PROMETHEUS
RAPID ULTRA-SHORT PULSE LASER SURFACE TEXTURING TECHNOLOGY

LASER**TEXTURING**

# PROMETHEUS **CATALOGUE**

PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

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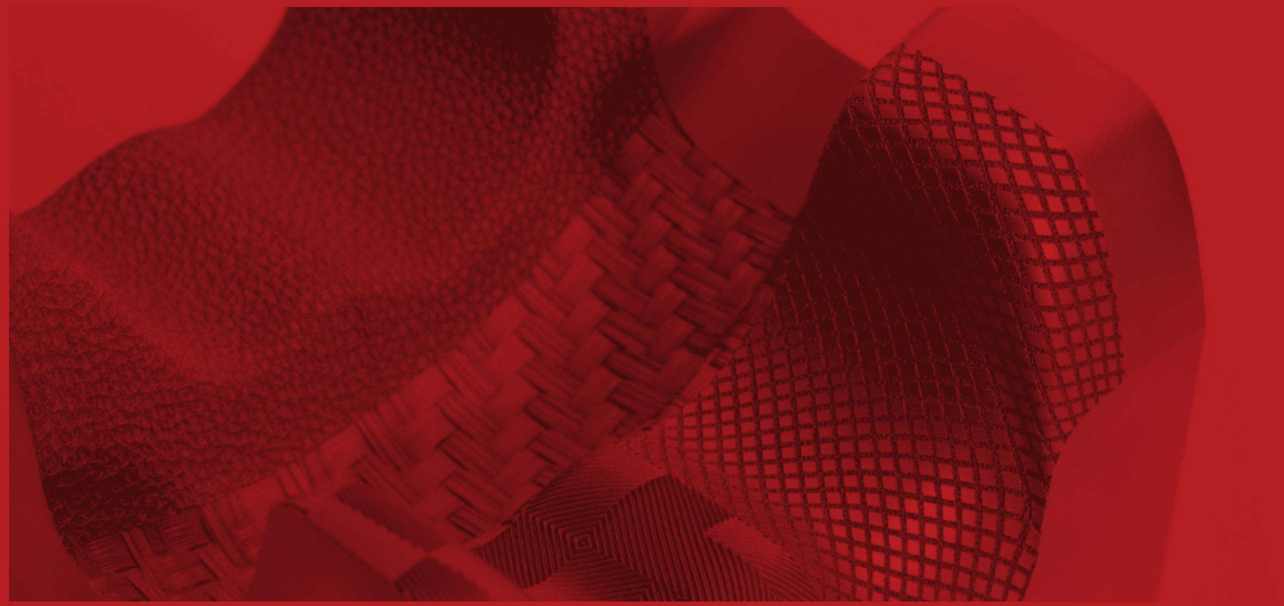
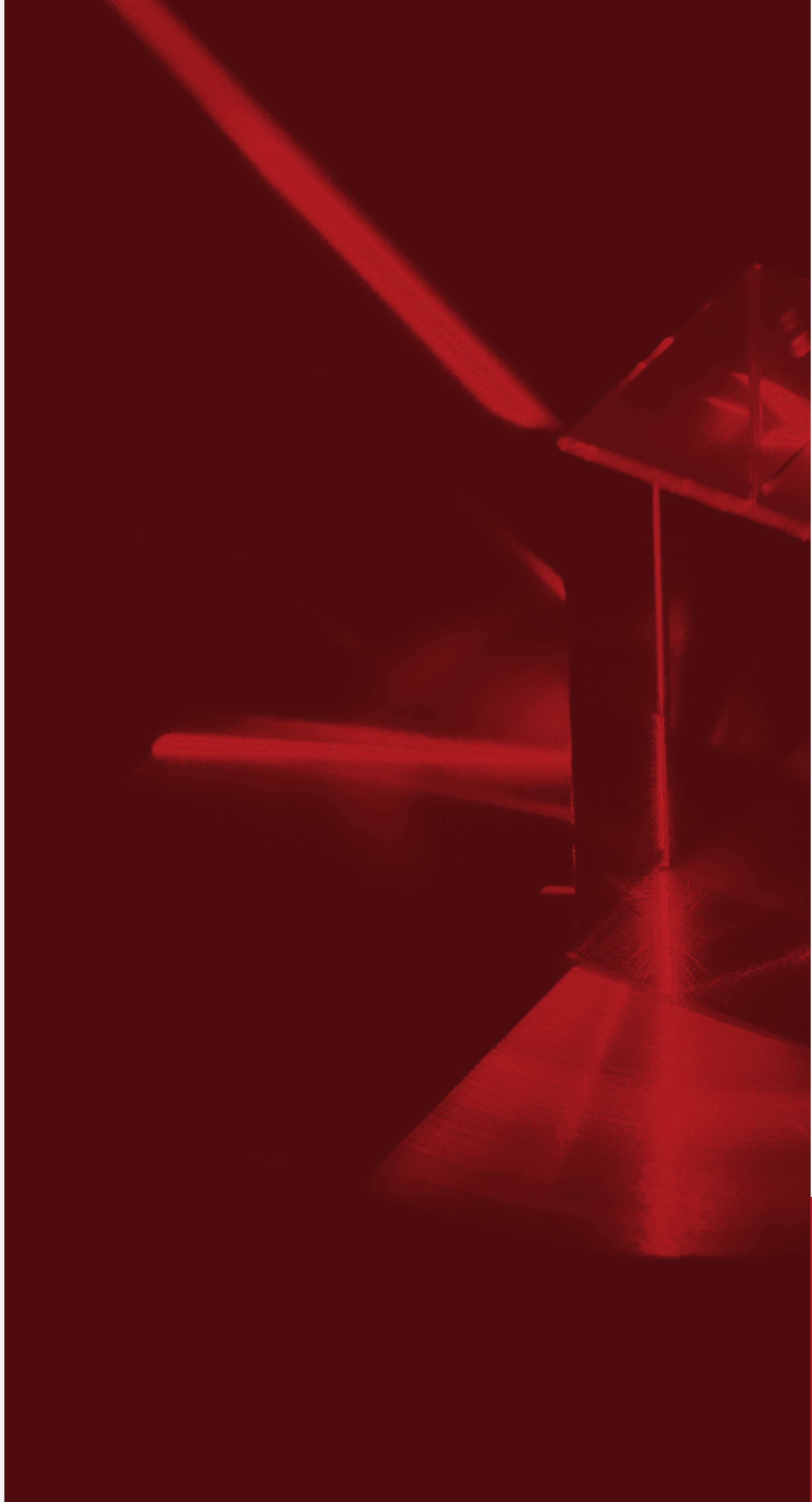
# 1. About PROMETHEUS



PROMETHEUS - **high power ultra-short pulse lasers** and the associated optics to enable the precise periodic texturing of surfaces to impart a range of surface functionalities at unprecedented processing speeds.

# 2. Aims & Goals



The PROMETHEUS project supports the European grand societal challenges. Creating a high potential high power ultra-short pulse laser processing technology with unprecedented processing speeds with in-line characterisation diffractographic / scatterometric monitoring system and associated control systems will contribute specifically to at least two out of five of the grand challenges, namely:

- **Supporting employment**
- **Increasing investment in innovation**
- **Increase EU industrial competitiveness and sustainability**
- **Promote EU targets of a smart, green and inclusive economy**
- **Support EU industrial policy targets**
- **Underpin EU trade and investment policy**

The PROMETHEUS project promotes a number of **broad qualitative objectives**, including:

- To manufacture textured functional surfaces utilising **fewer raw materials, less energy and less waste**.
- To **improve accuracy, power and control** over existing technologies.
- To achieve **fast materials processing** with processing speeds 2-5 $m^2$/min, representing a significant increase on current laser techniques.
- To **minimize heat impact** on sensitive materials.
- To **increase productivity**.
- To **increase product customization**.
- Significantly **reduce processing costs**.

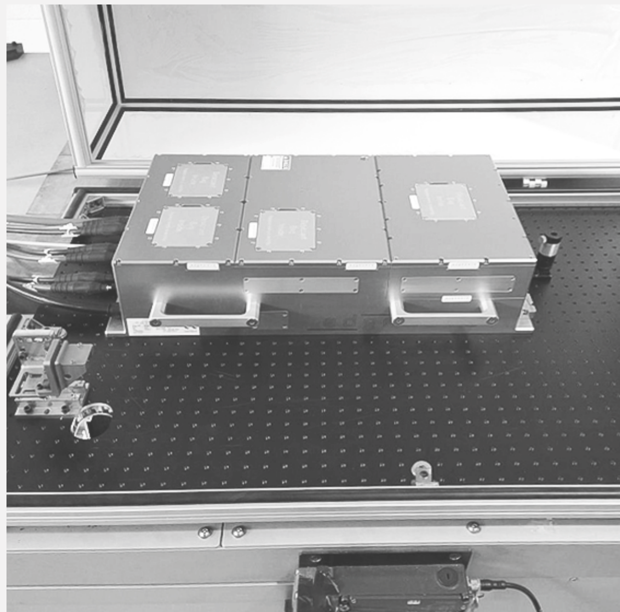
# 3. System

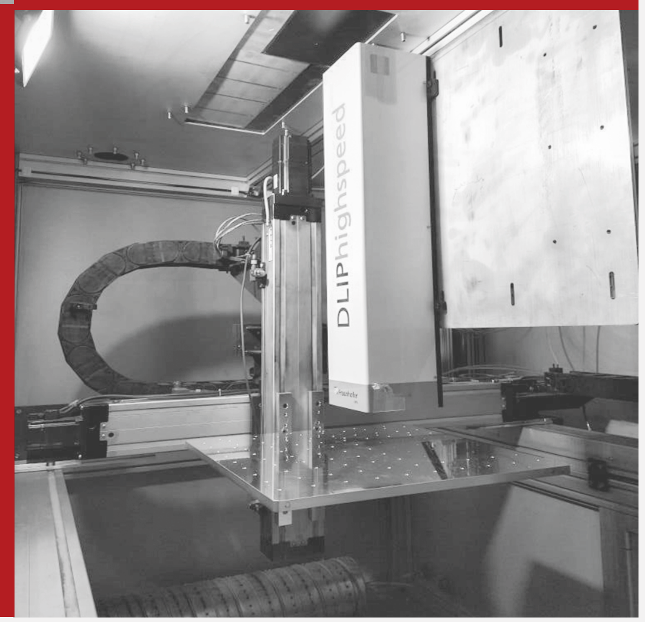
**PROMETHEUS** system has a 3-axis Cartesian machine equipped with a head capable of supplying energy to the process. This machine is made up from profiles and panels in anodized aluminum, with a working volume of 1000 X 750 x 500 mm. The machine allows manual handling from inside the working area. The movement of the gantry is delegated to linear modules consisting of ball screws actuated by servomotors.



| Technical Features | | | |
|---|---|---|---|
| **Axis** | **X** | **Y** | **Z** |
| **Stroke** | 1000 mm | 750 mm | 500 mm |
| **Acceleration** | 1 m/s² | 1 m/s² | 1 m/s² |
| **Speed** | 1 m/s | 1 m/s | 1 m/s |
| **Load** | 110 kg | 110 kg | 45 kg |
| **Power** | 0.4 kW | 0.4 kW | 0.75 kW |

**Table 3.1** – System technical features.





# 4.

# **Ultra-Short Pulse Laser** & *Direct Laser Interference Patterning*



## 1. Ultra-Short Pulse laser

The laser source, under development by EdgeWave (short EW), have the characteristics reported in **Table 4.1**.

| | |
|---|---|
| Wavelength (nm) | **1064** |
| Repetition rate (kHz) | **5 – 10** |
| Pulse energy (at 10 kHz) | **70 mJ** |
| Beam profile | **Gaussian** |
| Beam quality | **$M^2 < 2$** |
| Beam size (mm) | **5** |
| Pulse energy stability | **3% rms** |
| Spectral bandwidth (nm) | **< 0.1** |

**Table 4.1** – Laser beam characteristics.

## 2. Direct Laser Interference Patterning

In Direct Laser Interference Patterning, or short DLIP, two laser beams are superimposed and create an interference pattern. This pattern illuminates the substrate and, when the laser intensity is high enough, this can be treated directly, creating surface features in the range of a few micrometers. **(Figure 4.2.1)**

PROMETHEUS' system uses a millimeters-large laser beam in order to process the substrate faster, still keeping the features size small enough for producing surface functions like self-cleaning, decoration and friction reduction.

**Figure 4.2.1** – Front-view schematic representation of the High-speed DLIP setup (a), a depiction of the corresponding beam splitting concept (b) and close view of the two beams' overlapping region (c).

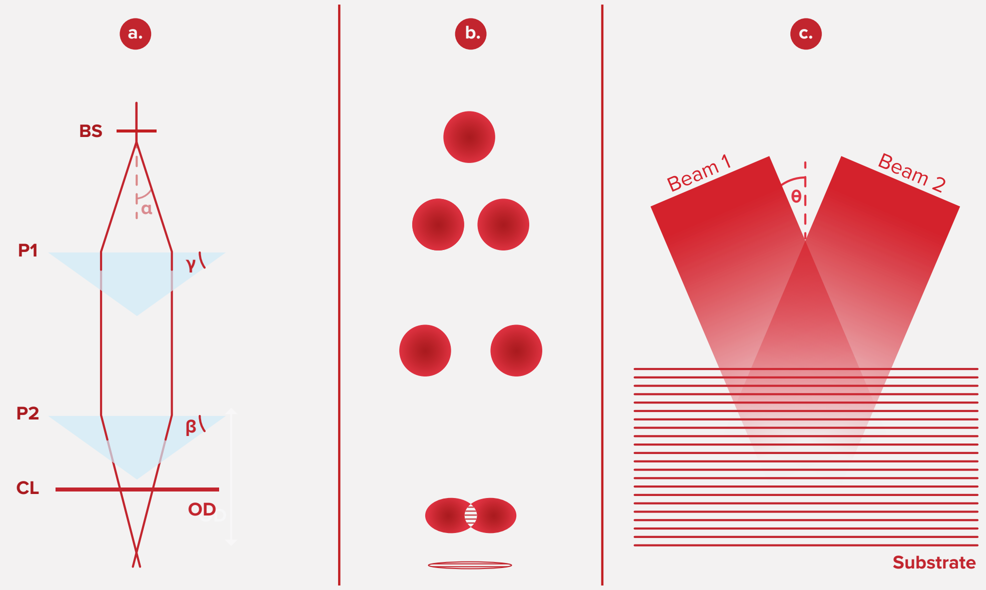
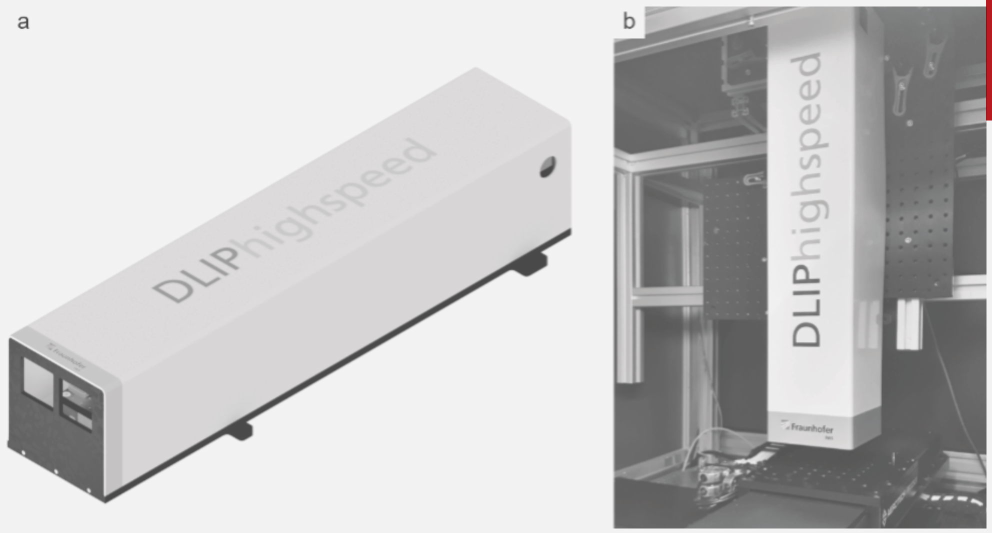



**Table 4.2.2** – Characteristics of the High-speed DLIP setup.

| | |
|---|---|
| Diffraction angle α (deg) | **5.09** |
| Prism P1 angle γ (deg) | **11** |
| Prism P1 angles β (deg) | **5.09**<br>**10.17**<br>**20.34** |
| CL focal length (mm) | **40 or higher** |
| Interference periods λ (µm) | **12.0**<br>**6.0**<br>**3.0** |

**Figure 4.2.3** – Image of the DLIP-module developed in D3.2 (a) and photo of the realised demonstrator (b).




The DLIP-module has an outer size of 712 mm x 195 mm x 150 mm and an approximate weight of 9.5 kg. **Figure 4.2.3a** shows an image of the designed DLIP-module and **Figure 4.2.3b** a photo of the prototype after its construction and installation in a machine for laser texturing trials at Fraunhofer IWS.



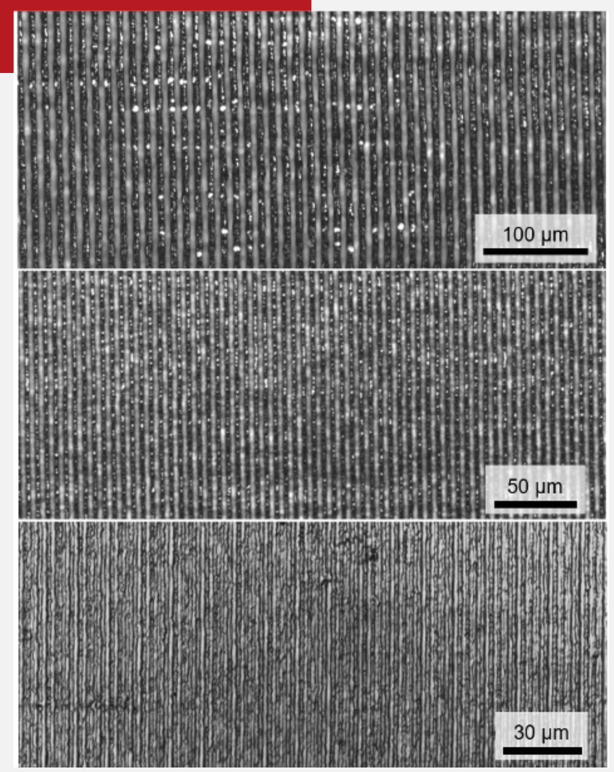
The module can be equipped with optical elements in two possible configurations:

**a. Standard (non-shaping) configuration**


**b. Shaping configuration:**


**Figure 4.2.4** – Possible configurations for optical elements.

**Figure 4.2.5** – Microscope images of the textures fabricated with a period of 12.0 µm (top), 6.0 µm (middle) and 3.0 µm (bottom) employing the designed DLIP-module.




For PROMETHEUS the standard configuration will be used. All components in the system, other than DS-033-I-Y-A, where custom designed and produced by Holo/Or for this project.

**Figure 4.2.5** shows the result of the texturing experiment using the three different diffractive elements for producing the spatial periods of 12.0 µm, 6.0 µm and 3.0 µm.
Within the module, a linear mechanical axis can be activated in order to shift part of the optical elements and induce a variation of the working position. The maximum variation of the working position is 250 mm, 130 mm and 30 mm, for the spatial periods of 12.0 µm, 6.0 µm and 3.0 µm, respectively.

# 5. Monitoring

The monitoring system developed aims to identify deviations in the textured surfaces during/after the fabrication by **comparing them with a target fingerprint characteristic pattern previously identified**.

Two optical techniques have been developed, namely: **scatterometry** and **diffractometry**, as well as different configuration possibilities thereof. Fundamentals, solution concepts, measurement principles, and prototypes for each technique being developed are presented in the following.

The two complementary optical inspection methods were **developed by AIMEN or IRIS**, respectively.

## Scatterometry Fundamentals

Scatterometry is an **optical technique that analyses the diffraction produced by a periodic texture when light interacts with it.** The diffraction light signal acts like a fingerprint of our textures, as this is unique for every texture. So, this can be used to characterize a textured sample and determinate if it remains within the expected quality control range.

The working principle of the scatterometry technique employed by AIMEN in the PROMETHEUS project is as follows:

**(A)** A set of calibration textures is fabricated with the PROMETHEUS machine. These calibration textures **replicate the most common problems that the machine can produce when operating** (out-of-focus, incorrect laser power, vibrations....) to produce a database of defective textures.

**(B)** The diffraction information produced by these textures is captured by the monitoring system and **a Machine-Learning based classification algorithm is trained with them.**

**(C)** The experimental diffraction signals are obtained when the light is illuminating the samples fabricated by the PROMETHEUS machine. The rays of light are **diffracted on the periodic pattern and captured by a detector.**

**(D)** The diffraction signal measured from the samples is **compared to the previously generated database**. In this way, the inspection and monitoring system developed in PROMETHEUS will be able to determine the validity of the fabricated textures.

For the PROMETHEUS project, a robust indirect colour scatterometry setup has been developed to **measure the spectrum and location of several diffraction orders**, giving us more information than only the main reflection spectrum and resulting less sensitive to misalignments. It also allows for the measurement of the diffraction of various sample locations if the incident light is shined onto different areas on the sample. To measure the full spectrum of each diffraction order, a hyperspectral camera has been integrated, allowing for up to 16 distinctive wavelengths to be measured at one.

As the processing laser of the PROMETHEUS DLIP system uses a line of 1.5 cm wide directed perpendicularly to the process movement and to the DLIP interference pattern (and therefore to the diffraction orders), to synchronize the monitoring solution with the process area of the PROMETHEUS machine, a robust and complex optical system was designed with various incidence angles and mirrors to avoid the overlap of the different diffraction orders, while keeping free from the fix elements of the system such as the measurement camera or the DLIP optical setup. The final scatterometry setup can be seen in **Figure 5.1.1** as installed in the laboratory and an example of a correct and incorrect diffraction pattern can be seen in **Figure 5.1.2**, where a sample with a good texture is compared with a sample with 2D structures. One can notice the advantage of the used geometry, as in neither of those cases **the diffraction order overlap on the screen**, while the full line of measurements (corresponding to the line of the processed area) **is visible and can be analyzed**.

To validate the process, both the shape of the diffraction pattern and the intensity of each wavelength are analyzed. Several failure mechanisms are studied in a first calibration phase, where a set of defective textures are fabricated to train a Machine-Learning based classification algorithm to **automatically detect these failures during the fabrication of textured samples** with the PROMETHEUS machine. The mechanism can be illustrated with the help of the **figure 5.3**, where different samples are compared to the reference sample, and three wavelengths (red, green and blue) are shown for illustration. One can easily see that **each sample gives a different intensity on at least one of the shown wavelengths**, and it is therefore rather easy to differentiate them. The scatterometry setup works in a similar way, although it can measure up to 16 different wavelengths which are used in combination with trained machine learning algorithm, allowing for a much higher precision.

This way, the scatterometry monitoring system can **easily detect process failure** such as laser power fluctuation of 5%, change in focus of mm, physical vibration of the machine in the µm scale, or any relevant failure mechanism that it has been trained on.

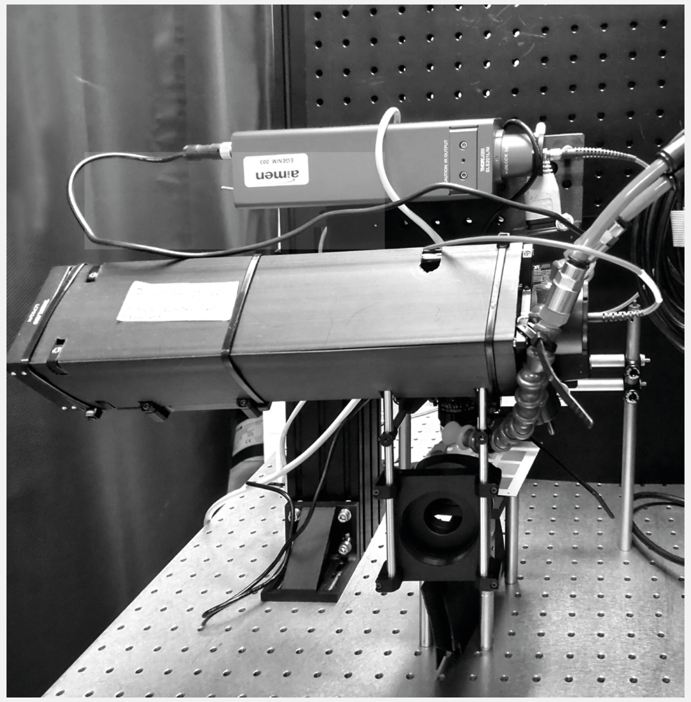


**Figure 5.1.1** – Scatterometry setup installed in the laboratory.

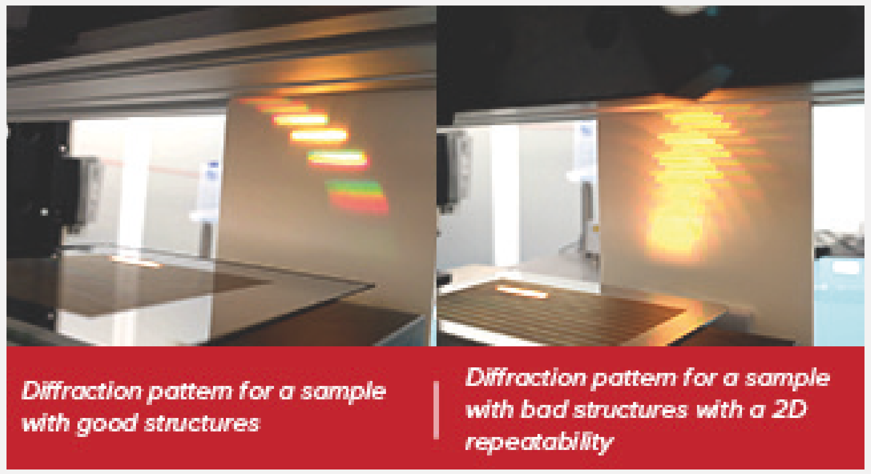



**Figure 5.1.2** – Example of a correct and incorrect diffraction pattern.

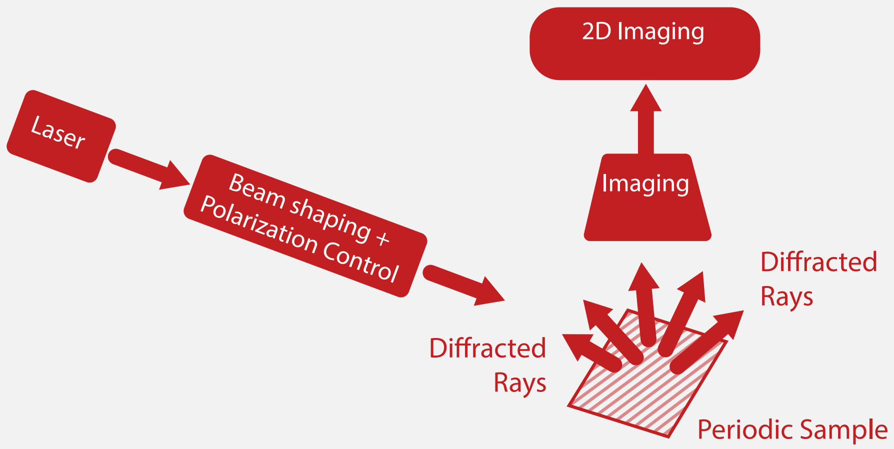



**Figure 5.1.3** – Illustration of indirect scatterometry sample identification with RGB scatterometry.

# Diffractometry Fundamentals

Diffractometry is another optical technique that analyses the diffraction pattern produced by a microstructured surface when light interacts with it. The technology is **based on the diffraction principle and imaging of the diffracted light pattern**, as illustrated in the schematic of **Figure 5.2.** Requirements for the illumination in a diffractometry measurement are the high directionality of the light and its monochromaticity. In case of periodic structures, the diffractometry technique enables to identify process deviations in the textured surfaces during or after the fabrication by **comparing the fingerprint characteristic pattern with that of a reference texture**. Additionally, the technique facilitates to deduce other sample features from the diffractometry measurement, like the period and orientation of the lines, the depth of the lines, the degree of order/disorder, etc. The technique provides average information of all the lines illuminated. Finally, machine learning models are built in order to correlate the diffraction measurement with the sample key features. Therefore, calibration textures with common defects are used to train the machine learning algorithm.

**Figure 5.2** – Basic schematic of the optical diffractometry technique. A laser beam, previously shaped and polarization-controlled, illuminates a periodic sample under an incident angle. The light diffracted by the sample is coupled into a lens and captured by a sensor,



# Installation

The finally installed IRIS in-line monitoring prototype is showcased in **Figure 5.3**. The inspection system itself has been **fully integrated onto the DLIP laser head** inside the PROMETHEUS workstation. The in-line monitoring unit consists of four main functional blocks, corresponding to the illumination, the integration interface with the DLIP laser head, the imaging of the resulting diffraction patterns, and finally the acquisition and analysis of these patterns. Data connectivity and system control is established via cable connection to a computer outside of the workstation.

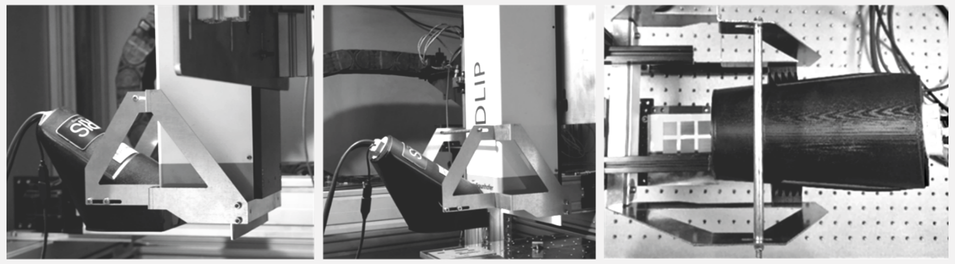


**Figure 5.3** – Left and center: IRIS monitoring system installed onto the DLIP laser texturing head at MTC. Right: Top view of the monitoring system hardware at lab scale.

# Software

The software developed by IRIS is intended for driving the inspection system, processing the acquired image data and delivering the results through the **user interface and towards the production line operators**. A schematic of the routine operation of the software is shown in **Figure 5.4.1**, which summarizes the steps of the user interaction.

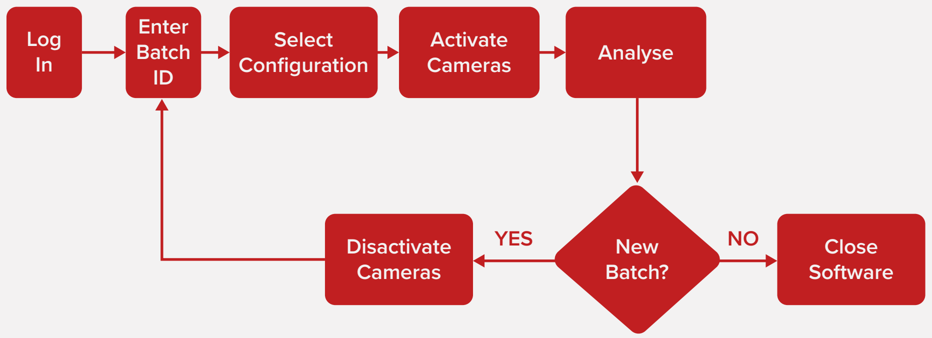



**Figure 5.4.1** – Routine operation.

The main functionality of the Graphical User Interface (**Figure 5.4.2**) is to control the acquisition and to visualise in real time the image caption and analysis result. When the Monitor or Record button is pressed, the camera starts acquiring frames, displaying them in real time in the GUI. The analysis result with the class detected is shown in the output view and is continuously being updated.
Additionally, the software offers functionality to control the configuration parameters for camera, analysis, model, etc. prior to the analysis. Multiple combinations of settings can be created and used, depending on the samples to inspect.

The results of the analysed samples are listed in the Datalog window (**Figure 5.4.3**) and stored in the system. The output contains information on when the result was obtained, the corresponding batch ID, and the detected class (class number and user defined label).

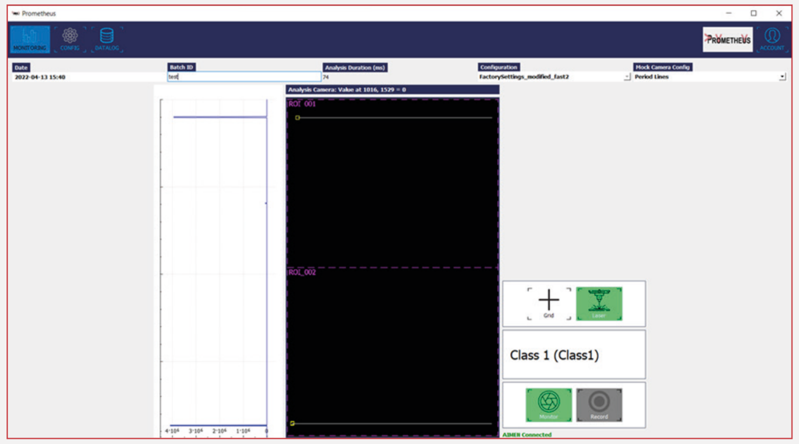
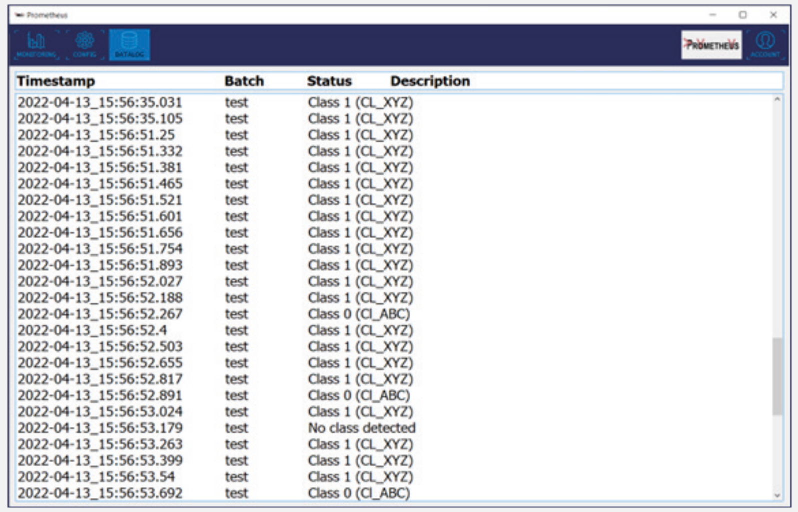
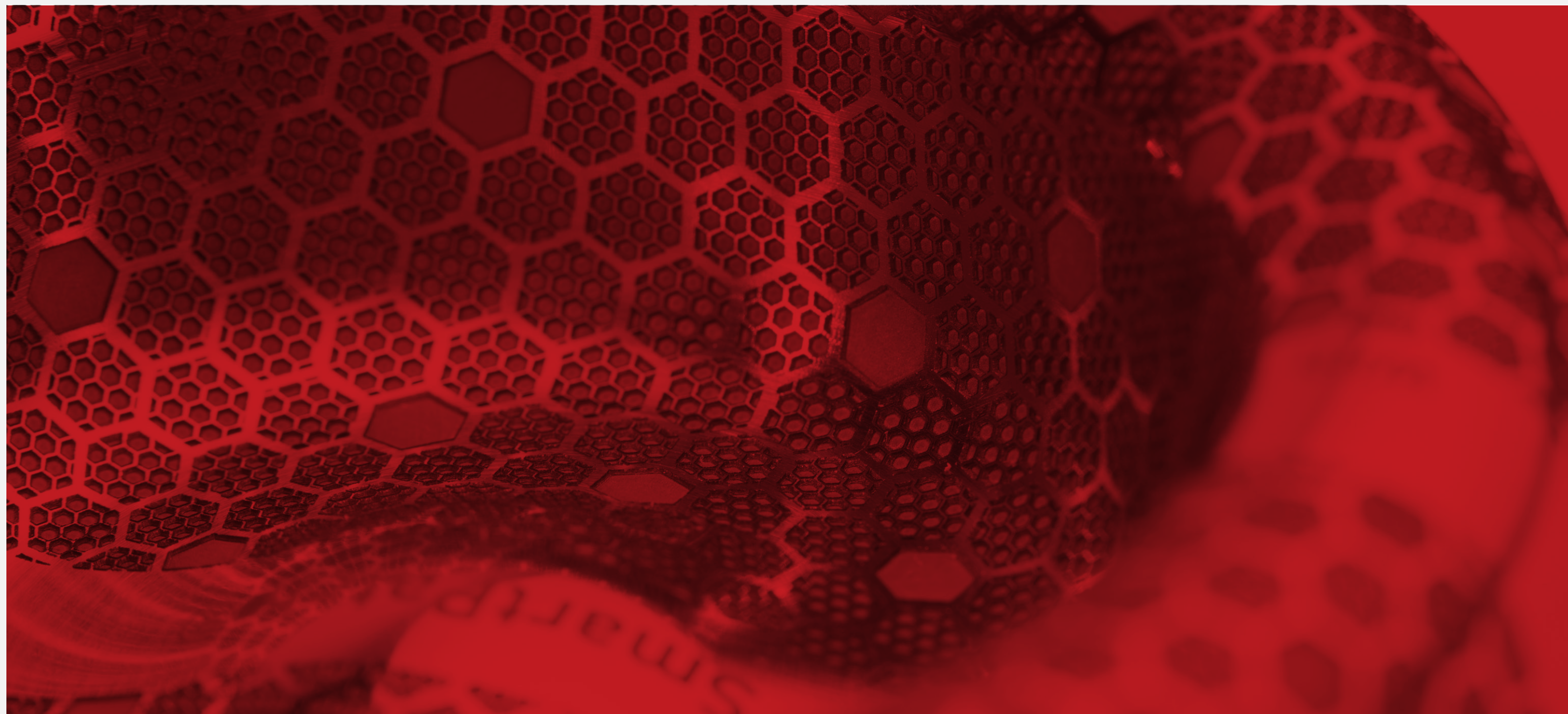



**Figure 5.4.2** – User-friendly GUI of the monitoring software.



| Timestamp | Batch | Status | Description |
|---|---|---|---|
| 2022-04-13_15:56:35.031 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:35.105 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.25 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.332 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.381 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.465 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.521 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.601 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.656 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.754 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:51.893 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:52.027 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:52.188 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:52.267 | test | Class 0 (Cl_ABC) | |
| 2022-04-13_15:56:52.4 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:52.503 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:52.655 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:52.817 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:52.891 | test | Class 0 (Cl_ABC) | |
| 2022-04-13_15:56:53.024 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:53.179 | test | No class detected | |
| 2022-04-13_15:56:53.263 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:53.399 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:53.54 | test | Class 1 (CL_XYZ) | |
| 2022-04-13_15:56:53.692 | test | Class 0 (Cl_ABC) | |

**Figure 5.4.3** – Datalog window with classification results.



# 6. Use Cases

## Orthopaedic Implants

- Surface texturing of medical implants and composites to improve functional outcomes.
- Increased polymer/metal surface energies to improve adhesion and bond strength at material and peri-implant interfaces.

## Dishwasher

- Improve the energy efficiency of dishwasher drying by 4%
- Residual water on the surface of the samples after the drying process has been reduced by 76-78%.

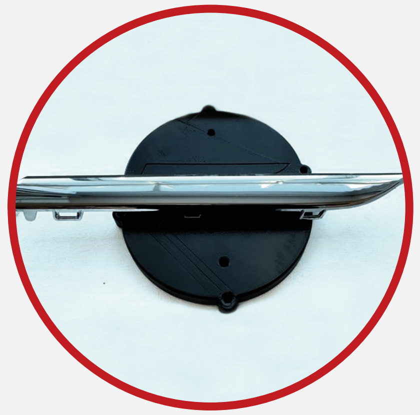


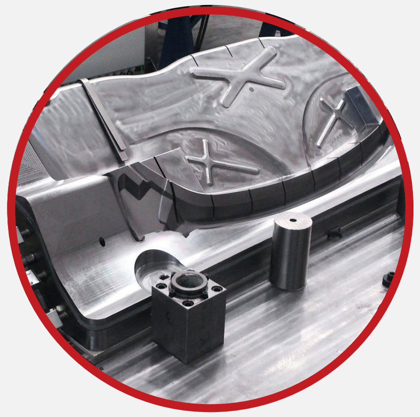
## Tumbledryer

- Improve the energy efficiency of tumble dryer heat exchangers by 5%
- The offset of 2538 tonnes of CO2 per year

## Aesthetic Chrome Components For Automotive

- Obtain super-hydrophobic textured surfaces on chrime polymer components
- Improve the easy-clean capability
- New changes to the design og the parts



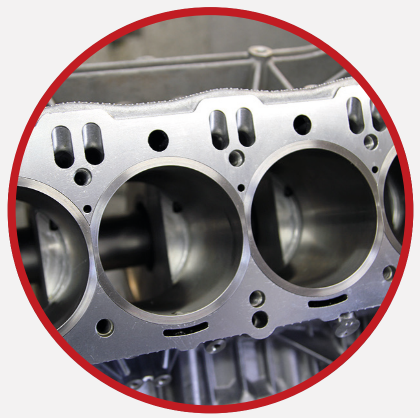


## Automotive High Strength Aluminium Pressing

- Improve friction and wear of stamping tool for cold forming and reduce the use of lubricant in the process
- Avoid aluminium adhesion on tool
- Reduce friction to increase sheet formability

## Automotive Cylinder Piston Liner

- Deliver piston cylinder inserts exhibit 30% less blow by and with 40% less friction enabling engines with > 1.1% reduction in fuel consumption
- Reduce friction
- Reduce engine oil consumption
- 257 million litres of fuel saving per year
- The offset of 664 million tonnes of CO2 per year

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