chapter 4 was to describe the test sequence and the recording results based on theoretical values calculated by using different parameters in section 3. However, the team has already problems with the IR camera so what I was trying to do is, to know how to use the camera and do documentation on how to use it with the TTL connection and frequencies values preferred.

From that, the general conclusion is, it is true we did not succeed at doing the Lock-In thermography, but this is due to lack of material since the government sponsors the project. Also, the fact that not all the team is working on it because they still doubt the solution. It turned out for them it is easier to work on Pulse phase thermography since we already have the material, and we should not waste time answering what we have no access to yet.

The perspective of the project, they will use all the information I gathered, mainly how to do the online processing and no longer the offline processing. Since there are only three months left to the end day of the project, they will try to accelerate the process. In general, the next step is to do the online LIT using an external Function generator and wait for the lab modulated chrome layer to do the comparison between the existed chrome layer and the one with spherical pores.

My whole perception on this internship, I did learn a lot of valuable soft skills and technical ones. I learned how to be self-driven and proactive. I learn how to work alone with no help. I learn how not to lose faith when my question doesn't have an answer even if they were related to the work and I should have an exhaustive description of the means and the project before starting digging and losing time. My whole experience might not be perfect, but it did give me a lot of qualities that I would not learn elsewhere.

Besides, this internship is R&D; it was a good plus for me since I am planning to be a researcher soon after finishing my master degree.

The value of the intern remain in the value that he brings to the company, and I believe that I have brought a lot of qualities to the company.

Annex

Disclaimer: The pieces of information provided in this annex are the results of a lot of research. I do not own any of what was presented here. The whole point of putting that information here even though they are on the internet is to help you have a better understanding of this topic and since I am not a scientist and I can't give these pieces of information nor write them in my style hope the plagiarism won't affect me. But the whole report from the introduction till the conclusion is my proper work except for the generic definitions. **Thank you!**

1. *Nondestructive testing:*

The Field of NDT is a very broad, interdisciplinary field that plays a critical role in inspecting that structural component and systems perform their function in a reliable fashion. Certain standards has been also implemented to assure the reliability of the NDT tests and prevent certain errors due to either the fault in the equipment used, the miss-application of the methods or the skill and the knowledge of the inspectors. [5]

Successful NDT tests allow locating and characterizing material conditions and flaws that might otherwise cause planes to crash, reactors to fail, trains to derail, pipelines to burst, and variety of less visible, but equally troubling events. However, these techniques generally require considerable operator skill and interpreting test results accurately may be difficult because the results can be subjective. [5]

These methods can be performed on metals, plastics, ceramics, composites, cermet, and coatings in order to detect cracks, internal voids, surface cavities, delamination, incomplete c defective welds and any type of flaw that could lead to premature failure. Commonly used NDT test methods can be seen in table 1. These are universal NDT methods; however, very special tests have been developed

Technique	Capabilities	Limitations
Visual Inspection	Macroscopic surface flaws	Small flaws are difficult to detect, no subsurface flaws.
Microscopy	Small surface flaws	Not applicable to larger structures; no subsurface flaws.
Radiography	Subsurface flaws	Smallest defect detectable is 2% of the thickness; radiation protection. No subsurface flaws not for porous materials
Dye penetrate	Surface flaws	No subsurface flaws not for porous materials
Ultrasonic	Subsurface flaws	Material must be good conductor of sound.
Magnetic Particle	Surface / near surface and layer flaws	Limited subsurface capability, only for ferromagnetic materials.
Eddy Current	Surface and near surface flaws	Difficult to interpret in some applications; only for metals.
Acoustic emission	Can analyze entire structure	Difficult to interpret, expensive equipments.

Figure 36: Commonly used NDT techniques [5]

for specific applications. [5]

2. *IR Thermography:*

IR thermography is the most elegant NDT since it can be applied to rough surfaces, and it can image the sample from a certain distance without contacting the surface at all. Most importantly, with the availability of modern focal plane array IR cameras combining high sensitivity with high frame rates, IR camera-based lock-in thermography systems have proven to provide today's best possible performances with respect to the detection sensitivity within a limited measure time. If electromagnetic radiation (light) falls onto the surface of a specimen, three and only three things possibly may happen with the irradiated light: It may be reflected from the surface, it may be absorbed by the specimen, or it may be transmitted if the specimen is totally or partly transparent to the light. The probabilities of these three processes to happen are described by the reflection coefficient or reflectance ρ, the absorption coefficient or absorbance α, and the transmission coefficient or transmittance τ. These three coefficients are usually wavelength-dependent and may depend on the directional distribution of the irradiation. They are dimensionless, and their sum is always unity. For an ideally reflecting specimen, ρ is unity, and α and τ are zero, for a non-reflecting totally transparent specimen, τ is unity, and α and ρ are zero, and for a black body, α is unity, and ρ and τ are zero. Each body at a finite temperature spontaneously emits electromagnetic radiation, which is called thermal radiation. The magnitude M_λ (in units of W $m^{-2}\mu m^{-1}$) is called the spectral specific irradiation. It describes the electromagnetic power, which is irradiated within a differential wavelength range by a plane unit area into one half- space. The specific irradiation of a black body as a function of the wavelength λ is given by Planck's law: [4]

$$M_\lambda(T) = \frac{2\pi hc^2}{\lambda^5}(e^{\frac{hc}{\lambda kT}} - 1)^{-1}$$

(h = Planck constant, c = velocity of light, k = Boltzmann constant, T = absolute temperature in Kelvin). For a real (not black) specimen, the thermal emission depends on optical properties of the specimen. Let us imagine a closed volume with homogeneous optical properties of the walls at a certain temperature in thermal equilibrium. Then the inner surface loses energy by thermal radiation, and it absorbs energy by radiation absorption. Thus at any wave- length, each part of the inner surface has to emit the same amount of radiation as it absorbs, otherwise the system would not be in thermal equilibrium. This means that the probability of a surface to emit radiation (the so-called emissivity ε) has to be equal to the absorption probability α at this wavelength. This identity is known as Kirchhoff's law. For an ideal black body α=ε=1 holds, for real bodies ε is more or less smaller than 1. If within a certain wavelength range the emissivity ε is < 1 but wavelength-independent, this specimen is called a "grey emitter". If ε strongly depends on the wavelength, this specimen is called a "selective emitter". In order to obtain the specific irradiation of a real body, has to be multiplied by the wavelength-dependent emissivity ε(λ). [4]

3. *Lock-In thermography:*

The principle of lock-in thermography consists of introducing periodically modulated heat into an object and monitoring only the periodic surface temperature modulation phase-referred to the modulated heat supply. Hence, if the surface temperature is measured via an infrared (IR) thermocamera, lock-in thermography means that the information of each pixel of the image is processed as if it were fed into a lock-in amplifier. As figure 35 shows, the digital lock-in correlation procedure consists in successively multiplying the incoming IR images by a set of weighting factors and summing up the results in a frame storage. The weighting factors are approximating a harmonic function and are synchronized to the pulsed bias applied to the sample. Since amplitude and phase of the measured surface temperature modulation may change with position, a two-phase lock-in correlation has to be used. Thus, a lock-in thermography measurement can yield either an amplitude and a phase image, or an in-phase (0°) and a quadrature (-90°) image, referring to the phase of the periodic heat supply. For non-destructive testing purposes, the phase image is often more informative than the amplitude one, which strongly depends on the local IR emissivity. For the detection of local heat sources in electronic devices, on the other hand, the amplitude signal is the more informative one, since it is directly related to the locally dissipated power. The advantage of lock-in thermography over stationary methods is not only its significantly improved sensitivity owing to the ac averaging technique but also an improved spatial resolution of the image. While in any stationary thermography the lateral resolution is strongly affected by lateral heat conduction, in lock-in thermography the periodic heat source acts as the origin of temperature waves, which are strongly damped . Owing to the detection wavelength of 3 ... 5 µm the spatial resolution of IR lock-in thermography is limited to this range. [6]

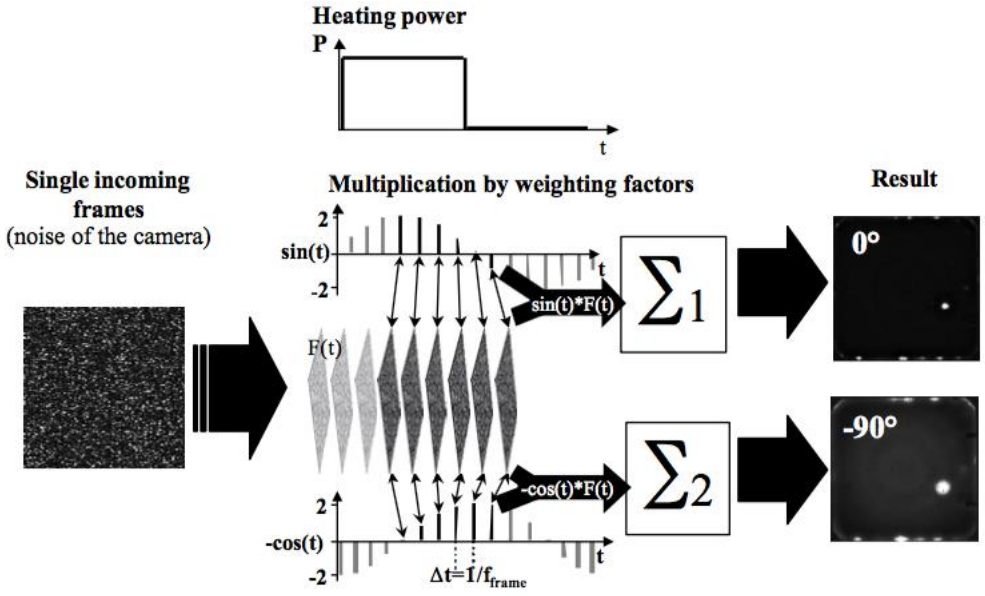

Figure 37: Principle of Lock-in IR-Thermography. [6]

The goal of the development of the TDL 384 M "Lock-in" system was to provide a commercial system combining an ultimate detection sensitivity with an industrially proven rugged construction and high resolution. The scheme of the system is shown in figure 36 The IR detector head is based on a Sterling-cooled mercury cadmium telluride (MCT) mid-wave (3 ... 5 µm) focal plane array having a resolution of 384x288 pixel. This array has a single detector size of 20x20 µm and can be equipped with a number of high brilliance (down to F#1.5) IR objectives. With a special microscope objective a spatial resolution of 10 µm is obtained, which may be lowered down to 5 µm by inserting a lens extender ring. In full frame mode the maximum possible frame rate is 140 Hz, which corresponds to a pixel transfer rate of about 15.5 MPixel/s. However, it is possible to select sub-frames of 288x288, 256x256, and 128x128 pixels with nearly the same pixel transfer rate, where the frame rate may increase up to 850 Hz. The higher the frame rate, the lower is the degradation of the spatial resolution caused by lateral heat conduction in the sample. The PC used is a 2x800 MHz dual Pentium III system running under Windows NT. As a frame grabber board a Matrox Vision board is used, which writes the captured frames cyclically by direct memory access (DMA) into a certain part of the RAM, where the PC software picks them up for correlation. A programmable hardware counter is provided, which is controlled directly by the frame grabber board and is used to provide the lock-in reference trigger and to ensure that only lock-in periods with a complete number of frames are used for correlation. The power supply for the sample bias is pulsed by a solid state relay switching unit. The whole electronics including the PC, the pulsed power supply, and the power supply for the detector head is combined within a rugged roll container, which is connected with the detector head by a 5 m long cable. If this system has to be used for investigating small objects like ICs, it can be equipped with a stable vertical support and an x-y-z movable device testing stage. Alternatively, for investigating larger objects like wafers, solar cells, or modules, it can be used in a horizontal arrangement. The achieved temperature resolution is 35 µK (effective value) after 16 min measurement time and further reduces with 1/(measurement time)$^{1/2}$. [6]

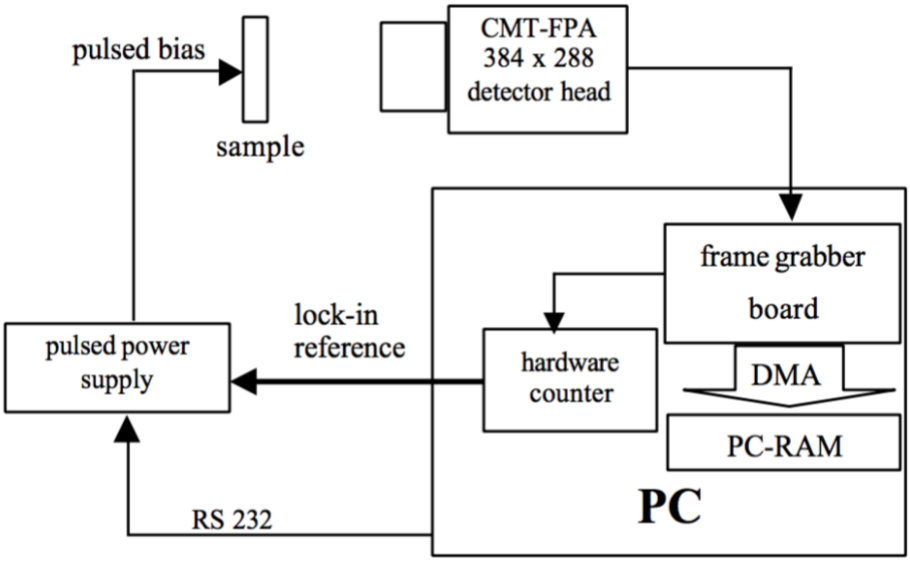

Figure 38: Scheme of the TDL 384 M "Lock-in" system [6]

4. *Matlab Codes:*

I did write so many Matlab codes to understand the results or just to test what I was doing for that reason many results from those scripts won't even figure in the report, but I've put them here to showcase my general work.

4.1. Frequency to depth

```
clc
close all
m1=1400 ; %micrometre
m2=1800 ; %micrometre
n=15 ; %steps
lam=91 ; %thermal conductivity [W/(m.K)]
Cp=0.44e3;%specific heat[J/(kg.K)]
gho=7.14e3;% density [kg/(m^3)]
a=lam/(Cp*gho) ; %thermal diffusivity of chrome:  m^2*s^(-1)
% d=linspace(m1,m2,n);%en micrometre
% f=zeros(1,n);
% for i=1:n
%    f(i)=a/(pi*((d(i)*10^(-6))^2));
% end
 f=[0.021 0.028 0.038 0.055 0.071 0.093 0.126 0.182];
 m=length(f);
 d=zeros(1,m);
 for i=1:m
  d(i)=10^(3)*sqrt(a/(pi*f(i)));  %depth in mm
 end
ax1 = subplot(1,1,1);
plot(ax1,f,d,'r-o')
xlabel(ax1,'frequency(Hz)')
ylabel(ax1,'depth(µm)')
```

4.2. Calculate maximum and average of temperature from different files:

This code help understand the problems with each file in addition had help me detect the problems of chosen frequency.

```
n=50 ; %number of files it chabges whenever we chabge test object
temperatureFile = cell(1,n); %cell of csv files % n is the total of csv files
mintemperature=[]*n;
MAXtemperature=[]*n;

for k = 1:n %n %loop to read and open csv files with matlab
  name = sprintf('%i.xlsx',k);
  temperatureFile{k} = xlsread(name,'A17:WJ476');
  mintemperature(k)=min( temperatureFile{k}(:));
  MAXtemperature(k)=max( temperatureFile{k}(:));

end

show temperature profil of each pixel
Temp=zeros(y,x);  %temperature
```

```
  for i=1:y
  for j=1:x
    Temp(i,j)=temperatureFile{1}(i+ymin,j+xmin)-IniTemp;%data
    Temp(i,j)=temperatureFile{25}(i+ymin,j+xmin)-IniTemp;%data
    Temp(i,j)=temperatureFile{50}(i+ymin,j+xmin)-IniTemp;%data
  end
  end
    figure
    mesh(X,Y,Temp)%plot it
    title(['temperature profil t=' num2str(1)])
    figure
    mesh(X,Y,Temp)%plot it
    title(['temperature profil t=' num2str(25)])
    figure
    mesh(X,Y,Temp)%plot it
    title(['temperature profil t=' num2str(50)])

figure
plot(1:50,MAXtemperature)
hold on
plot(1:50,mintemperature)
```

4.3. Calculate FFT and phase and amplitude of the data using all files:

This code was useful before discovering that the IR camera can do all this work. This script process all the data which are quite tiring and take a lot of time and sometimes Matlab crush because it cannot handle all this data.

```
tic
n=50; %number of files
IniTemp=0; %The initial temperature that before mesuring
temperatureFile = cell(1,n); %cell of csv files % n is the total of csv files
for k = 1:n %n %loop to read and open csv files with matlab
  name = sprintf('Experience(1)%i.csv',k);
  temperatureFile{k} = xlsread(name,'A17:XP528');
end

toc
tic
I=imagesc(temperatureFile{1}); % I is the image that display all the
temperature contain in the csv file
[I2, rect] = imcrop(I); % I2 is the cropped image of I and rect gives us the
coordination of I2
%the coordination can be float for that reason we need to round it since
%pixels are integer
xmin=round(rect(1))-1 ;ymin= round(rect(2))-1; longueur=round(rect(3))-1
;largeur= round(rect(4))-1;
xmax=xmin+longueur; ymax=ymin+largeur;

%axis
X=xmin-1:xmax-1 ; % X pixels : pixels in the X axis
Y=ymin-1:ymax-1 ; % Y pixels : pixels in the Y axis

% length of each axis

x=length(X);  %lentgh of X axis
```

```
y=length(Y);  %lentgh of Y axis

%This part of the script is to see the chosen rectangle and if it is
%compatible with your expectations you can delete it if you want
hold on;
rectangle('Position',rect,...
          'LineWidth',2,'LineStyle','--')
grid minor
toc

% the objective of this small script is to show temperature profil of each
% pixel
Temp=zeros(y,x);  %temperature
for k=1:20:n %to avoid show all th files and thus crashes our code
  for i=1:y
  for j=1:x
    Temp(i,j)=temperatureFile{k}(i+ymin,j+xmin)-IniTemp;%data
  end
  end
    figure
    mesh(X,Y,Temp)%plot it
    title(['temperature profil t=' num2str(k)])
end

fs=1;                   %sampling frequency Hz
%ts=1;                  %sampling period s
T=n*[];                 %array of temperature of a given pixel
F=cell(y,x);            %cell of fft of each pixel
M=cell(y,x);            %cell of magnitude of each pixel
P=cell(y,x);            %cell of phase of each pixel
t=0:89;                %duration of the experiment
l=n;                    %length of the signal
f=(-l/2:l/2-1)/l*fs; %frequency Hz


%loop that calculate the fft, phase and magnitude of each pixels during t
for j=1:x
for i=1:y
 for k=1:n
    T(k)=temperatureFile{k}(i+ymin,j+xmin); % temperature of each pixels
during t
 end
    F{i,j}=abs(fft(T));                 %FFT of T of the pixel (i,j)
    M{i,j}=((F{i,j}));  %magnitude of the last FFT
    P{i,j}=unwrap(angle(F{i,j}));  %phase of the last fft

end
end

% plot of phase and magnitude of the pixel (1,2)
% example
figure
plot(f,M{1,2})      %example
xlabel 'Frequency (Hz)'
ylabel '|F|'
figure
plot(f,P{1,2})      %example
xlabel 'Frequency (Hz)'
ylabel 'Phase'
```

```
grid

phase=cell(1,n);    %cell of phases that regroupes the phases of each pixel at
a giving frequence
amplitude=cell(1,n);%cell of amplitudes that regroupes the amplitudes of each
pixel at a giving frequence

for k=1:n
for j=1:x
for i=1:y
  phase{k}(i,j)= P{i,j}(k);    %the difference between 'phase' and 'P' is
parametrazation: 'P' is the phase of a given pixel for all frequencies and
'phase' the phase of all pixels for a given frequency
  amplitude{k}(i,j)=M{i,j}(k); %the difference between 'amplitude' and 'M' is
parametrazation :'M' is the amplitude of a given pixel for all frequencies and
'amplitude' the phase of all pixels for a given frequency
end
end
end

% testing : f=0,02 ; f=0 ; f=0,1
% example
e=find(f==0.1);
m=find(f==0);
p=find(f==0.02);
figure
imagesc(phase{e})
title('phase image for f=0,1 Hz')
figure
imagesc(amplitude{e})
title('amplitude image for f=0,1 Hz')
figure
imagesc(phase{m})
title('phase image for f=0 Hz')
figure
imagesc(amplitude{m})
title('amplitude image for f=0 Hz')
figure
imagesc(phase{p})
title('phase image for f=0,02  Hz')
figure
imagesc(amplitude{p})
title('amplitude image for f=0,02 Hz')
```

4.4. Chrome layer modelization:

Chrome layer modelization is not a simple task for that reason the following code will only give us a chrome layer with spherical pores.

Function 1

```
function [v,Dt]=volume(r,i,a,b,depth,phi)
%this function gives us the volume of each pore the total valume of all
%pores and the error of the difference between the phi we predicted and the
%real phi
%"i" is the numver of pores and "r" is the radius of each pore
%a,b and depth are the dimensions of our chrome layer and phi is the
%hypothetical porosity
```

```
v=i*[];
V=0;
Vt=a*b*depth; %total volume of the crome layer mm^3
for k=1:i
     v(k)=(4*pi*(r(k)^3))/3; %te volume of each pores
     V=V+v(k); %the total volume of defects
end
Phi=(V/Vt); %the real porosity
Dt=(Phi-phi)*100; %the percentage of the error between the real prorosity and
the hypothetical porosity
end
```

Function 2

```
function [R,x,y,z]=pores(phi,a,b,depth,rm)
% i is the number of pores
% a,b and depth are the dimensions of our chrome layer
%this function gives us the radius "r" of each pore and its coordinates
(x,y,z)
%generation of random spheres inside a cuboid %
i=0;
%phi is the porosity of the chrome layer
%a and b are fixed dimensions and depth is a variable one, it varies between
100µm and 300µm
%rm is the mean radius that will gives us a hypothetical total number of pores
%this function guives us the total number of iterations/pores
%assuming that all defects have the same diameter
Vt=a*b*depth; %volume expression mm^3
v=phi*Vt;
x=(3*v)/(4*pi*(rm^3));
     while i<=x
        i=i+1;
     end
n = rand(i, 3) * diag([a, b, depth]);
r=abs(normrnd(0.005,0.05,[1 i])); %mu=0,005 mm ==>5µm
x=n(:,1);
y=n(:,2);
z=n(:,3);
R=r'; % to have the same size and to be able to concatenate the 4 matrices
End

function i = numofpores( phi,a,b,depth,rm )
%phi is the porosity of the chrome layer
%a and b are fixed dimensions and depth is a variable one, it varies between
100µm and 300µm
%rm is the mean radius that will gives us a hypothetical total number of pores
%this function gives us the total number of iterations/pores
%assuming that all defects have the same diameter
i=0;
Vt=a*b*depth; %volume expression mm^3
v=phi*Vt;
x=(3*v)/(4*pi*(rm^3));
     while i<=x
        i=i+1;
     end
end
```

Function 3

```
function i = numofpores( phi,a,b,depth,rm )
%phi is the porosity of the chrome layer
```

```
%a and b are fixed dimensions and depth is a variable one, it varies between
100µm and 300µm
%rm is the mean radius that will gives us a hypothetical total number of pores
%this function gives us the total number of iterations/pores
%assuming that all defects have the same diameter
i=0;
Vt=a*b*depth; %volume expression mm^3
v=phi*Vt;
x=(3*v)/(4*pi*(rm^3));
     while i<=x
        i=i+1;
     end
end
```

The script

```
clc
close all
a=10; % mm
b=10; % mm
depth=0.3; %mm
phi=0.02; %porosity
rm=0.005; %mm ==> 5 µ

%generatin of random spheres inside a cuboid %

e=numofpores( phi,a,b,depth,rm );
[r,x,y,z]=pores(phi,a,b,depth,rm);
M=[r,x,y,z]; % The matrix m gives us the informnations about each pore
[v,Dt]=volume(r,e,a,b,depth,phi);

%%different plots of volume radius and coordination

%chrome layer

scatter3(x,y,z,r,'fill','r')
title('Example of a chrome layer filled with spheric defects and pores')
xlabel('a "mm"')
ylabel('b "mm"')
zlabel('Depth "mm"')

%volume

figure
plot(v)
title('the volume "v" of each sphere inside the cuboid')
xlabel('Number t of pores')
ylabel('volume of the pore "mm^3"')

%radius

norm=normpdf(r,0,1);
figure;
plot(r,norm,'.')
title('normal distribution of the radius "r" of each sphere')

%x,y,z
```

```
figure
subplot(3,1,1),histogram(x)
title('histogram of the axis x')
subplot(3,1,2),histogram(y)
title('histogram of the axis y')
subplot(3,1,3),histogram(z)
title('histogram of the axis z')
```

4.5. The comparison of temperatures:

```
clc
close all
n=5; %number of files
% traditional hand to hand sctript
% plot temperature change depending on the index(and thus time)
index=0:49;

name1 = sprintf('chrom_0_1(2hz)1.csv');
name2 = sprintf('chrom_0_1(2hz)2.csv');
name3 = sprintf('chrom_0_1(2hz)3.csv');
name4 = sprintf('chrom_0_1(2hz)4.csv');
name5 = sprintf('chrom_0_02(2hz)1.csv');
name6 = sprintf('chrom_0_02(2hz)2.csv');
name7 = sprintf('chrom_0_02(2hz)3.csv');
name8 = sprintf('chrom_0_02(2hz)4.csv');


averageValues{1}= xlsread(name1,'B3:B52');
averageValues{2}= xlsread(name2,'B3:B52');
averageValues{3}= xlsread(name3,'B3:B52');
averageValues{4}= xlsread(name4,'B3:B1002');
averageValues{5}= xlsread(name5,'B3:B52');
averageValues{6}= xlsread(name6,'B3:B52');
averageValues{7}= xlsread(name7,'B3:B52');
averageValues{8}= xlsread(name8,'B3:B1002');

X=index;
Y1=(abs(averageValues{1}-averageValues{1}(1)))';
Y2=(abs(averageValues{2}-averageValues{2}(1)))';
Y3=(abs(averageValues{3}-averageValues{3}(1)))';
Y4=(abs(averageValues{4}-averageValues{4}(1)))';
Y5=(abs(averageValues{5}-averageValues{5}(1)))';
Y6=(abs(averageValues{6}-averageValues{6}(1)))';
Y7=(abs(averageValues{7}-averageValues{7}(1)))';
Y8=(abs(averageValues{8}-averageValues{8}(1)))';

% a1=polyfit(X,Y1,1);
% a2=polyfit(X,Y2,1);
% a3=polyfit(X,Y3,1);
% a4=polyfit(X,Y4,1);
% a5=polyfit(X,Y5,1);
% a6=polyfit(X,Y6,1);
%
% y1=a1(1)*X+a1(2);
% y2=a2(1)*X+a2(2);
% y3=a3(1)*X+a3(2);
% y4=a4(1)*X+a4(2);
```

To do the regression

```
% y5=a5(1)*X+a5(2);
% y6=a6(1)*X+a6(2);

figure
subplot(2,1,1)
plot(index,abs(averageValues{1}-averageValues{1}(1)))
hold on
plot(index,abs(averageValues{2}-averageValues{2}(1)))
hold on
plot(index,abs(averageValues{3}-averageValues{3}(1)))

title('Comparison of results Chrome layer 0,1mm for 2 HZ')
xlabel('Index')
ylabel('\DeltaT')
legend('0,1mm test 1','0,1mm test 2','0,1mm test 3')
grid minor
subplot(2,1,2)
plot(0:999,abs(averageValues{4}-averageValues{4}(1)))
legend('test 4 0,1 mm 2 hz')
grid minor
figure

subplot(2,1,1)
plot(index,abs(averageValues{5}-averageValues{5}(1)))
hold on
plot(index,abs(averageValues{6}-averageValues{6}(1)))
hold on
plot(index,abs(averageValues{7}-averageValues{7}(1)))
legend('0,02 mm test 1','0,02 mm test 2','0,02 mm test 3')
title('Comparison of results Chrome layer 0,02mm for 2 HZ')
xlabel('Index')
ylabel('\DeltaT')
grid minor

subplot(2,1,2)
plot(0:999,abs(averageValues{8}-averageValues{8}(1)))
legend('test 4 0,02 mm 2 hz')

grid minor
```

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