

# JOULIA D7.2

## Predictive maintenance platform

CERTH

5/2026



## Project Information

|                           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|---------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ACRONYM                   | <b>JOULIA</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
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| COORDINATOR               | CIRCE – Technology Center                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| PROJECT OVERVIEW          | <p>The JOULIA project is focused on <b>transforming energy-intensive industries by replacing traditional fossil fuel-based heating methods with advanced electric technologies</b>. These industries rely on <b>high-heat processes</b>, which are critical for manufacturing products like <b>rubber, ceramics, and plastics</b>. By focusing on specific, high-heat applications, JOULIA seeks to <b>showcase the potential of electrification to decarbonise operations, enhance efficiency, and drive sustainable industrial transformation</b>.</p> |

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This project has used a standard methodology already developed in the eLITHE (Grant Agreement number: 101138325), following EU recommendations. Ad hoc modifications were added to comply with the conditions of the Grant Agreement for JOULIA (Grant Agreement number: 101192555).

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## Abbreviations

Table 1: Abbreviations

|       |                                           |
|-------|-------------------------------------------|
| APE   | Advance Plateau Equalisation              |
| CERTH | Centre for Research and Technology Hellas |
| D     | Deliverable                               |
| FFT   | Fast Fourier Transform                    |
| FOV   | Field of view                             |
| ICA   | Independent component analysis            |
| IRT   | Infrared thermography                     |
| kPCA  | Kernel principal component analysis       |
| NDT   | Non-destructive testing                   |
| PCA   | Principal component analysis              |
| PE    | Plateau Equalisation                      |

 ROI

Region of interest

## Executive Summary

This document presents **Deliverable-D 7.2 Predictive maintenance platform**, developed within **Work Package 7** of the JOULIA project. The purpose of the deliverable is to describe the initial research that has been carried out for the development of a predictive maintenance platform that aims to monitor key parameters of heating systems through the use of infrared thermography and provide predictions and alerts for abnormal behaviour. Two heating systems are investigated in this phase of the project that will be replaced or retrofitted by the technologies developed within JOULIA project. Specifically, 1) a rotary curing press for flooring rubber production, located at Artigo S.p.A. (ART), that will be retrofitted by an induction heating process and 2) an induction heating process for gluing multilayered plastic insulation pipes PERT II, located at K-FLEX Polska Spolka Ograniczona Odpowiedzialnoscia, that will be replaced by a microwave heating system.

To describe the development of the proposed maintenance platform the following topics are presented within this deliverable:

- A state of the art on infrared thermography.
- Image preprocessing and processing techniques that are required to denoise, remove reflections and enhance the thermal images that the system will collect.
- Description of the ARTIGO and K-FLEX processes visits with the aim of describing the operational environment and challenges for the application of infrared thermography.
- Analysis of the thermal acquisitions that were carried out at the two companies in order to identify the feasibility of applying thermography for thermal anomaly detection on different parts of the production
- Suggestion of the potential areas where thermography will be applied in the two heating systems.
- Preliminary approach of the proposed for the predictive maintenance platform that relies on two stages: 1) preprocessing for removing reflections from surfaces, 2) anomaly detection based on image processing and ML techniques using thermal images that will be used as ground-truth and comparison of those with new images after the new heating processes have been implemented.

The main body of the deliverable presents the various acquisitions that were carried out. In the case of ARTIGO the areas that were thermally imaged was the main vulcanisation drum, the heating plates of the rotocure and the top drum. These areas pose certain challenges due to emissivity and reflectance issues caused by their smooth surface finish making the monitoring of surface temperatures difficult. Hence, why de-reflection pre-processing is suggested as a first stage for anomaly detection.

In the second case of K-FLEX's PERT II pipe production line, although the majority of the production was thermally imaged, the main area of interest was the induction coil and the production exiting the final stage of production.

Further, development of the predictive maintenance platform will continue in the next phase of the project where more images will be collected, processed and used as ground truth in order to be compared with new images when the new heating systems are going to be incorporated into the production of the two companies.

## 1. Introduction

Deliverable D7.2 “Predictive maintenance platform” aims to describe the initial research for the development of a platform tool that monitors key parameters of heating systems in order to perform a prediction on upcoming failure and through heuristic formulation, create a predictive maintenance alert in case that process parameters go out of their operating range and may risk the safety of the operation or the machinery itself. Two heating systems are investigated with the framework of JOULIA project. Specifically, 1) a rotary curing press for flooring rubber production, located at Artigo S.p.A. (ART), that will be retrofitted by an induction heating process and 2) an induction heating process for gluing multilayered PERT<sup>1</sup> II plastic insulation pipes, located at K-FLEX Polska Spolka Ograniczona Odpowiedzialnoscia, that will be replaced by a microwave heating system.

An initial investigation of the current manufacturing processes is carried out within D 7.2, in order to understand how they work and the operational environments where these processes are located in the two respective companies. An in-depth analysis of the current processes will be used to identify current and potential future challenges with order to design process of the predictive maintenance solution. D 7.2 describes the two manufacturing aforementioned processes and presents the application of contactless technologies such as thermal imaging to detect anomalies in the heat distribution of the product or in the machinery prompting a maintenance alert.

The predictive maintenance platform will consist of a thermal imaging system that will monitor the temperature distribution of the product and process as well as the machinery, coupled by predictive failure models that will rely on using advanced data analytics and advanced image processing.

### 1.1 Contribution from partners

Table 2: Contribution table

| Partner               | Contribution                                                                                                                                                          |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. CERTH              | Thermal imaging of machinery at ARTIGO and K-FLEX, data analysis and deliverable writing.                                                                             |
| 2. ART                | Demonstrator I. Provide information regarding the rotocure for vulcanisation process and allow access to facilities to carry out thermal imaging and experimentation. |
| 3. K-FLEX             | Demonstrator II. Provide information regarding the PERT II pipe manufacturing and allow access to facilities to carry out thermal imaging and experimentation.        |
| 4. STAM               | Provider of information from Deliverable D 4.1 “Characterisation of demo sites”                                                                                       |
| 5. CIRCE/ SIMIC/SIMLB | Provider of information from Deliverable D 5.1 “Conceptual design of the induction system”                                                                            |

<sup>1</sup> Polyethylene of Raised Temperature Resistance

## 1.2 Relation to other project activity table

Table 3: Relation to other project activities

| Task                                                                                                          | Relation to other project activities                                                                                                                                                                                     |
|---------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| T4.1 Analysis of use cases and definition of main system requirements, functionalities and flexibility        | Extract information gathered regarding the two demonstrators and the manufacturing processes applied by ART and K-FLEX                                                                                                   |
| T5.1 - Conceptual design                                                                                      | Extract information from T 5.1 regarding the design of the induction heating process to be retrofitted at ART                                                                                                            |
| T6.1 - Conceptual design                                                                                      | Extract information from T 6.1 regarding the design of the microwave system to be used at K-FLEX                                                                                                                         |
| T8.2 Design and development of digital predictive maintenance tools                                           | T 7.2 will provide input to 8.2 acting as its basis for the finalisation of the latter. Further, thermal imaging will be carried out on the new processes when they will be implemented at the two respective companies. |
| T9.2 Preindustrial trials and equipment fine-tuning<br>T9.3 Installation and integration at ARTIGO facilities | Following the installation of the induction system at ARTIGO, CERTH will carry out additional thermal imaging of the new system.                                                                                         |
| T10.2 Pre-industrial trials and fine tuning<br>T10.3 Installation and commissioning at K-FLEX facilities      | Following the installation of the microwave heating systems at K-FLEX, CERTH will carry out additional thermal imaging of the new system.                                                                                |

## 2. Methodology

### 2.1 Preliminary description of the predictive maintenance platform

D 7.2 aims to provide a baseline for the description of the development of the predictive maintenance platform. The key objective of this deliverable are the following:

- Provide a description of the manufacturing processes in place at ART and K-FLEX in order to understand the operational challenges of the environment where the proposed thermal imaging will take place.
- Describe the state of the art of the application of infrared thermography (IRT).
- Provide a description of the image processing techniques that will be deployed in the predictive maintenance platform in order to improve image quality and enhance detection of potential thermal gradients that cannot be identified in the raw thermograms<sup>2</sup>.
- Describe the process of carrying out thermal monitoring of the current manufacturing process in place at the two respective companies.

<sup>2</sup> A thermal image is also known as thermogram

- Link the current deliverable with the work to be carried out in D 8.2 which will be the finalization of the platform that will be delivered at the end of JOULIA project.

## 3. State of the art on infrared thermography of industrial processes and image processing

### 3.1 Infrared thermography

Infrared thermography (IRT) is a widely used non-destructive testing (NDT) technique for inspecting various applications, covering both structures and individual components. Materials that can be inspected can be metals, composites, wood, ceramics, construction materials and others. Non-destructive testing consists of methods that can be used to monitor or inspect components or materials of a system without impairing its future use (Maldague et al., 2001a). The future use of the material/component refers to the practice of sampling that might be required to test its integrity. A technique is classified as non-destructive testing when the tested sample is returned to service.

IRT identifies thermal patterns on the surface of objects/materials under inspection and is used to assess the integrity of the material, products and processes under inspection, by diagnosing the thermal behaviour of the subject over time. Any object above  $-273\text{ }^{\circ}\text{C}$  emit electromagnetic radiation in the infrared band (wavelength of  $0.75\text{--}1000\text{ }\mu\text{m}$ ) (Kim et al., 2023). This emitted radiation from an object can be measured using a thermal camera, which is then translated into radiometric (values) and measured in temperature values (Maldague, 2002) expressed as a spatial thermal map of the object that is commonly referred as a thermogram.

When a heat flux  $\Phi^3$  falls on the surface of a body, part of it, is absorbed  $\Phi_A$ , reflected  $\Phi_R$  and transmitted  $\Phi_T$  (Minkina, 2021). This phenomenon introduces three coefficients (Minkina, 2021):

- absorption coefficient (absorptance):  $A = \Phi_A / \Phi$ ,
- reflection coefficient (reflectance):  $R = \Phi_R / \Phi$ ,
- transmission coefficient (transmittance):  $P = \Phi_T / \Phi$ .
- For a perfect blackbody that absorbs all the radiation that falls on it  $A=1$  ( $R = 0$ ,  $T = 0$ )
- For a perfect transparent body that transmits the radiation that falls on it  $T=1$  ( $A = 0$ ,  $R = 0$ )

Kirchhoff's law provide a relationship between these bodies

$$A + R + T = 1$$

This absorbed heat flux  $\Phi_A$  will cause the internal thermal energy of the body to increase as well as its temperature. The distribution of surface temperature and radiation of energy over time is used to assess surface and subsurface defects from a structure. Spatial temperature differences over time in a material/component/surface, commonly referred as  $\Delta T$  value or hot spot, may indicate abnormal behaviour. Discontinuities in the inspected component are detected as localised temperature differences in the object's surface that can be the result of changes in the heat flow that are caused by

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<sup>3</sup> The amount of heat per unit of time

discontinuities in the inspected component (Maldague et al., 2001). Blackbody<sup>4</sup> and Planck's law<sup>5</sup> are important concepts in IRT that describes the capability of an object that can absorb all irradiated energy from any direction and wavelength (Maldague, 2001).

IRT can be categorised into two passive and active. The main difference between these two categories is the use of an external heating source. Under passive IRT, the object under inspection is studied within its own ambient environment without the use of any external excitation source. Passive IRT is generally used on materials, components or systems that are at a different temperature compared with the ambient and the temperature gradient is generated by self-heating or even potentially the sun. From a practical perspective, only an infrared camera is required for this type of inspection. Applications of passive thermography are numerous and can be used on both continuous monitoring and periodic inspections. Specifically, civil engineering applications are very common (Kim et al. 2023; Shrestha et al. 2025; Ham et al. 2013; Pozzer et al. 2024; Brooke, 2018) while thermal drone applications is also a growing field (Kulkarni et al. 2023; Kim et al. 2024; Wang et al. 2026; Panigati et al. 2025). Industrial applications of thermography cover the periodic monitoring of electric induction motors to predict failures of components or the motor itself (Piechocki et al. 2023; Alvarado-Hernandez et al. 2022; Munoz-Ornelas et al., 2016; Dahmer dos Santos, 2023; Resendiz-Ochoa, 2024; Balakrishnan et al. 2022). Other industrial applications include the monitoring of welding processes to ensure the stability of welding parameters, detection of defects and quality analysis of welds (Murariu et al. 2014). Ukiwe (2023) provides a review of research papers on electrical equipment covering power transformers, rotating machinery, photovoltaic systems, power systems, surge arresters and power lines. The work carried out within this deliverable deals with passive thermography.

In contrary, active thermography requires the use of an external excitation source to induce a thermal flux on the subject that will create temperature differences between defective and non-defective areas of the component or object (Ibarra-Castanedo et al., 2009). Active thermography involves the use of various techniques and complex additional equipment compared to passive. The classification of the methods is based on the type of heating source i.e. optical (halogen lamps, photographic flashes, laser beam), mechanical (ultrasonic and sonic transducers), electromagnetic (eddy currents/induction, microwaves). A breakdown of the methods is provided in Figure 1. Active methods are not limited to heating only and authors like Zymanik et al. (2020) and Łukaszuk et al. (2023) have carried out research by applying forced cooling as an additional excitation method to heating, to induce rapid temperature change and reveal defective areas within structures. Typical applications of active IRT is the detection of subsurface defects i.e. cracks, disbonds, delaminations, impact damage, porosity, water ingress, in materials such as metals, composites (monolithic or sandwich type), plastics, concrete, ceramics etc. Research examples on pulsed thermography can be found in Rodríguez-Martín et al. (2024), Maldague (2001), Wei et al., (2023), Vavilov et al. (2019), Deane et al. (2019). Other references on a commonly used technique such as optical lock-can be found in D'Accardi et al. (2021), Shrestha et al. (2021), Chung et al. (2021), Łukaszuk et al. (2023). Finally, step-heating is another optical method that has good

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<sup>4</sup> A perfect blackbody is a body that absorbs all the radiation that falls on it (Minkina, 2021)

<sup>5</sup> Plank's law describes the distribution of emitted energy as a function of the wavelength at a given temperature (Maldague, 2001)

performance and is used for thicker materials (Tromaras et al. 2025, Tromaras and Kappatos 2022, Roche and Balageas, 2015). Techniques like flash thermography have been also used to evaluate the lack of adhesion of thermal spray coated surfaces including plastic pipes (Murariu et al., 2014). Both induction and microwave heating are used as active thermography techniques capable of heating the subject internally.

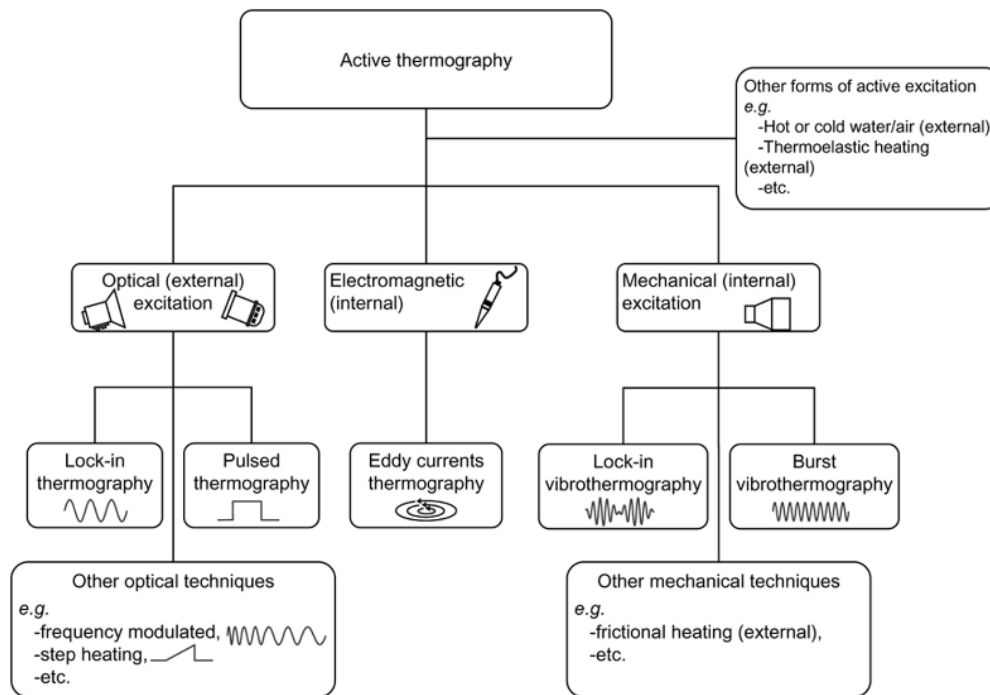


Figure 1. Active thermography methods

Source: Ibarra-Castanedo et al. (2009; 2)

## 3.2 Image processing techniques for image improvement in fault detection and prediction

The following section provides a literature review on image processing techniques that are applicable to infrared thermography and suitable for industrial production environments and prediction monitoring. These can be used for removal of reflections or improve poor quality raw thermal images in order to achieve results, as it is essential for defects detection and predictions. In addition, temperature errors of several degrees can be caused due to moving objects and thermal reflections from low-emissivity metallic surfaces. The following methods cover the entire processing pipeline from image enhancement, denoising, and thermal contrast quantification, to advanced data-driven approaches.

### 3.2.1 Pre-processing: Denoising and enhancement

#### **Convolution and gaussian filtering**

Spatial denoising is performed by convolving each thermogram with a two-dimensional Gaussian kernel, where the convolution operation  $g(x, y) = \omega * f(x, y)$  replaces each pixel with a weighted average of its neighbourhood. The Gaussian kernel  $G(\sigma) = (1/2\pi\sigma^2) \cdot \exp(-(x^2 + y^2)/2\sigma^2)$  is constructed with a size of  $2 \cdot \lceil 3\sigma \rceil + 1$  to capture 99.7% of the distribution's energy, with a moderate  $\sigma$  value to ensure effective noise suppression while preserving the spatial detail necessary for accurate defect localisation.

#### **Min-max scaling**

A statistically guided min-max scaling is applied to normalise the wide dynamic range typical of thermal

imagery:  $\sigma = \sqrt{\left( (1/(N-1)) \cdot \sum (x_i - \mu)^2 \right)}$ .

The pixel intensity distribution is characterised by its mean  $\mu$  and standard deviation  $\sigma$ , and values within the  $\mu \pm \sigma$  interval, which encompasses approximately 68% of data, are retained and linearly rescaled to the [0, 255] range.

#### **Cold image subtraction and gaussian threshold segmentation**

Quasi-static thermal background is removed by averaging a set of pre-excitation frames to form a reference image, which is then subtracted from each excitation-phase frame using a two-dimensional median filter to suppress residual spatial non-uniformities (Burrows et al. 2011). The resulting differential thermograms are subsequently segmented via Gaussian thresholding, where a statistically derived intensity threshold combined with binary morphological operations isolates defective regions from the sound<sup>6</sup> background (Hwang et al. 2020).

### 3.2.2 Processing techniques

#### **Contrast enhancement (CLAHE)**

Contrast limited adaptive histogram equalization (CLAHE) (Reza, 2004) divides the image into small tiles, typically 8×8, performs independent histogram equalization on each tile, and reconnects them through bilinear interpolation. The clip limit caps the cumulative distribution function slope in order to prevent noise amplification. CLAHE is particularly effective when the thermal scene contains significant hot equipment compared to ambient-temperature backgrounds.

#### **Plateau equalization (PE) and advanced plateau equalization (APE)**

Plateau equalization (PE) is an automatic gain control (AGC) algorithm, which has been specifically developed for real-time display of infrared imagery. Introduced by Vickers (1996), PE operates on the

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<sup>6</sup> Non-defective

image histogram by imposing a ceiling, which is the plateau threshold, on the bin counts before computing the cumulative distribution function. Those bins that exceed the threshold are clipped and the excess counts are redistributed uniformly across all occupied bins. Afterwards, the standard histogram equalization mapping is applied. The plateau value acts as a maximum gain parameter: when it is set to the peak bin count, PE reduces to histogram projection, thus there is no enhancement, and when it is removed entirely, PE becomes conventional histogram equalization with maximum enhancement. But at the latter case, it is prone to noise amplification and grey-level coalescence. By choosing an intermediate plateau, PE achieves a controlled contrast stretching that enhances the low-populated grey levels, in which the targets and anomalies typically reside, without over-amplifying the dominant background (Wang et al 2006).

Advanced plateau equalization (APE), also referred to as adaptive double plateaus histogram equalization, extends PE by introducing an upper and a lower plateau threshold. The upper plateau limits the maximum gain like in classical PE, while the lower one suppresses the grey levels with very low populations, which typically correspond to noise or insignificant background fluctuations. Li et al. (2018) introduced a feedback mechanism in which the normalised coefficient of variation of the histogram (NCVH) serves as a measure of enhancement level: the two plateau thresholds are iteratively adjusted until the NCVH converges to a target range, ensuring a scene-adaptive contrast enhancement without manual parameter tuning. This self-adaptive behaviour makes APE particularly suited to industrial thermography, where scene content varies between acquisitions, e.g., different pipe sections, different heating cycle phases, and a fixed plateau value would either under- or over-enhance certain frames.

The difference between the two techniques can be seen in Figure 2.

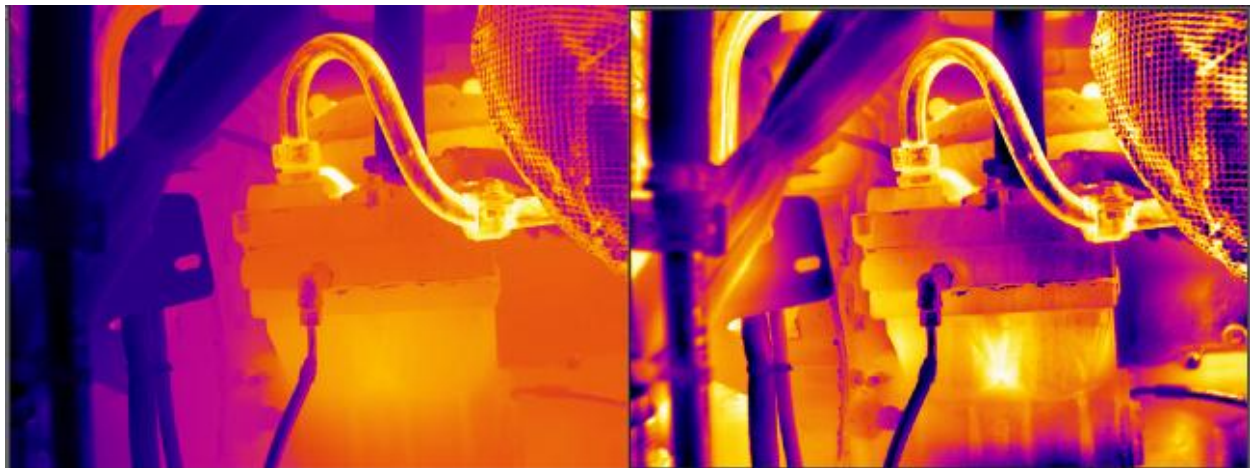


Figure 2: Thermal images of a compressor engine using PE (left) and APE algorithm (right)

## Spatial gradient operators and edge detection

Spatial gradient analysis can highlight the regions of rapid thermal transition, with the Sobel operator that computes the first-order directional gradients (Cervantes et. al. 2025b). A standard operator that

uses 3x3 masks computes the magnitude of the gradient of the thermal image, thus it effectively identifies edges.

The Laplacian operator computes the second-order spatial derivative ( $\nabla^2 T = \partial^2 T / \partial x^2 + \partial^2 T / \partial y^2$ , where T the temperature in directions x and y), corresponding to the curvature of the temperature field, making it particularly sensitive to point-like anomalies such as individual failed heating elements. Laplacian of Gaussian (LoG) filtering is preferred for noisy thermal images. The Canny edge detector (Ding et al. 2001) combines Gaussian smoothing, gradient computation, non-maximum suppression, and hysteresis thresholding for sub-pixel thermal boundary delineation.

A spatiotemporal methodology has been proposed using high-resolution infrared thermography to monitor the steel oxidation dynamics during heating (Cervantes et. al. 2025a). The preprocessing pipeline employs edge detection via the Sobel operator to delineate the region of interest (ROI) from raw thermograms, followed by adaptive filtering and longitudinal segmentation. In a normally operating heating system, unexpected sharp gradients indicate potential faults. Pixel-level metrics such as anomaly percentage and frame-by-frame analysis can reveal the continuous micro-scale surface reorganization, even under nominally isothermal conditions, with more pronounced effects in hotter regions.

Additional edge detection methods include Roberts and Prewitt algorithms for calculating vertical and horizontal edges individually (He et al. 2020), while the Laplace transform can reduce noise and provide finer diffusivity measurement (Maldague 2001). Furthermore, a predictive maintenance methodology combining infrared thermography with machine learning and augmented reality for industrial equipment, has utilized 3D object detection and pose estimation to enable automatic handheld thermal inspections (Venegas et al. 2022).

## **Segmentation and statistical anomaly detection**

### Otsu's thresholding

Otsu's method is an automatic thresholding technique that segments a grayscale image into foreground and background, by finding the optimal threshold that maximizes the separation between the two-pixel intensity classes. A study proposes an optimized Otsu segmentation algorithm accelerated by the Gray Wolf Optimization (GWO) method for IR image processing of electrical equipment (Liu et al. 2024). Also, for thermal scenes with complex multimodal structure, multi-level Otsu or fuzzy C-means (FCM) clustering algorithm may be needed (Hu et al. 2020).

### **Differentiated absolute contrast (DAC)**

DAC is an advanced image processing technique which is used to detect subsurface defects by calculating the temperature difference between defective and sound areas. DAC eliminates the need for manual reference zone selection, and enhances the contrast and reducing errors from non-uniform heating. It is based on the 1D Fourier heat equation solution, effective in reducing artefacts from non-

uniform heating or surface geometry, and the key advantage is avoiding the need for a fixed sound-area location (Maldague, 2001)

### Principal component analysis (PCA)

PCA reduces the dimensionality of thermal image data while it retains variation (Mishra et al. 2017). In thermography, PCA represents the thermal response as an orthogonal transformation  $T(i, j, t_n) = \sum_{k=1}^m c(i, j, k) \cdot v_k(t_n) + \mu(i, j)$ , where  $c(i, j, k)$  are coefficients (eigenvalues),  $\mu(i, j)$  is the mean response, and  $v_k(t_n)$  are orthogonal eigenvectors (Winfree et al. 2015). The covariance matrix is:  $C = \sum_{i,j} (T(i, j) - \mu(i, j)) \cdot (T(i, j)^T - \mu(i, j))$ .

### Singular value decomposition (SVD)

SVD is the mathematical engine underlying PCA. Applied to the pixel-by-frame data matrix, SVD factorizes  $A = U\Sigma V^T$ , where  $U$  contains spatial empirical orthogonal functions (EOF),  $\Sigma$  contains singular values, and  $V^T$  contains temporal modes (Rajic 2002). The first EOF capture the dominant thermal pattern, while the subsequent EOF separate the subtler defect-related signatures, thus achieving noise reduction, data compression, and defect contrast enhancement. SVD can estimate the average flaw depth within a flawed zone (Ciampa et al. 2009). Robust Principal Component Thermography (PCT) can extend this by decomposing  $A = L + S$  (low-rank + sparse defects), achieving contrast-to-noise ratio (CNR) 40% higher than standard PCT (Fang et al, 2023)

### Kernel PCA (KPCA)

Kernel PCA is a nonlinear extension of standard PCA. Instead of working directly in the original feature space, it maps the data into a higher-dimensional space via a kernel function (commonly RBF/Gaussian, polynomial, or sigmoid) and performs PCA on that (Liu et al. 2021).

KPCA maps data into a higher-dimensional Hilbert space using kernel functions and then performs PCA:

$$k(x, y) = \exp\left(-\|x - y\|^2 / \sigma^2\right), \quad k(x, y) = (x \cdot y)^d.$$

The "kernel trick" allows to compute dot products in that high-dimensional space without explicitly constructing it, keeping things computationally tractable.

In practice this means KPCA can capture the nonlinear structures in data that linear PCA would miss entirely. In the context of thermography and NDT, this can be useful when the thermal response over a defect does not vary linearly with depth or material properties. Therefore, KPCA can extract defect signatures that standard PCT would fold into noise or spread across many components.

The trade-off is choosing and tuning the kernel and its hyperparameters, e.g., the bandwidth  $\gamma$  for an RBF kernel, and the fact that the resulting components are less straightforward to interpret physically compared to linear EOFs.

### Independent component analysis (ICA)

ICA assumes that the observed thermographic sequence is a linear mixture of statistically independent, non-Gaussian source signals, and seeks a de-mixing matrix that maximizes the statistical independence of the recovered components (Lafargue-Tallet et al. 2022; Zhang et al. 2023). Unlike PCA, which decorrelates based on second-order statistics, ICA exploits higher-order statistics, making it better suited to separating physically distinct thermal sources that may share similar variance but differ in their statistical distributions.

### Fast Fourier Transform (FFT) analysis

FFT can extract a spatial frequency, from a single frame, and a temporal, from the evolution of a pixel over time:  $X(k) = \sum_{n=0}^{N-1} x(n) \cdot (\cos(2\pi kn/N) - i \cdot \sin(2\pi kn/N))$ .

Spatial FFT is the most practical approach for moving objects because it does not require temporal pixel correspondence. It reveals periodic patterns in heating element spacing and spatial non-uniformities along pipes. Temporal FFT requires synchronised acquisition, thus, phase images are less sensitive to emissivity variations (Ibarra-Castanedo et al. 2009)

### Thermal reflection mitigation

#### *Radiometric model*

The total spectral radiance measured by an IR camera from an opaque surface is (Lafargue-Tallet et al. 2022; Li et al. 2023):

$$L_{meas}(\lambda) = \varepsilon(\lambda) \cdot L_{bb}(\lambda, T_s) + \rho(\lambda) \cdot L_{env}(\lambda)$$

where  $\varepsilon$  is emissivity,  $L_{bb}$  is Planck blackbody radiance,  $\rho$  is reflectivity, and  $L_{env}$  is the environmental irradiance. For an opaque body, as transmittance  $\tau$  is considered zero, from Kirchhoff's law of thermal radiation it is then  $\varepsilon + \rho = 1$ , where  $\rho$  is the reflectance. The resulting temperature error is  $\Delta T \approx [(1 - \varepsilon)/\varepsilon] \cdot (T_{refl} - T_s)$ .

For a low-emissivity metallic surface, in which i.e.  $\varepsilon = 0.3$ , viewing a nearby heat source at 200°C when  $T_s = 50^\circ\text{C}$ , the error reaches  $\Delta T \approx 350^\circ\text{C}$ .

### Physical and emissivity-based correction

Physical mitigations include camera positioning to avoid specular paths, high-emissivity coatings, i.e.  $\varepsilon > 0.95$ , thermal shielding, and reflected apparent temperature compensation. For quantitative emissivity measurement, active thermo-reflectometry determines  $\varepsilon = 1 - (L_{on} - L_{off})/L_{bb}(T_{ref})$ .

The reference subtraction, cold-state minus operational thermogram, cancels the  $\rho(\lambda) \cdot L_{env}(\lambda)$ , isolating the emitted component. Multi-spectral approaches (Zhang et al. 2023) model the emissivity spectrum using polynomial interpolation, achieving temperature uncertainties below 5% for aluminium alloys.

### Deep learning and phase-based approaches

HRRNet (Wei et al. 2026) is the first deep learning approach for removing specular reflections from thermal infrared imagery. Its training loss combines:  $L_{total} = \lambda_1 \cdot \left\| I_{clean} - I_{gt} \right\|_1 + \lambda_2 \cdot L_{perceptual} + \lambda_3 \cdot L_{adv}$ .

The network is trained using a composite loss function that jointly penalises pixel-wise reconstruction error and perceptual discrepancy. This, enables to learn the mapping from reflection-contaminated thermograms to reflection-free counterparts directly from data. As an alternative, phase-based thermographic methods offer inherent immunity to reflections without requiring explicit correction. Since reflected radiation from quasi-static external sources contributes a near-constant offset to the temporal thermal signal at each pixel, this component is confined to the DC term of the discrete Fourier transform. Therefore, it extracts information from the higher-frequency harmonics, and inherently rejects the reflection contribution, preserving only the modulated thermal response associated with subsurface features.

Deep learning has been also utilised for defect detection. Fang et al. (2023) compared various models thermography data, while classical processing as preprocessing, such as PCT, significantly enhances deep learning accuracy.

### Moving objects

Moving objects, such as rotating machinery or continuous production processes that are the main areas of interest in this project and described in the later sections, cause a pixel in an image to no longer represent the same corresponding physical point during the whole sequence of an acquisition. This, interrupts the time-invariance that most advanced processing methodologies rely on.

This challenge is addressed by two complementary strategies. The first relies on frame-by-frame spatial analysis, applying spatial filtering, local contrast enhancement, or spatial-FFT to each thermogram. Since each frame is processed independently, no inter-frame pixel correspondence is required, making this approach inherently tolerant of arbitrary object motion. The trade-off is the loss of temporal depth, so that transient thermal evolution, which carries information about defect depth and thermal diffusivity, remains inaccessible.

The second strategy restores the temporal analysis by compensating for, or eliminating, the apparent motion. As an example for rotating drums, the trigger-synchronised acquisition that captures exactly one frame per revolution, ensures that each pixel maps to the same physical location across the entire sequence. This, recovers the stationarity which is required by PCA, kPCA, ICA and temporal-FFT, without any image registration overhead.

For linearly translating objects, such as pipes or conveyor-fed products, an equivalent effect is achieved by defining a fixed inspection station with consistent framing geometry, so that each product segment dwells within the field of view for a reproducible thermal history. In both cases, the synchronized

acquisition is the most robust solution, as it avoids the interpolation artefacts and computational cost associated with post-hoc motion compensation algorithms.

## 4. Characterisation of demonstrators

The following section aims to describe the processes that are currently in place at Artigo S.p.A. (ART) and K-FLEX Polska Spolka Ograniczona Odpowiedzialnoscia, where the two JOULIA project heating systems will be implemented. In order to carry out this task, visits by CERTH were carried to each manufacturing facilities of each company, in order to collect information about the processes, the operational environment, potential challenges and understand how the thermal imaging can be applied in order to develop the predictive maintenance platform.

### 4.1 ARTIGO S.p.A. (ART)

ART has been part of the Mondo Group since 1992, a leading worldwide manufacturer and supplier in the flooring sector. In 1996, the company moved from Milano, where it was founded during the 1960s as a part of the Pirelli Group and settled in Cairo Montenotte (Savona, Liguria). ART produces and commercialises high-performance flooring products for several different sectors, such as schools, hospitals and airports.

#### 4.1.1 The Flooring Rubber Vulcanisation Process

The core of the rubber flooring production is the vulcanisation. This process takes place continuously through the use of a rotocure machine that is designed for continuous vulcanisation of rubber flooring that is finally delivered in rolls. The rotocure consists of four main drums:

1. Lower drum
2. Main drum
3. Upper drum
4. Tensioning drum

A metal belt (steel band) wraps around all four cylinders, as shown in Figure 3.

The uncured rubber flooring enters the machine on the metal belt above the lower drum, then moves toward the main drum. During this stage, the material is pressed and heated between the steel belt and the main drum along approximately two-thirds of the circumference of the main drum, where vulcanisation takes place. . The pressure between the belt and the material is ensured by a tensioning drum. After leaving the main drum, the vulcanised flooring wraps around the upper drum before exiting the rotocure.

Vulcanization is governed by three key parameters: temperature, time, and pressure. These parameters are adjusted according to the thickness of the flooring, which typically ranges between 2 and 5 mm. In

general, a greater thickness requires longer curing times or slightly higher temperatures to ensure complete and uniform vulcanisation.

The lower drum and the main drum are heated with diathermic oil, while the heating elements can be heated up electrically or by diathermic oil too. The working temperature, measured at the exit of each component, and the power absorbed are reported. The power and the temperatures are thickness dependent.

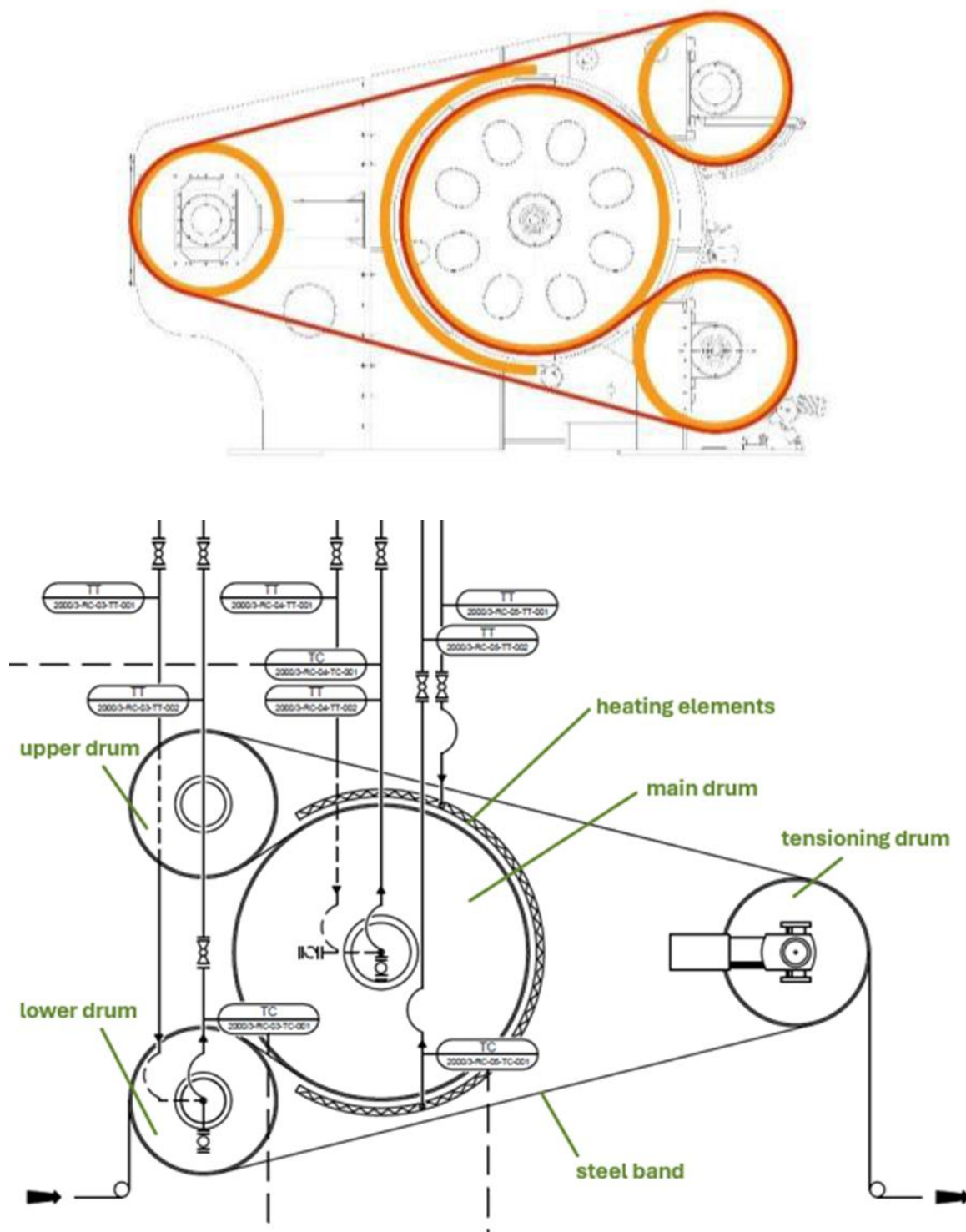


Figure 3 Scheme of the rotocure

Table 4: Typical working parameters for the vulcanisation .

| Component        | Working temperature |
|------------------|---------------------|
| Lower drum       | 100-125 °C          |
| Main drum        | 170-180 °C          |
| Heating elements | 200-220 °C          |

The dwell time of rubber inside the rotocure is between 5-8 minutes depending on the speed of the belt.

The rotocure includes three loops of diathermic oil for all the heated components of the machine. These are connected to a manifold (hydraulic compensator), which receives the hot oil from the boiler room (at around 250 °C) and sends it back at a temperature 10-15 °C lower. The oil flowing in the three loops connected to the manifold is recirculated and regulated using three-way valves, which receive the working temperature of the oil exiting from each component and compare it to the set point value.

ARTIGO has a monitoring system for recording process parameters which are recorded every minute. Temperatures of various locations are monitored in different locations on all drums, heating elements and manifold for diathermic oil and a hydraulic unit.

Within JOULIA project other suitable technological configurations for the electrification of the rotocure heating system are being studied, ensuring technical feasibility, energy efficiency, and cost-effectiveness. Within this research scope, different induction heating configurations were studied using multi physics simulations within WP5. The configuration that has been selected is a multiphase induction system capable of directly heating both the rotocure cylinder and the steel belt from the same electromagnetic structure. This system will be retrofitted into one existing rotocures within ARTIGO's production facility.

## 4.2 K-FLEX

K-FLEX, situated in Uniejów, Łódź (Poland), is a multinational manufacturing company specialised in the production of thermal and acoustic flexible elastomeric insulation materials. The company has production facilities and a network of subsidiaries around the globe, in order to provide its products and services to customers wherever they are in the world.

### 4.2.1 The Glue Thermal Activation Process

JOULIA project focuses on the production process of multilayered plastic insulation pipes PERT II, shown in Figure 4 . PERT II is a type II polyethylene with enhanced temperature properties, capable of operating

at temperatures of up to 95°C. PERT is structured like a woolen collar, strong and difficult to break but flexible.

The process starts with the internal layer extrusion, which is stabilised before the glue application. Once the glue wraps the inner layer, the pipe is coated with aluminium, butt welded and then covered with glue and overlaid with PERT. After all these steps, all layers are placed, and, with the stabilisation of the pipe, the process is finished. Due to confidentiality reasons only a limited amount of information can be circulated in this deliverable due to its public nature.

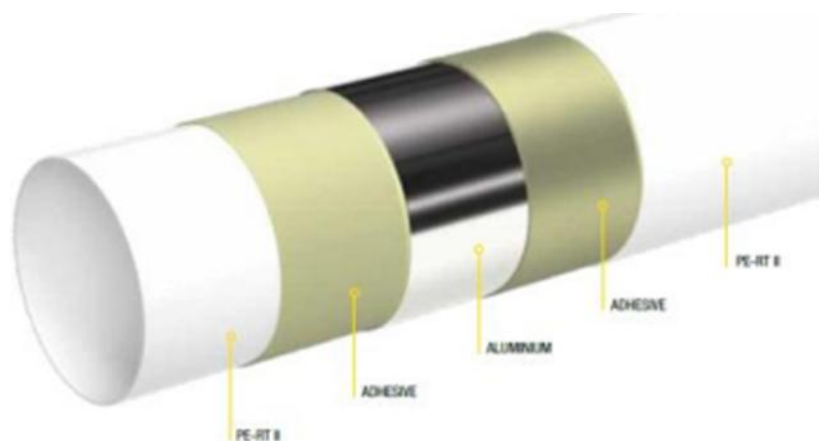


Figure 4: Structure of multilayered plastic insulation pipes PERT II

The production process overall consists of:

- Extruder for the internal plastic layer which is stabilised before glue application
- Pullers for pulling the pipe as it being produced in a continuous process.
- An aluminium coil that is being pulled and rolled into a cylindrical shape and wraps the inner pipe layer that has been wrapped with glue.
- TIG welding machine for joining the aluminium pipe that covers the inner pipe layer.
- The aluminium layer and inner layer are then covered with glue and overlaid with PERT.
- Induction coil for adhesion activation to join the different layers of the pipe together
- The process ends with cooling and winding of the pipe into a large coil.

Within the framework of JOULIA project, the current induction process in place, has been selected to potentially be replaced by a microwave heating process. This study is work in progress and no further information can be provided at this stage.

## 5. Application of thermography at demonstrators

This section contains the application of thermography as method capable of monitoring the structural health of machinery that are provided by ARTIGO and K-FLEX.

### 5.1 Experimental apparatus

In both cases the same thermography equipment was used. Specifically, a FLIR A655sc uncooled microbolometer was used (Figure 5) with a 45° lens (wide) and a secondary 15° lens (narrow) was used for some close-up acquisitions. The FLIR A655sc is a high-resolution camera that is normally used for lab applications and active thermography. The camera is powered through a power socket and requires an ethernet connection to transmit the data to a PC. The acquisition of the data and the camera settings are controlled through FLIR's proprietary ResearchIR Max software. The technical characteristics of the camera are provided in Table 5.



Figure 5: FLIR A655sc thermal camera

Source: FLIR (2026)

Table 5: Technical specification of FLIR A655sc camera

| Camera specifications    | Details                              |
|--------------------------|--------------------------------------|
| IR resolution            | 640 x 480 pixels                     |
| Thermal sensitivity/NETD | < 0.03°C @ +30°C (+86°F) / 30 mK     |
| Field of view (FOV)      | 45° x 34° (55° diagonal)             |
| Image frequency          | 50 Hz (100/200 Hz with windowing)    |
| Spectral range           | 7.5–14 μm (long wave)                |
| Accuracy                 | ±2°C (±3.6°F) or ±2% of reading      |
| USB, communication       | TCP/IP socket-based FLIR proprietary |
| External power operation |                                      |

Source: FLIR (2026)

## Acquisition software

FLIR's ResearchIR Max is the initial standard software tool is used for image acquisition, camera control setup and initial analysis of the raw data. Acquisition parameters such as recording duration, manipulate the recording acquisition Hz, temperature range calibration, file naming, taking snapshots etc. are all controlled through this software.

Furthermore, ResearchIR Max is a strong tool for carrying out analysis of the acquisitions and allows different visualisations that enhance image contrasts between colder and hotter areas of an object. Some of the basic functions is that allows it the user to plot temperature (T) rise diagrams ( $\Delta T$  diagram) over time/frame number, on a specific region of interest (ROI).

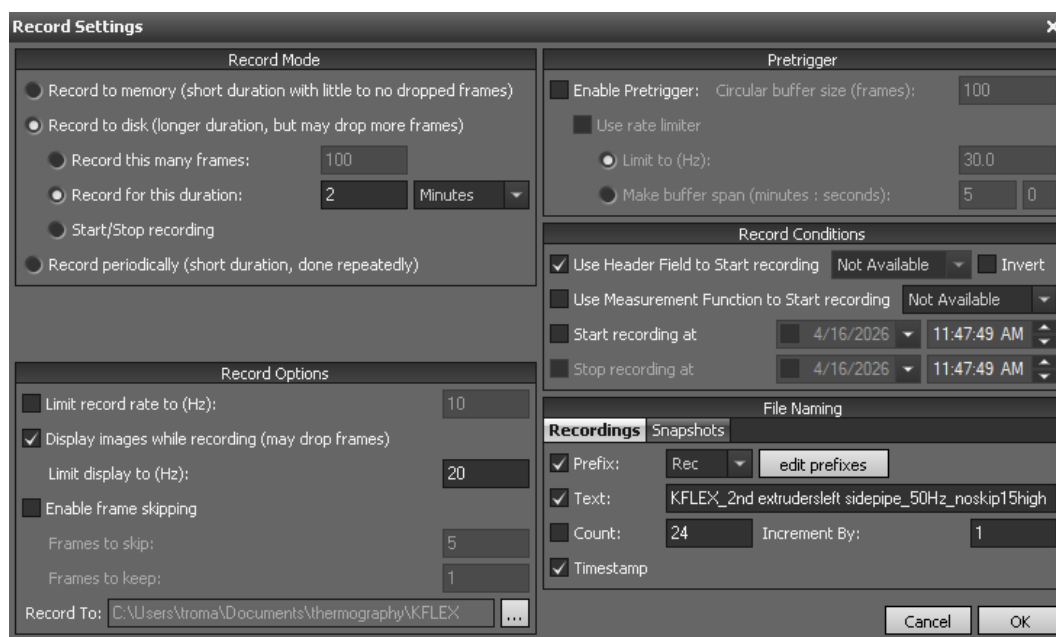


Figure 6: FLIR ResearchIR Max record settings menu

Additionally, the software offers different automatic gain control algorithms that improve the visibility of the difference between thermal gradients in an image. The algorithms that are mostly used are Plateau Equalisation and Advanced Plateau Equalisation that have already been described.

## 5.2 ARTIGO thermal images and analysis

CERTH staff visited ARTIGO's premises in Cairo Montenotte (Savona, Liguria, Italy) to familiarise itself with the production line and the equipment being currently used. During this initial visit, ARTIGO staff explained to CERTH, how the rubber flooring is produced and provided initial information about the induction process that will be retrofitted in one of the production lines.

Three areas were indicated by ARTIGO staff that would be of interest for closer monitoring using non-invasive methods like IRT. These locations of the machinery also did not pose any health & safety risks to the people that are around. It needs to be noted that the rotocure has both rotating and hot parts. The areas of interest where the acquisition were carried out were the following:

- the lower drum

- a small gap where that provided line of sight to the vulcanised floor
- the heating elements of the main drum

A number of acquisitions were carried out to see what was visible in the infrared spectrum and see what temperature anomalies could be detected (if any) in those locations. Apart from accessibility to these areas of the rotocure, another significant factor was the emissivity of the surfaces of drums which were made of stainless steel and their surface finish. Specifically, the surface texture of the drums have a smooth surface finish making them more difficult to read their temperature through remote sensing.

In each case the camera was placed at an optimal position given the space that was available and allowed the object under inspection to be captured within the camera's field of view (FOV). During the acquisitions the rotocure operated continuously without any interruptions. The descriptions that are provided in the ARTIGO section are more detailed due to the difficult nature of the machinery that are being studied. Hence, more explanations are required for the reader to understand what the images show.

**Table 6. Acquisition parameters and camera settings used in ARTIGO**

| Acquisition #    | Description                              | Settings <sup>7</sup>       | # of frames recorded | Duration (s) | Lens size | Details                                                                                                                                   |
|------------------|------------------------------------------|-----------------------------|----------------------|--------------|-----------|-------------------------------------------------------------------------------------------------------------------------------------------|
| A <sup>8</sup> 1 | Preliminary acquisition of the main drum | 50Hz,<br>10 to 1 frame skip | 1360                 | 300          | 45°       | First acquisition of the main drum to establish the camera's settings. Distance between camera and drum 2.1m                              |
| A2               | Acquisition of the main drum             | 50Hz                        | 6001                 | 120          | 45°       | 2 <sup>nd</sup> acquisition of the main drum. 2.1m distance between camera and target. No frame skip to assure more frames were recorded. |

<sup>7</sup> Settings: refers to acquisition settings used in the software. No frame skip refers that no frames were skipped and the camera recorded 50 frames per second. A 5 to 1 frame skip refers to every 5 frames 1 is recorded. This way the file size is minimised when the process that is being observed does not happen very fast.

<sup>8</sup> A: for ARTIGO

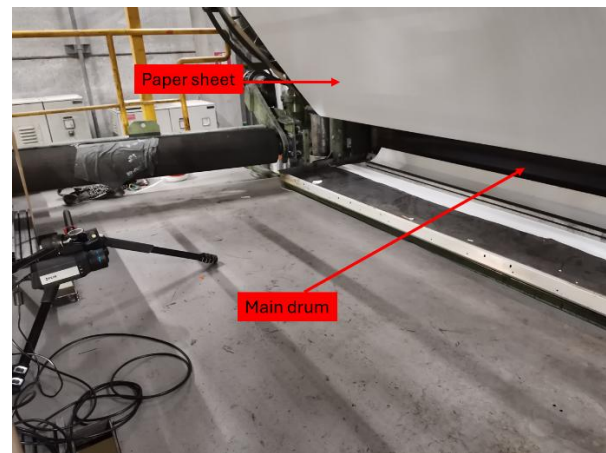
| Acquisition # | Description                                                           | Settings <sup>7</sup> | # of frames recorded | Duration (s) | Lens size | Details                                                                                                                                                                                                      |
|---------------|-----------------------------------------------------------------------|-----------------------|----------------------|--------------|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| A3            | Acquisition of the main drum                                          | 50Hz                  | 6001                 | 120          | 45°       | 3 <sup>rd</sup> acquisition of the main drum with lower acquisition rate. A small readjustment of the camera was made on the vertical axis but the distance to the drum remained the same at 2.1m            |
| A4            | Acquisition of the vulcanised rubber floor and side of the upper drum | 50 Hz                 | 15001                | 300          | 45°       | 4 <sup>th</sup> acquisition of the upper drum from a different location where a small area of the vulcanised rubber and the side of the main drum can be captured. Distance between camera and target 0.51m. |
| A5            | Acquisition of the vulcanised rubber floor and side of the upper drum | 25 Hz                 | 45002                | 180          | 45°       | 5 <sup>th</sup> acquisition of the upper drum following acquisition A4. Lower frame rate. Distance between camera and target 0.51m.                                                                          |
| A6            | Acquisition of the heating elements                                   | 50Hz                  | 9001                 | 180          | 45°       | Acquisition of the heating elements of the rotocure. Distance to centre of the heating plates area = 3.6m                                                                                                    |
| A7            | Acquisition of the heating elements                                   | 25Hz                  | 4501                 | 180          | 45°       | Follow up of acquisition A6 with lower frame rate. Distance to centre of the heating plates area = 3.6m                                                                                                      |

### Acquisition A1

A1 was the first acquisition that was carried out to see what was visible to the IR camera, the temperature range and to see how fast the manufacturing process was. To capture the entirety of the main drum's area, the camera had to be placed at the maximum available distance (2.1m between the lens and the drum) that was available in the rotocure platform (Figure 7). Also, the camera had to be placed as low as possible due to the drum being situated at a low level (Figure 7). Figure 8 shows thermal images taken at two instances from the acquisition using the PE and APE scale to enhance temperature differences. The APE scale helps to understand more these temperature variations. Figure 9 provides an explanation of the thermal image acquired from the main drum compared to its RGB image. This explanation is added mostly for the reader to understand what can be seen in these thermal images. The image itself shows that the drum's surface is reflective and there almost two sections created. The top one (Figure 9 c) is influenced by the reflection of the hot surface of the vulcanised floor that is behind it Figure 10. These temperature gradients in the paper sheet are caused possibly from hot pockets of air due to the vulcanised rubber located behind it.



(a)

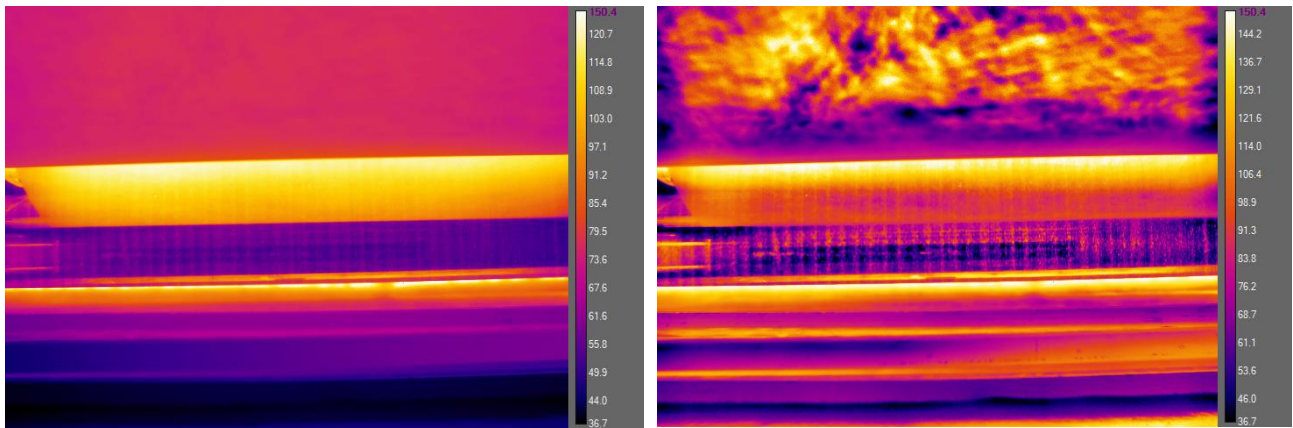


(b)



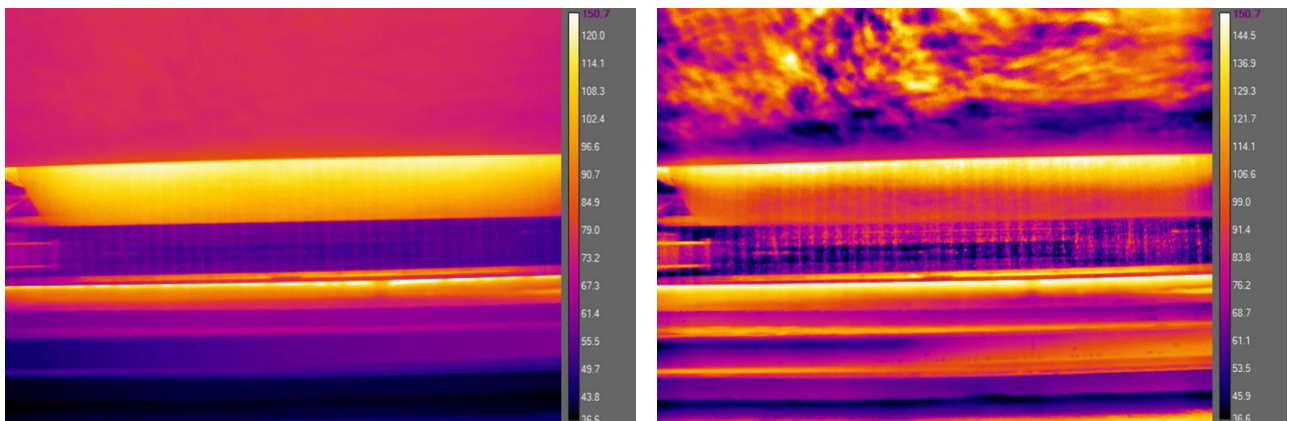
(c)

Figure 7: Position of the IR camera and explanation of the main drum area



(a)

(b)



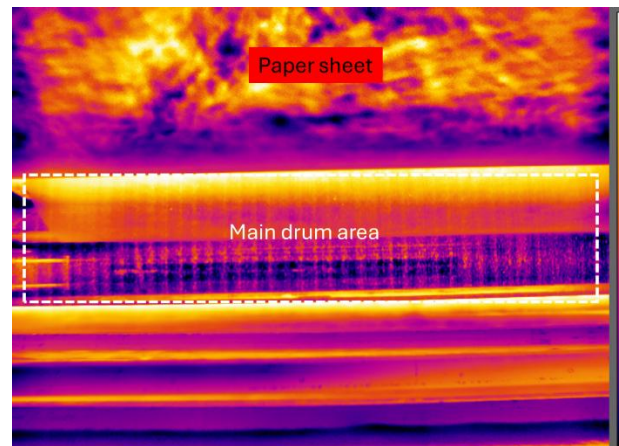
(c)

(d)

Figure 8: A1 acquisition frame 877 at  $t = 192.4$  s on PE scale (a), APE scale (b) and frame 1062 at  $t = 233$  s on PE scale (c) and APE scale (d)



(a)



(b)

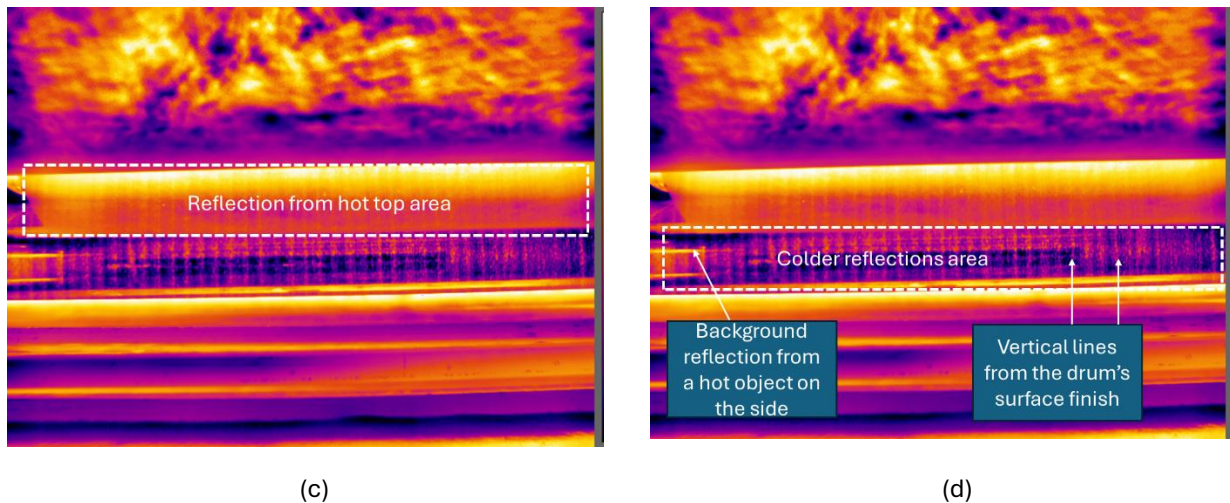


Figure 9: Explanation of the thermal image captured. (A) RGB image of the main drum and paper sheet, (b) thermal image distinguishing the paper sheet area and main drum metal section, (c) upper section of the drum with hot reflections from the vulcanised floor behind the paper sheet, (d) main section of the drum with other colder reflections

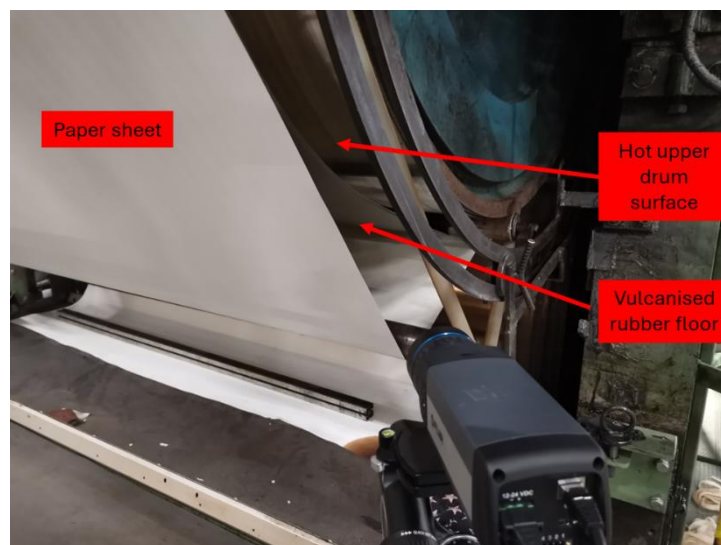


Figure 10. Area behind the paper sheet

To analyse the acquisition, a  $\Delta T$  diagram was plotted using a line ROI. The latter is basically a line that can be drawn on the software and provides a mean temperature of the pixels across the region (in this case the line). The line was drawn at the area where paper sheet and the roller meet and form a wedge, where the hotter temperatures of the drum are observed (see Figure 11). This method is suggested by Usamentiaga et al. (2014) to overcome emissivity issues in such surfaces. Two types of temperature plots were used to see what provided more useful results. These are presented in Figure 12. The top diagram is a temporal plot which shows how the mean temperature deviates over the duration of the acquisition and the bottom diagram is a profile plot. The latter is the temperature of each pixel in the line ROI for a specific frame of the acquisition. Since one of the main aims in these acquisitions is to capture

thermal anomalies in the objects that might indicate non uniform heating and potentially defects in the machinery or the process itself, the profile plot is a more suitable type of analysis that shows the temperatures across the part of the drum that within the camera's FOV. Overall, the profile plots showed that there is a deviation of temperatures in the drum's profile with temperatures on the left side being slightly higher by ~4 °C. These deviations are throughout the acquisition with the difference being smaller in other frames. The deeps at the edges of the profile plot are possibly attributed to respective temperatures of the drum being lower since it's the edge of the drum. The saw-like form of the plot is attributed to the vertical lines from the surface finish of the drum that are described in Figure 9 (d).

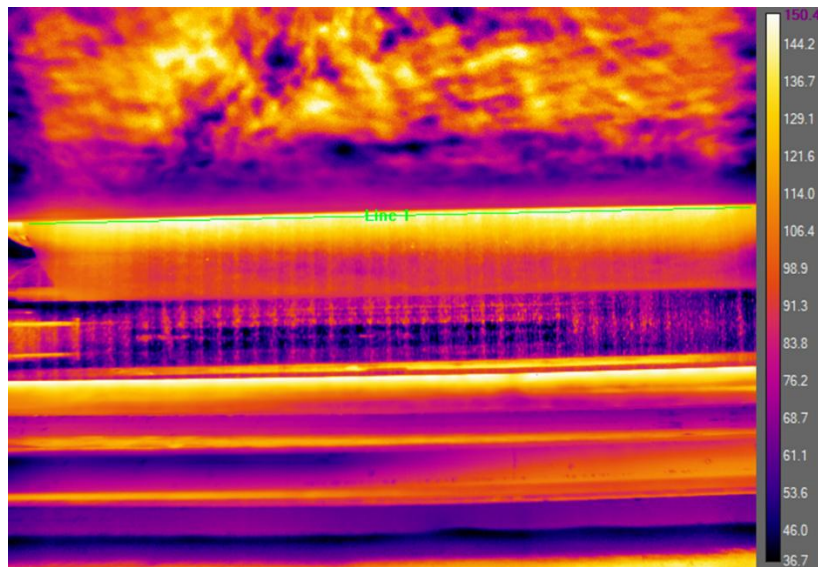


Figure 11: Line ROI between the metal drum and paper sheet. Frame 877 of A1

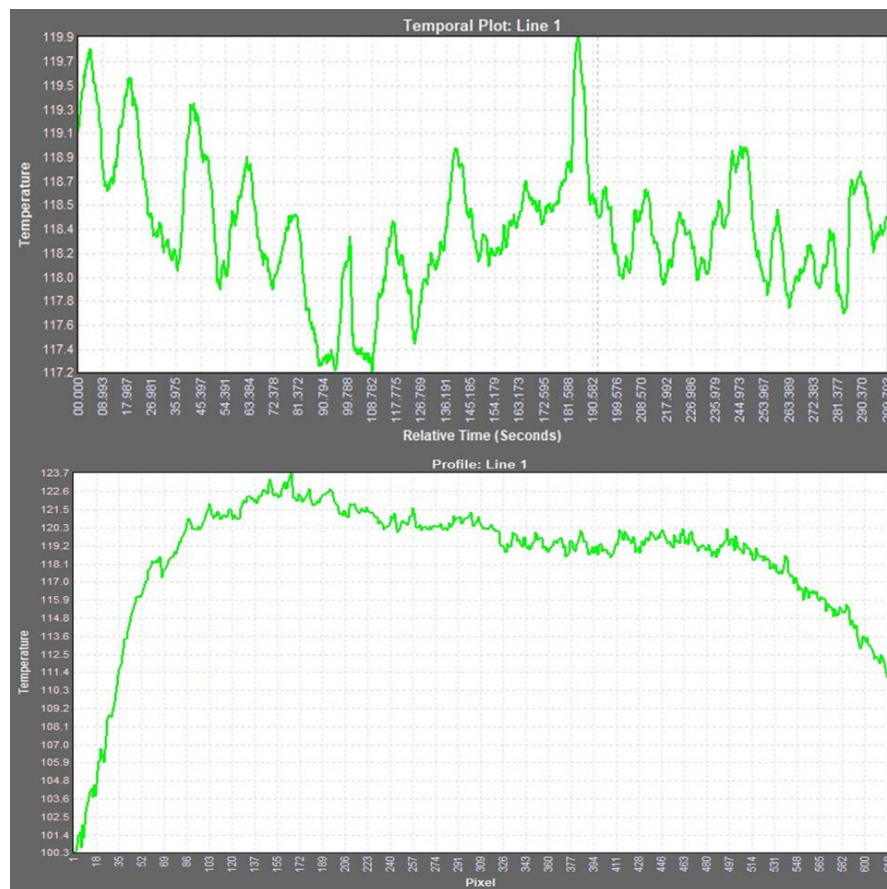
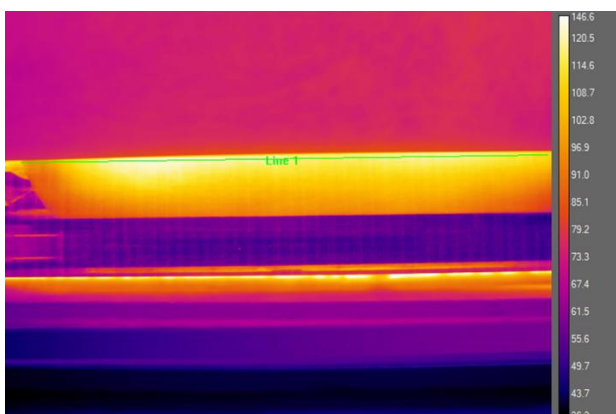


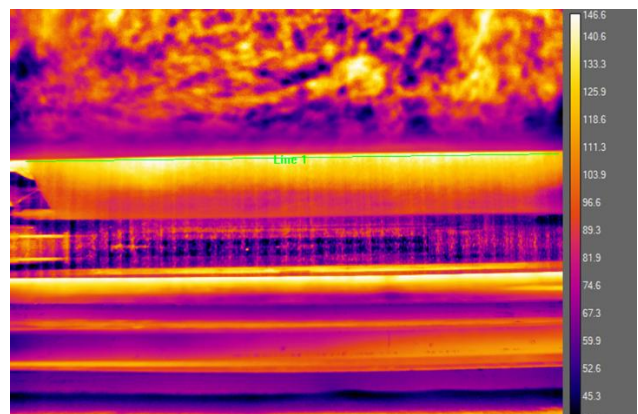
Figure 12. Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 877 of A1<sup>9</sup>

### Acquisition A2

Acquisition A2 has a duration of 120s at 50Hz acquisition rate. The results are the same as A1. The same pattern of a slightly hotter left side of the drum is repeated in this acquisition as observed in Figure 13 and Figure 14.



(a)



(b)

<sup>9</sup> Temperatures are in °C

Figure 13: Frame 3347 of A2 at t= 66.9s. (a) PE scale and APE scale (b)

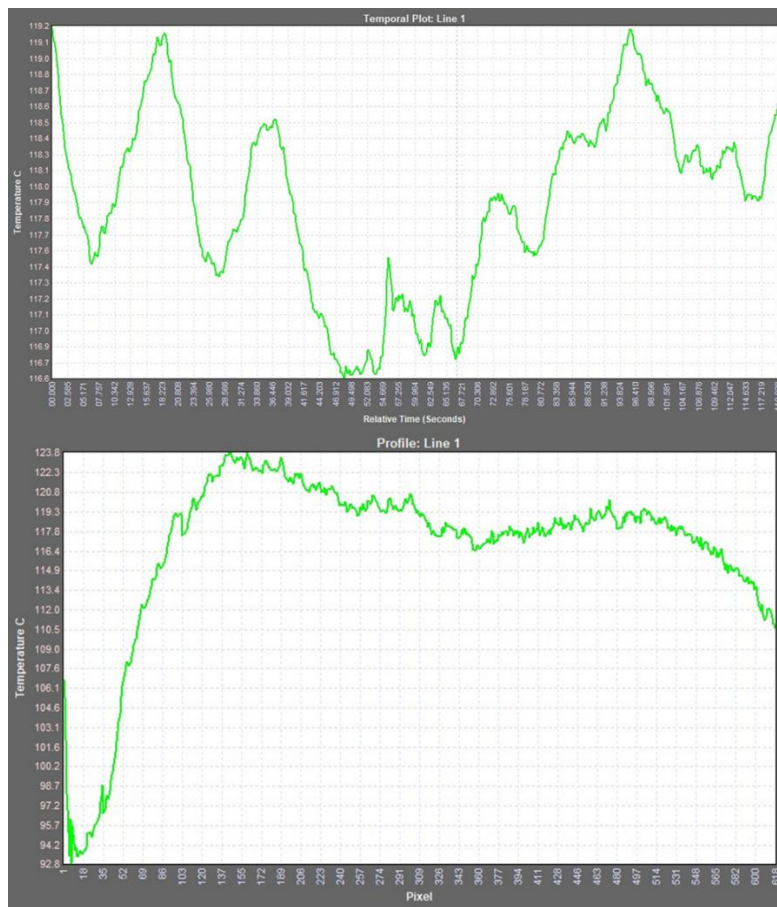
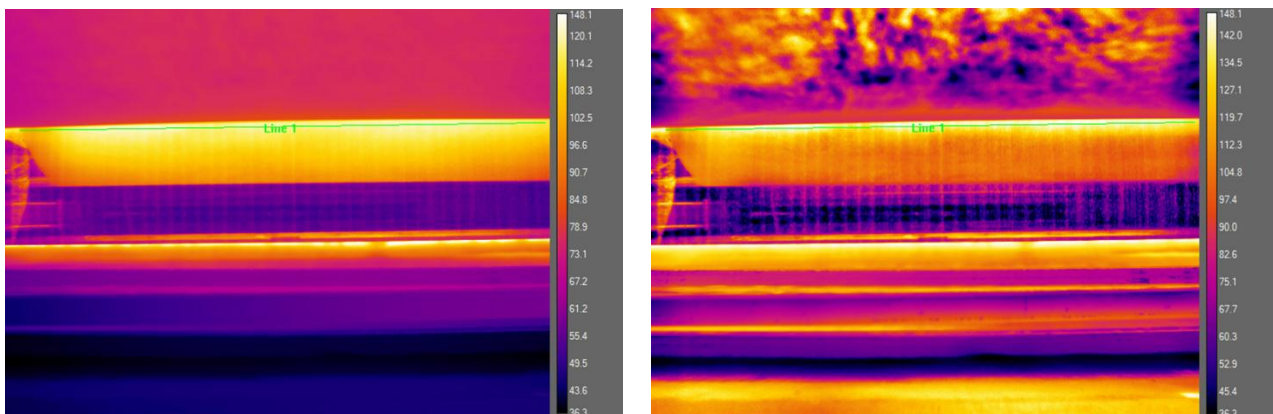


Figure 14: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 3447 of A2

### Acquisition A3

Acquisition A3 has a duration of 120s at 50Hz acquisition rate. During this acquisition a surface feature of the drum was captured on the left side of the FOV. The feature is shown in Figure 17 as it enters the FOV. This feature might not be necessarily a defect but could have been caused from oil residue or other causes. However, this shows that abnormal features that deviate from the typical images can be captured by an IR camera and can potentially be assessed through further image processing.



(a)

(b)

Figure 15: Frame 4466 of A3 at  $t = 89.2\text{s}$ . (a) PE scale and APE scale (b)

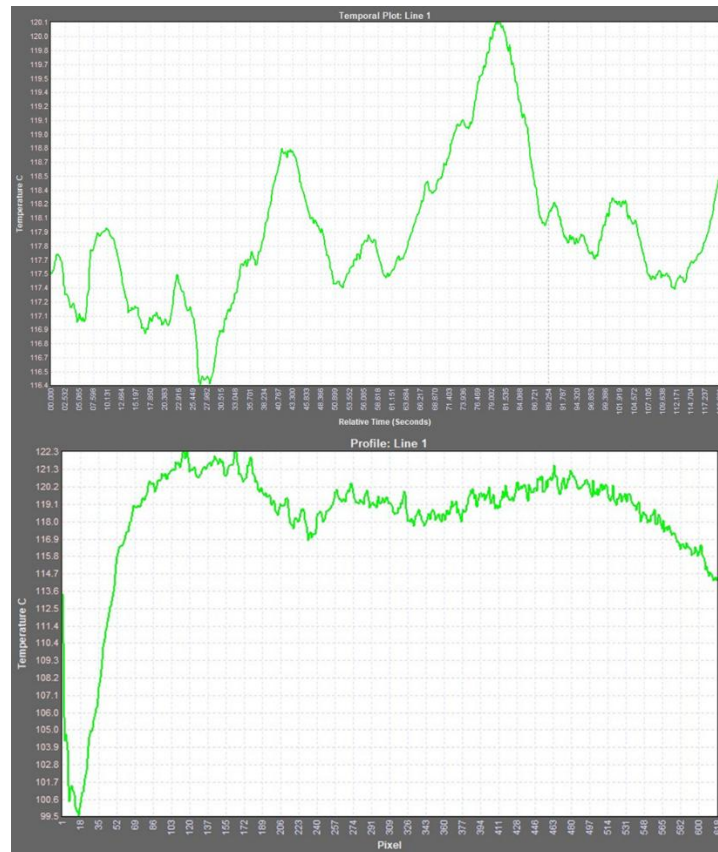


Figure 16: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 4466 in A3

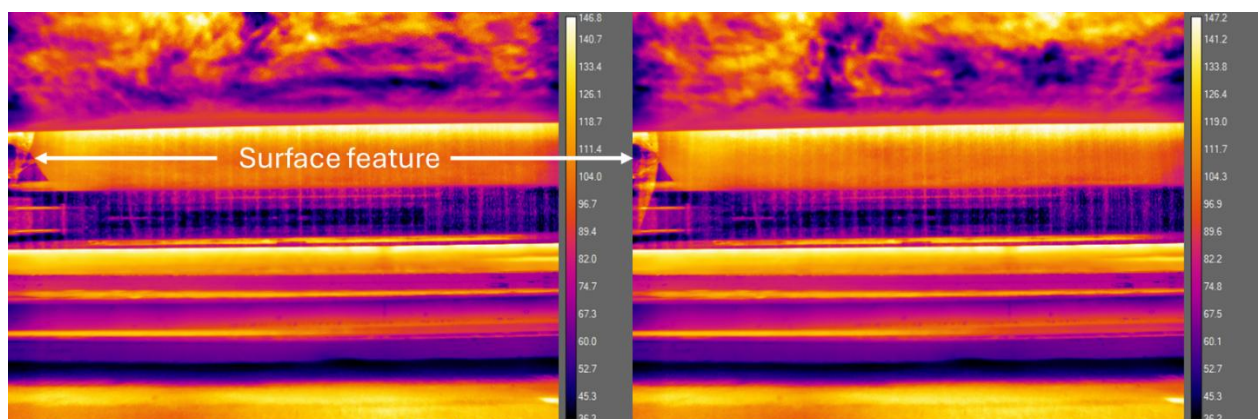


Figure 17: Surface feature on the drum captured on A3

### Acquisition A4

Acquisition A4 captures the upper drum of the rotocure, as shown in Figure 18. This location is above the main drum that were imaged during the three previous acquisitions and allows to capture the vulcanised rubber product. However, only a small surface of the product is visible. In addition, this location allows the camera to see the side part of the upper drum. This acquisition was 5min long.

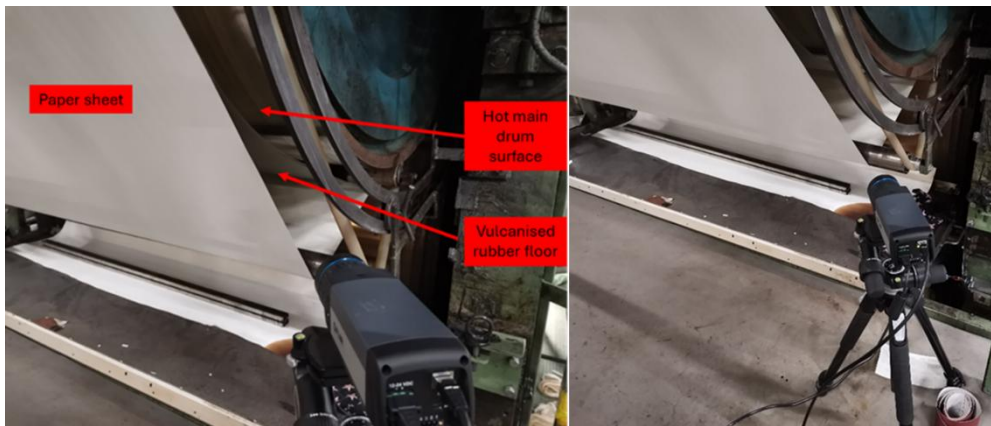
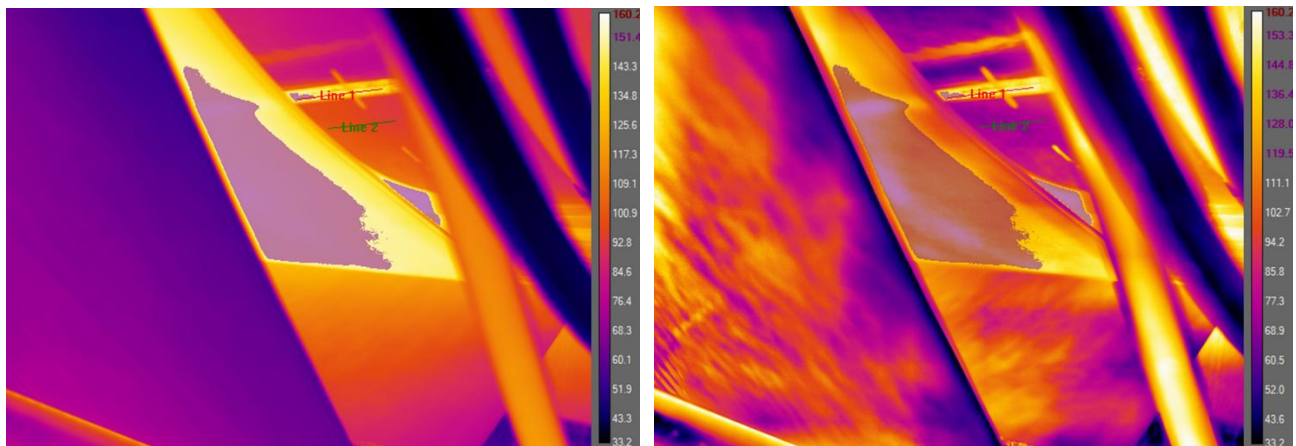


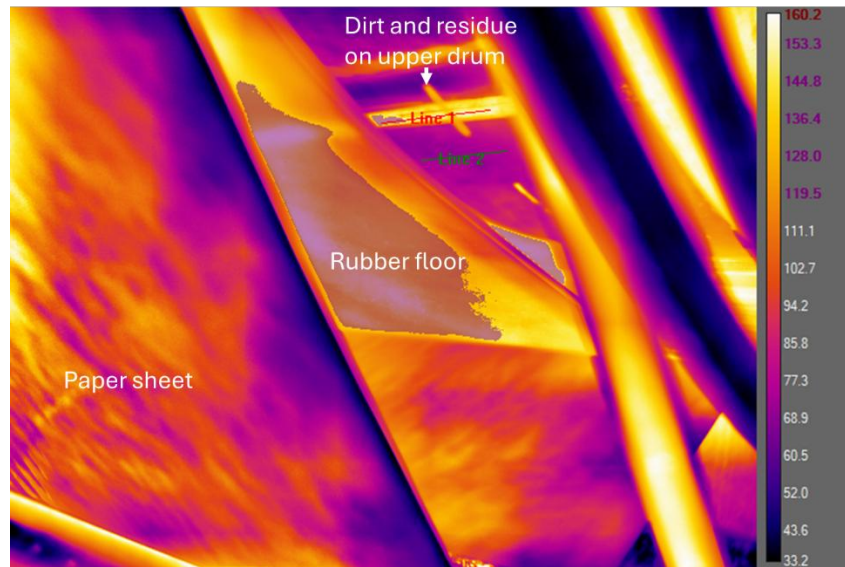
Figure 18: Area where the vulcanised rubber floor is visible and the side of the upper drum

To analyse this acquisition two line ROIs were drawn on the main drum (Figure 19). One part of the drum that seems to come to contact with the rubber floor has a higher temperature where line 1 was placed.



(a)

(b)



(c)

Figure 19: Frame 1456 of A4 at  $t = 290$ s. (a) PE scale, APE scale (b) and explanation of the image (c)

An unexpected pattern is observed when plotting the mean temperature of line 1 ROI over time. The fluctuations in the mean temperature are in the region of  $\sim 38$  °C as shown in Figure 20. For line 2 ROI the temperatures are lower. During the end of Acquisition A4, on the right side of the upper drum some dirt

and residue can be observed, as shown on Figure 19 (c). This dirt and residue are also the cause for the temperature drop in the profile plot of line 1 shown in the bottom part of Figure 20.

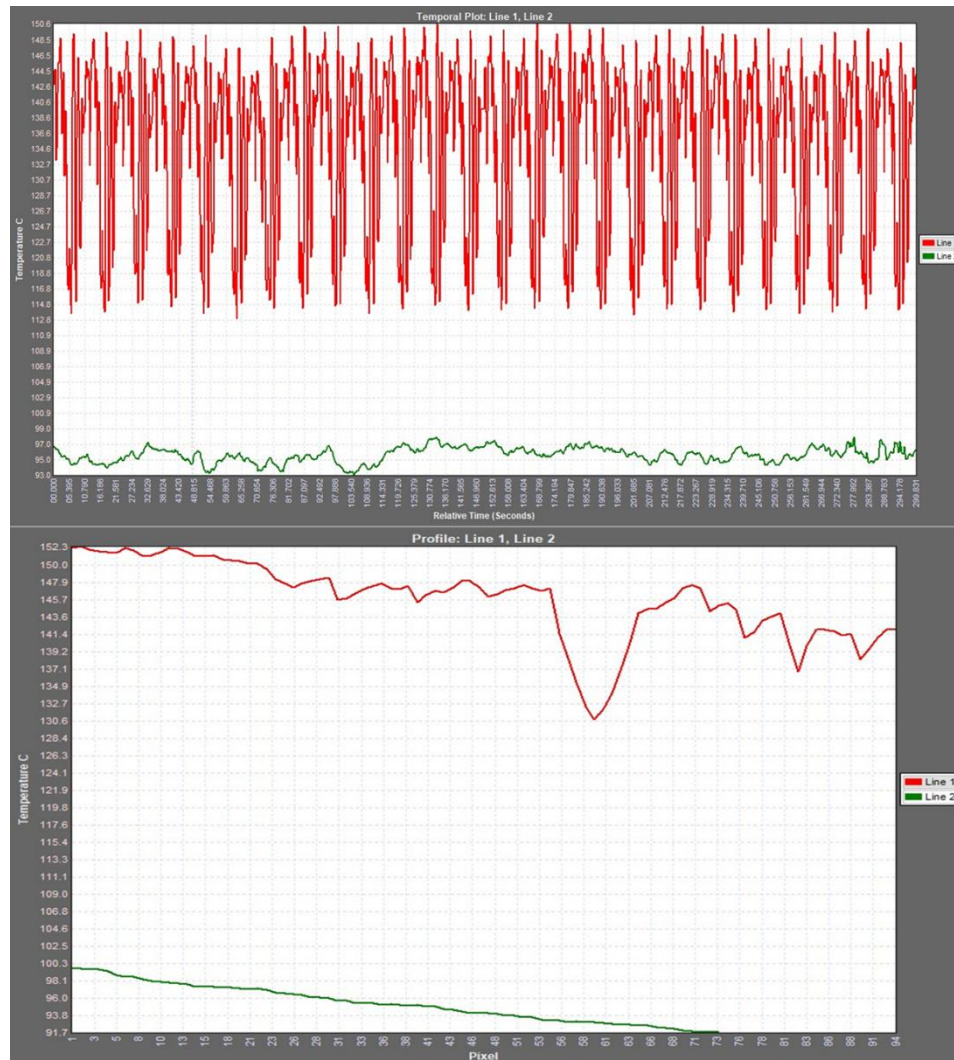


Figure 20: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 1456 of A4

### Acquisition A5

Acquisition A5 is a follow up to A4 with the difference of having a lower frame rate and a smaller duration. Although, difference can be observed due to the loss of frame rate the same patterns are observed in Figure 21 and Figure 22.

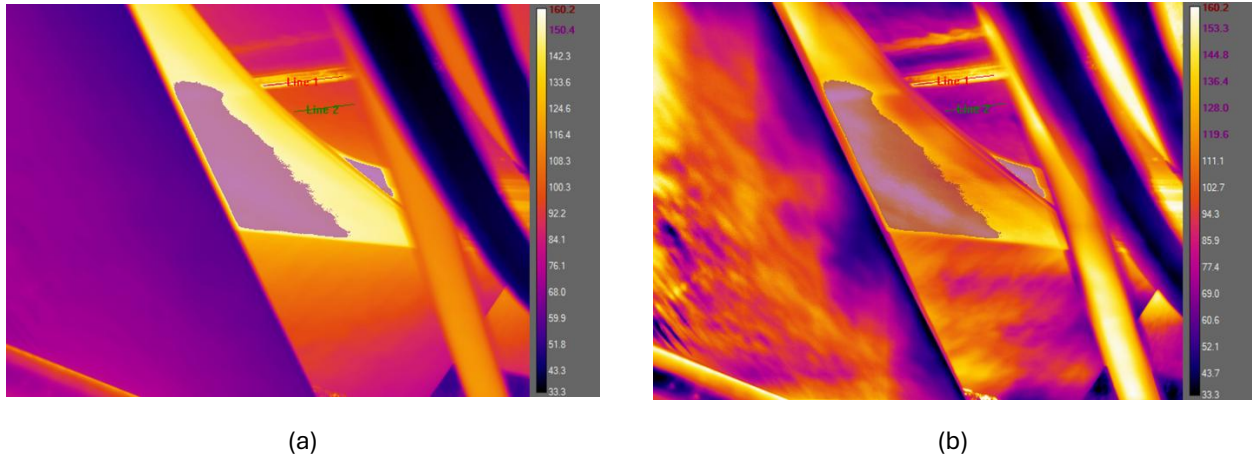


Figure 21: Frame 889 of A5 at  $t = 35.2$  s. (a) PE scale and APE scale (b)

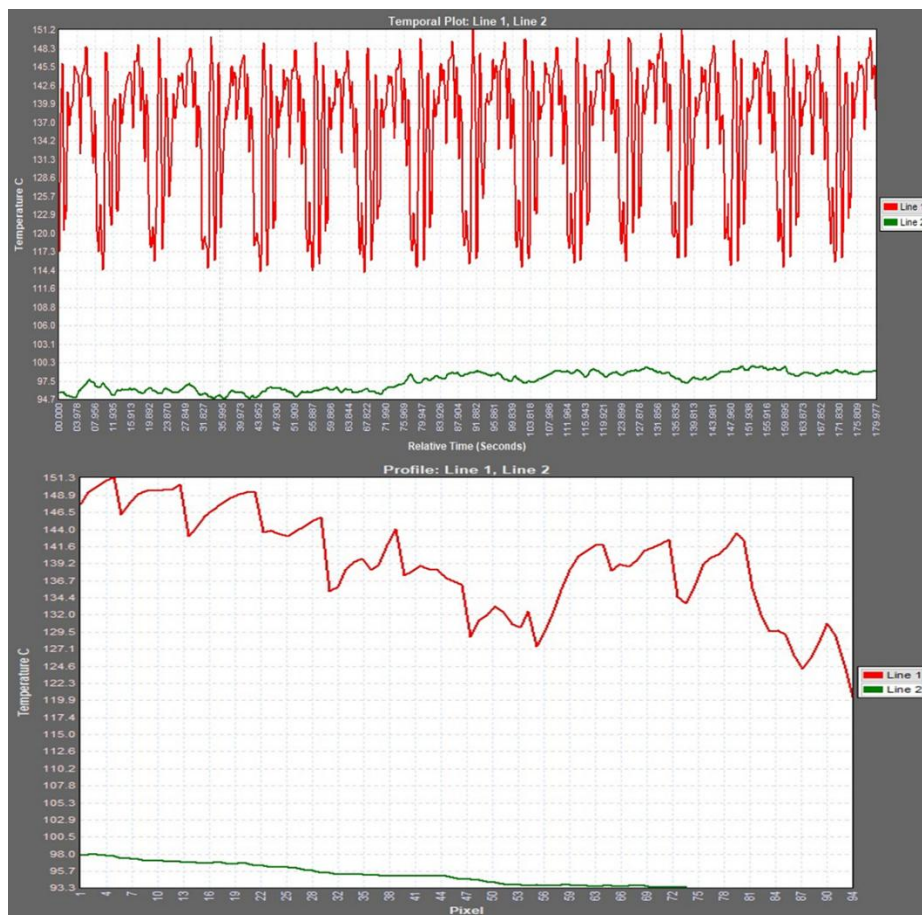


Figure 22: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 889 of A5

### Acquisition A6

Acquisition A6 is from a new location of the rotocure with the camera capturing the heating elements of the main drum shown in Figure 23. The heating elements are located in the centre of the image. To analyse the temperatures across the heating elements, a line ROI was drawn. The latter only captures a part of the drum because other parts of the machinery intersect the camera's FOV as shown in Figure 23. A sudden dip in temperature is recorded in the temporal plot in Figure 25 (top) at 122s of A6. Although the heating elements at the centre of the drum seem to have a lower temperature compared to the edges, no malfunction was reported during the shift where the acquisitions took place.



Figure 23. Heating elements of the rotocure

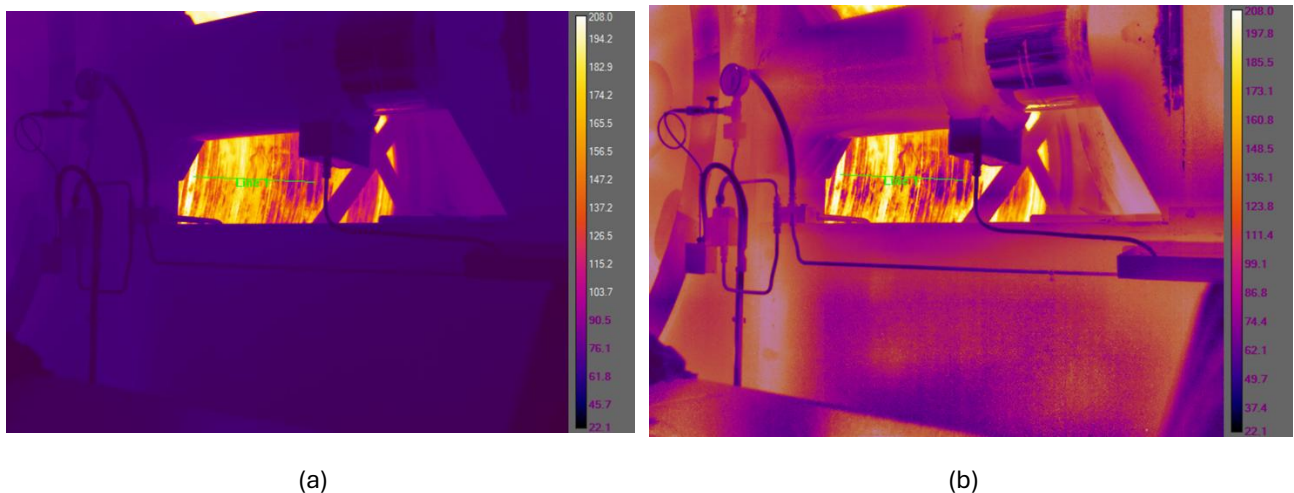


Figure 24: Frame 6119 of A6 at  $t = 122$  s. (a) PE scale and (b) APE scale

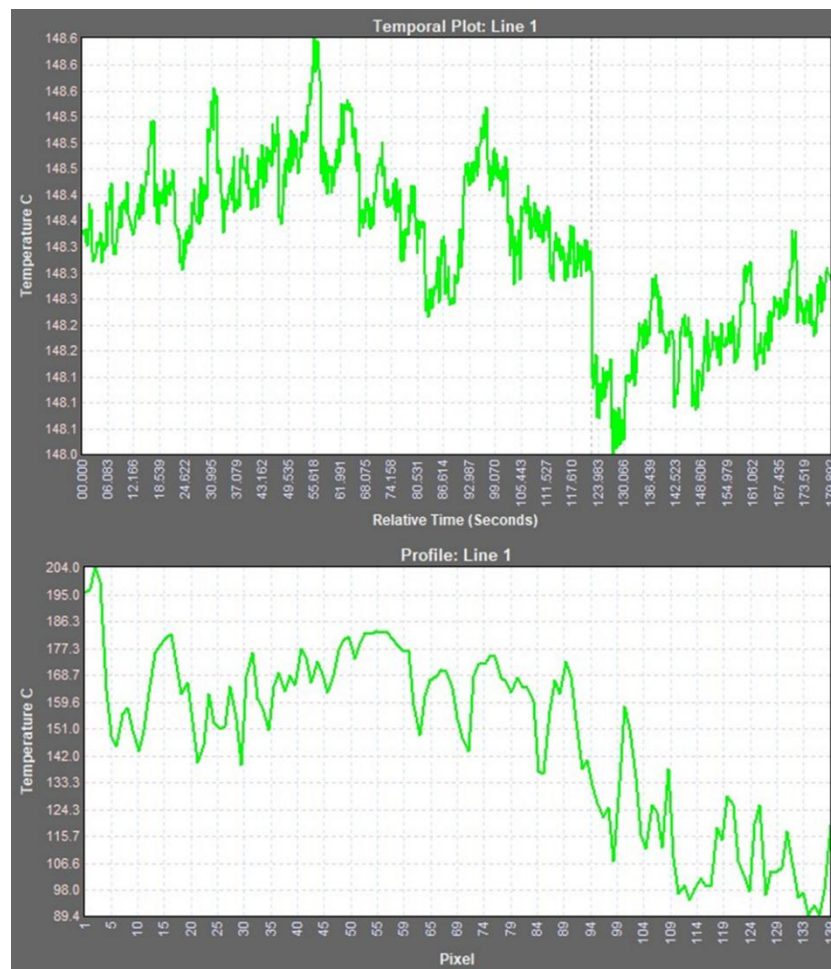


Figure 25: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 6119 in A6

### Acquisition A7

Acquisition A7 is similar to A6 but with lower frame rate. The same patterns are observed as in A6.

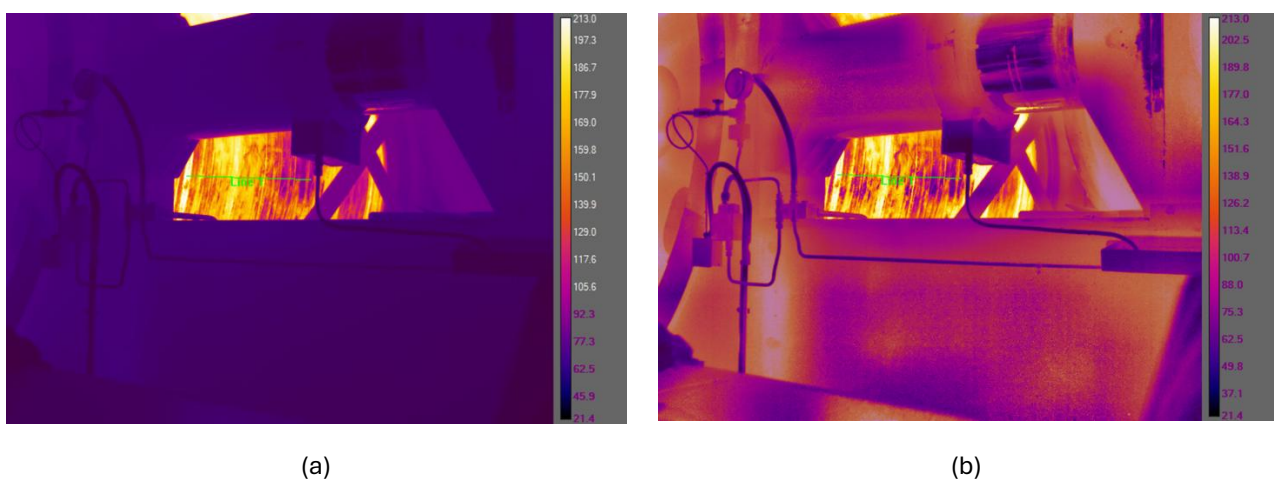


Figure 26: Frame 1948 of A7 at  $t = 78$  s. (a) PE scale and APE scale (b)

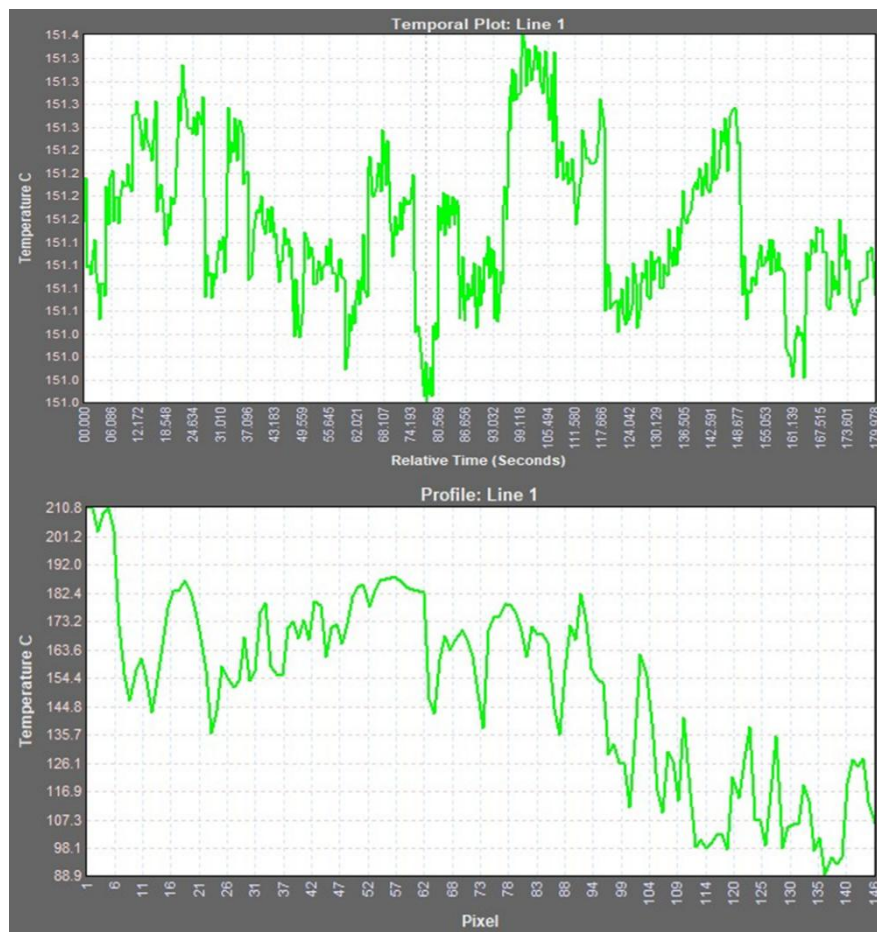


Figure 27. Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 1948 in A7

### 5.2.1 Brief observations from ARTIGO acquisitions

Based on the acquisitions that were carried out at ARTIGO under the current setup of the machinery the following observations- conclusions can be drawn.

- Thermal imaging of the main drum is possible. However, improving the accuracy of the readings require further camera calibration using emissivity and reflected temperature corrections which can be challenging due to health and safety implications for someone working in such proximity to hot surfaces.
- The acquisition showed that a potential area that could provide temperature reading of the drum is the side acquisitions A4 and 5 where the main drum exposed. On that strip of the main drum a high emissivity paint could be applied to reduce the reflections and the accuracy of the measured temperature. Such paints are available in spray or liquid format. This approach will require further consultation with ARTIGO and the manufacturer of the rotocure to ensure that such paint can be applied.
- Based on the suggested induction heating system that will be retrofitted on the rotocure and will be placed on the back plate of the rotocure, the camera could be positioned as performed in

acquisition A7 close to the surface of the back heating plate. This task will require the camera to be placed closer to the rotocure. Under this case, a thermal enclosure for the camera might be required.

### 5.3 K-FLEX thermal images and analysis

During CERTH's visit, all the main processing stations of K-FLEX's production line of the PERT II pipes were thermally imaged. However, the main area of interest is the induction coil machine that is used to activate the adhesive in the multilayer pipe. Although, this process was thermally imaged, under JOULIA project it will be replaced by a microwave heating process. Thus, the current images and visit is meant to be used to familiarise with the overall production and identify the aim of what the predictive maintenance platform will do in the case of K-FLEX. During this visit multiple acquisitions of the equipment were made, from different angles including both 45° and 15° degree lenses.

Due to confidentiality reasons only thermal images of the machinery can be provided. A large number of acquisitions were carried out during this visit, due to the amount of machinery involved, which required in some cases images to be take from different angles and distances. The most significant acquisitions are presented within this deliverable. Out of all of these acquisitions the most important in terms of relevance to the work that needs to be carried out are those showing the induction coil and the final product exiting the final extrusion.

| Acquisition #   | Description                                            | Settings <sup>10</sup> | # of frames recorded | Duration (s) | Lens size | Details                                                                                                                                                                                                     |
|-----------------|--------------------------------------------------------|------------------------|----------------------|--------------|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| K <sup>11</sup> | Acquisition of the 1 <sup>st</sup> extruder's die side | 50Hz, no skip          | 9001                 | 180          | 45°       | Acquisition of the 1 <sup>st</sup> extruder's die side where the inner pipe layer is extruded. Distance from target 1.40m. Ambient temperature 24.5 °C. Humidity 30%. Camera at 90 ° degree angle to target |

<sup>10</sup> Settings: refers to acquisition settings used in the software. No frame skip refers that no frames were skipped and the camera recorded 50 frames per second. A 5 to 1 frame skip refers to every 5 frames 1 is recorded. This way the file size is minimised when the process that is being observed does not happen very fast.

<sup>11</sup> K: for K-FLEX

| Acquisition # | Description                                                      | Settings <sup>10</sup> | # of frames recorded | Duration (s) | Lens size | Details                                                                                                                                                                                               |
|---------------|------------------------------------------------------------------|------------------------|----------------------|--------------|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| K2            | Acquisition of the 1st extruder's die front side                 | 50Hz, no skip          | 6001                 | 120          | 15°       | Acquisition of the 1st extruder's die front side where the inner pipe layer is extruded. Distance from target 1.97m. Ambient temperature 24.5 °C. Humidity 30%. Camera at 45 ° degree angle to target |
| K3            | Acquisition of the 1st extruder (left section)                   | 50Hz, no skip          | 9001                 | 180          | 45°       | Acquisition of the 1st extruder's left side where the inner pipe layer is extruded. Distance from target 1.2m. Ambient temperature 24.7 °C. Humidity 30%.                                             |
| K4            | Acquisition of the 1st extruder (right section)                  | 50Hz, no skip          | 9001                 | 180          | 45°       | Acquisition of the 1st extruder's left side that extrudes the inner pipe layer. Distance from target 1.2m. Ambient temperature 24.7 °C. Humidity 30%.                                                 |
| K5            | Acquisition of the 1st extruder entire side                      | 50Hz, no skip          | 9001                 | 180          | 45°       | Acquisition of the 1st extruder's left side for the inner pipe. Ambient temperature 24.7 °C. Humidity 30%.                                                                                            |
| K6            | Acquisition of gluing extruder's front side for inner pipe layer | 50Hz, no skip          | 9001                 | 120          | 15°       | Acquisition of the extruder that applies glue to the surface of the inner pipe layer. Distance from target 1.5 m. Ambient temperature 23.6 °C. Humidity 31%.                                          |

| Acquisition # | Description                                                      | Settings <sup>10</sup>  | # of frames recorded | Duration (s) | Lens size | Details                                                                                                                                                                                                                  |
|---------------|------------------------------------------------------------------|-------------------------|----------------------|--------------|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| K7            | Acquisition of gluing extruder's side for inner pipe layer       | 50Hz, 5 to 1 skip ratio | 501                  | 60           | 45°       | Acquisition of the extruder that applies glue to the surface of the inner pipe layer. Distance from target 2.4 m. Ambient temperature 23.6 °C. Humidity 31%.                                                             |
| K8            | Acquisition of gluing extruder's right side for inner pipe layer | 50Hz                    | 5942                 | 119          | 15°       | Acquisition of the extruder that applies glue to the surface of the inner pipe layer from its right side, where the pipe enters the gluing stage. Distance from target 1.2 m. Ambient temperature 23.6 °C. Humidity 31%. |
| K9            | TIG welding process, using high temperature camera calibration   | 50Hz                    | 3001                 | 60           | 15°       | Acquisition of the welding process using a high temperature calibration 300- 2000 °C focusing on the welding torch and electrical spark. Distance to target 1.1m. Ambient temperature 23.6 °C. Humidity 31%.             |

| Acquisition # | Description                                                      | Settings <sup>10</sup> | # of frames recorded | Duration (s) | Lens size | Details                                                                                                                                                                                                               |
|---------------|------------------------------------------------------------------|------------------------|----------------------|--------------|-----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| K10           | TIG welding process, using medium temperature camera calibration | 50Hz                   | 3001                 | 60           | 15°       | Acquisition of the welding process using a medium temperature calibration 100- 650 °C focusing on the welding torch and electrical spark. Distance to target 1.1m. Ambient temperature 23.6 °C. Humidity 31%.         |
| K11           | TIG welding process, using medium temperature camera calibration | 50Hz                   | 3001                 | 60           | 45°       | Same acquisition as K9 and K10 but with 45° lens using a medium temperature calibration 100- 650 °C focusing on wider FOV of the welding process. Distance to target 1.1m. Ambient temperature 23.4 °C. Humidity 31%. |
| K12           | Post welding inspection station                                  | 50Hz                   | 6001                 | 120          | 15°       | Acquisition at the eddy current welding seem inspection station. Distance to target 0.66m. Ambient temperature 23.4 °C. Humidity 31%.                                                                                 |
| K13           | Induction coil                                                   | 50Hz                   | 3001                 | 60           | 45°       | Acquisition of the induction coil that is used to activate the adhesion between the inner pipe layer and the aluminium core. Distance to target 0.91m. Ambient temperature 23.4 °C. Humidity 31%.                     |

| Acquisition # | Description                                          | Settings <sup>10</sup> | # of frames recorded | Duration (s) | Lens size | Details                                                                                                                                                                                              |
|---------------|------------------------------------------------------|------------------------|----------------------|--------------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| K14           | Induction coil                                       | 50Hz                   | 3001                 | 60           | 45°       | Acquisition of the induction coil. Small adjustment of camera angle. Distance to target 0.91m. Ambient temperature 23.4 °C. Humidity 31%.                                                            |
| K15           | 2 <sup>nd</sup> extruder right side                  | 50Hz                   | 6001                 | 120          | 15°       | Acquisition of the 2 <sup>nd</sup> extruder's right side where the top pipe layer is extruded around the core. Distance to target 1.6m. Ambient temperature 23.4 °C. Humidity 31%.                   |
| K16           | 2 <sup>nd</sup> extruder left side                   | 50Hz                   | 6001                 | 120          | 15°       | Acquisition of the 2 <sup>nd</sup> extruder's left side where the top pipe layer is extruded around the core. Distance to target 1.6m. Ambient temperature 23.4 °C. Humidity 31%.                    |
| K17           | Top layer pipe after 2 <sup>nd</sup> extruder's head | 50Hz                   | 6001                 | 120          | 15°       | Acquisition of the top layer pipe after it has exited the 2 <sup>nd</sup> extruder's head. The camera is placed above the pipe. Distance to target 0.9 m. Ambient temperature 23.4 °C. Humidity 31%. |

### **Acquisition K1**

Acquisition K1 captured the 1<sup>st</sup> extruder die that creates the shape of the inner pipe layer. No significant findings were observed in this acquisition. The camera was placed at 90 ° degrees relative to the surface

of the extruder die. The aim was to observe any potential anomalies on the surface of the die. In addition, a box ROI was drawn on the plastic pipe that comes out of the die to see if there are significant temperature deviations in the material that could indicate non uniform heating during the extraction process. A temporal graph of is provided on Figure 29. The max range of this deviation is 0.68 °C. The PE scale highlights a lot better the foreground where the equipment is located. It needs to be noted that the pipe moves from right to left direction in all acquisitions.

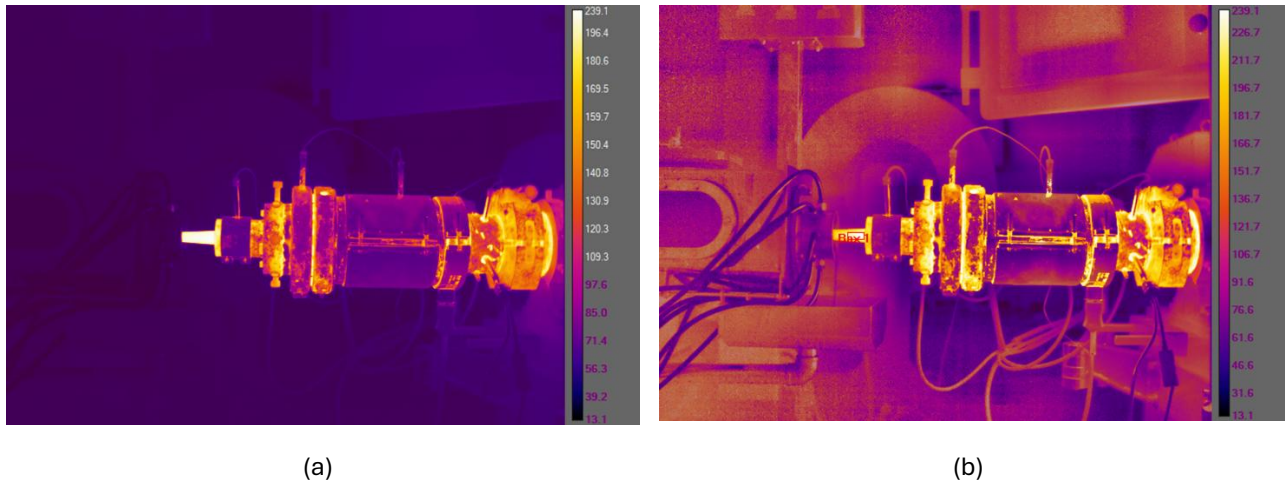


Figure 28: Frame 5765 of K1 at  $t = 115.5$  s. (a) PE scale and APE scale (b) from the 1<sup>st</sup> extruder die side

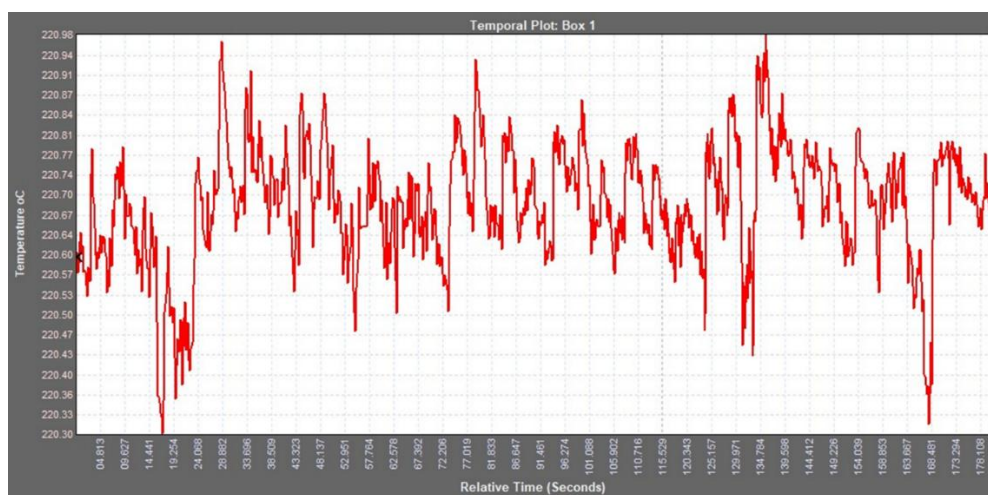


Figure 29: Temporal  $\Delta T$  diagram for the inner pipe coming out of the 1<sup>st</sup> extruder die side

### Acquisition K2

Acquisition K2 captured the front side of the 1<sup>st</sup> extruder that is used for the inner pipe layer. Similar to K1 no significant observations are captured during this acquisition. The difference in this acquisition is that a 15° lens was used to provide more details on the thermal gradients across the extruder side.

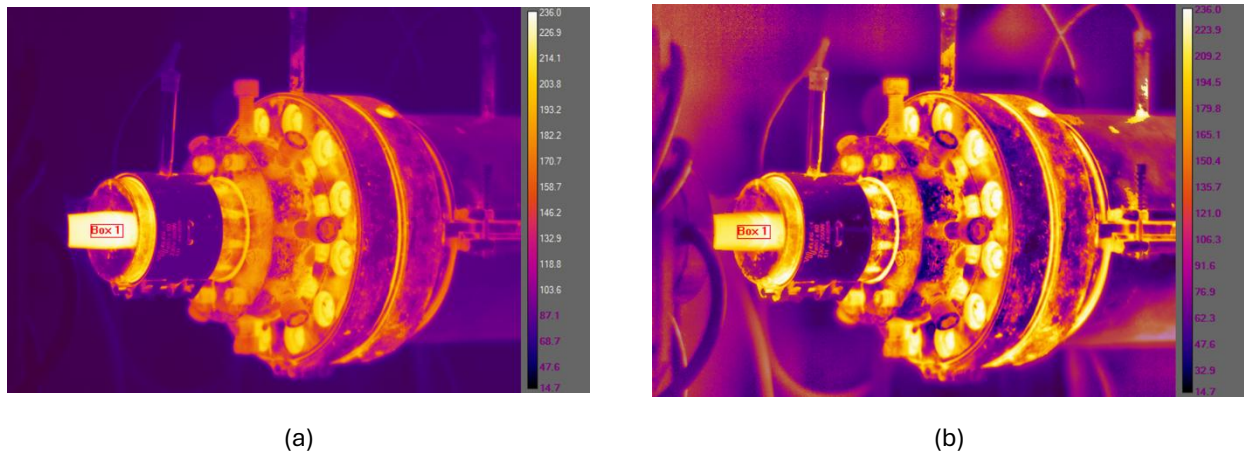


Figure 30: Frame 2839 of K1 at  $t = 56.7$  s. (a) PE scale and APE scale (b) from the 1st extruder die front

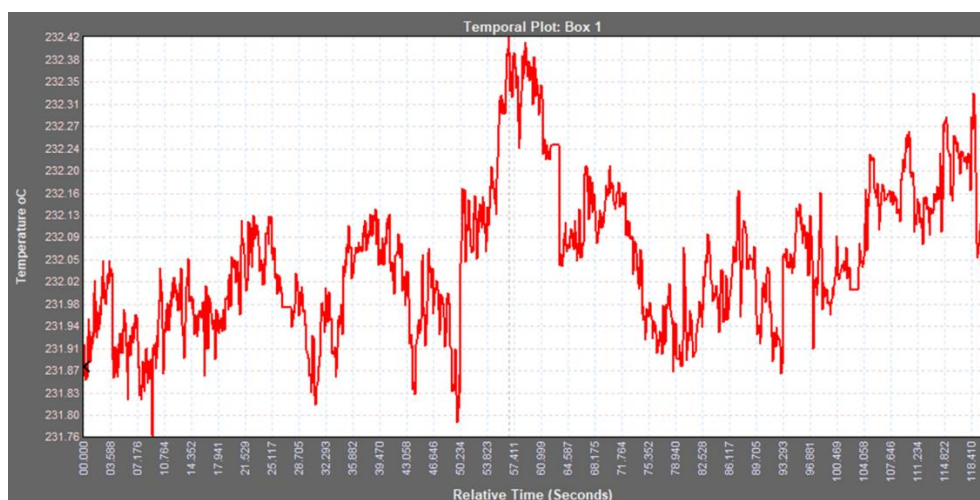


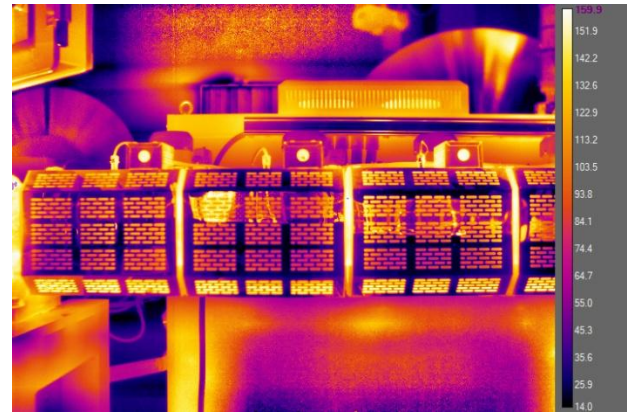
Figure 31: Temporal  $\Delta T$  diagram for the inner pipe coming out of the 1st extruder die front

### Acquisition K3 & K4

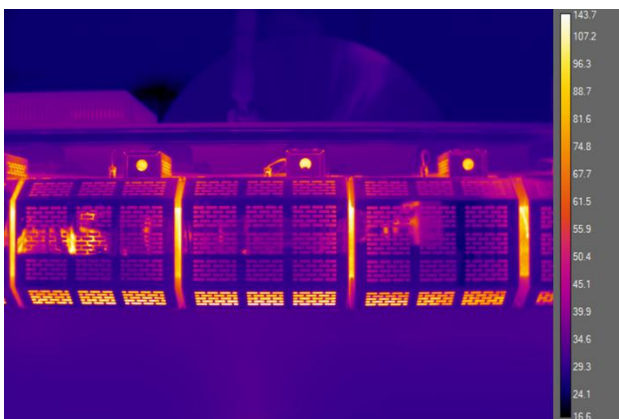
Acquisition K3 and K4 capture the side of the extruder aiming at its left and right section since it could not be captured in a single FOV from a  $90^\circ$  degree angle. The side of the extruder is covered with polished stainless-steel grills making it difficult to see any internal temperature anomalies. For this reason, both sides are presented in this section in Figure 32. It needs to be noted that the stainless steel surface creates reflections that are visible on the left side of the images and appear as hot spots. These reflections are from another production line's extruder that is next to the one that was imaged, including the thermal camera itself.



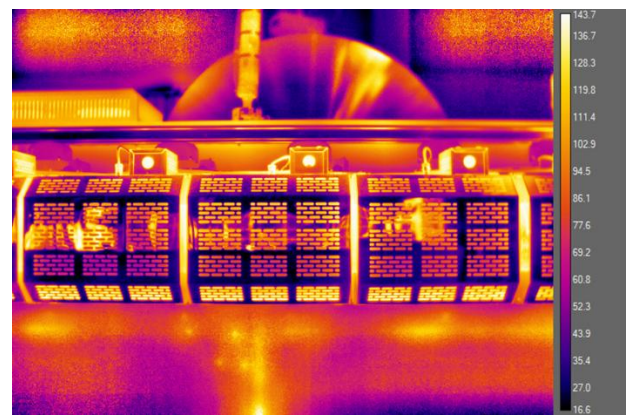
(a)



(b)



(c)

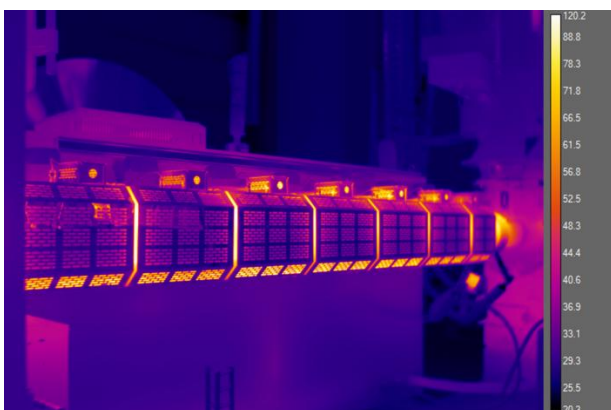


(d)

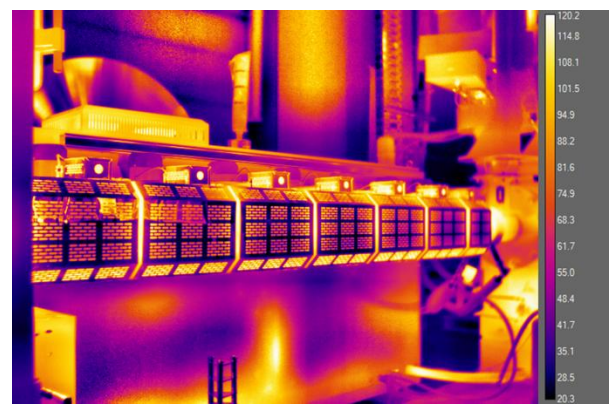
Figure 32: Frame 2325 of K3 at  $t = 46.8$  s. (a) PE scale and APE scale (b) from the 1st extruder left section and frame 2325 of K4 at  $t = 46.8$  s. (c) PE scale and APE scale (d) from the 1st extruder right section

### Acquisition K5

Acquisition K5 shows the 1<sup>st</sup> extruder's entire side. No abnormal thermal gradients are detected.



(a)



(b)

Figure 33: Frame 2325 of K5 at  $t = 46.8$  s. (a) PE scale and APE scale (b) showing the entire side of the 1<sup>st</sup> extruder

### Acquisition K6

Acquisition K6 shows the part of the extruder where the glue is applied on the inner pipe layer. Two cursor<sup>12</sup> ROIs were drawn on the glue residue around the pipe. The resulting temporal plots are shown on Figure 35. Another ROI was drawn on the inner pipe with the applied glue as it exits the head of the extruder shown in Figure 36. The dark sections on the surface of the extruder's head are burnt glue residues that cause different thermal gradients.

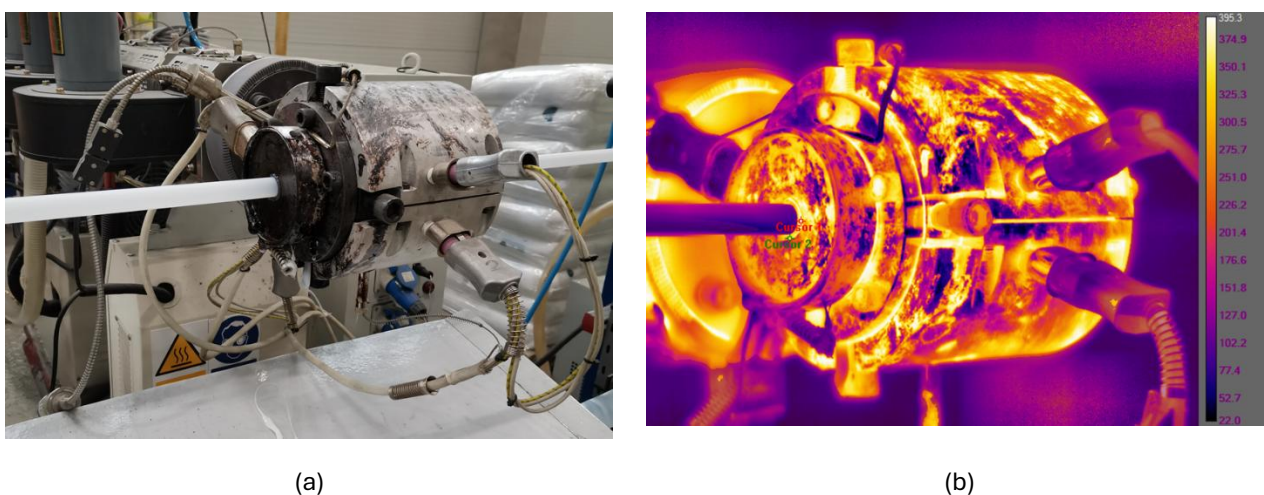


Figure 34: Glue application on inner pipe layer (a), frame 1632 of K6 at  $t = 32.5$  s on APE scale (b)

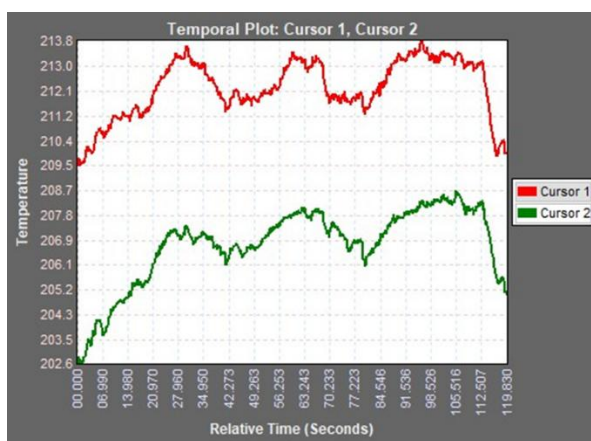


Figure 35: Temporal  $\Delta T$  diagram from the 2 ROIs on the glue residue. Cursor 1 located on right side of the pipe and cursor 2 on bottom.

<sup>12</sup> Cursor ROI in FLIR ResearchIR Max software is 3x3 pixel ROI

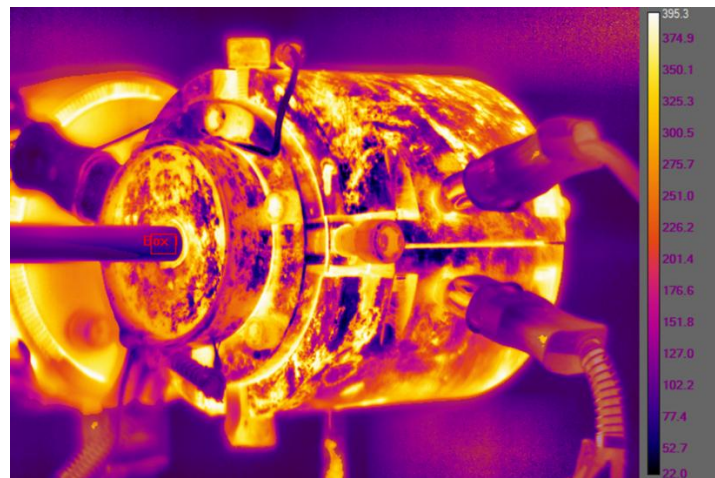


Figure 36: Glue application on inner pipe layer, frame 1632 of K6 at  $t = 32.5s$  on APE scale

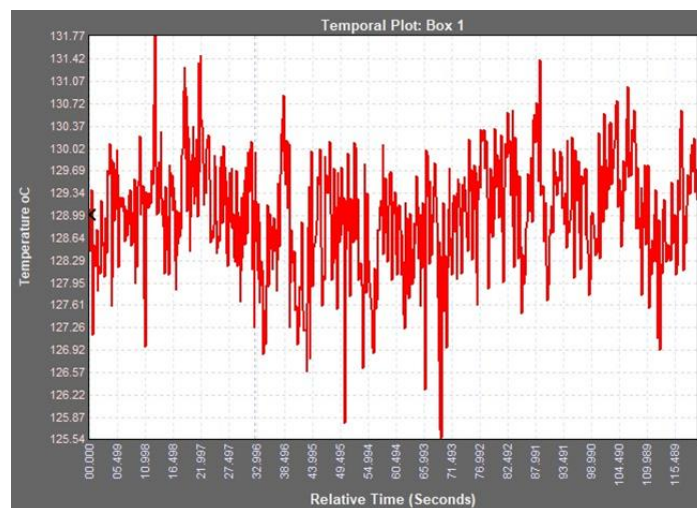


Figure 37: Temporal  $\Delta T$  diagram from the box ROI on the inner pipe with the applied glue

### Acquisition K7

Acquisition K7 shows the side of the same equipment captured in K7 from its side. This acquisition was performed to see if any different thermal gradients could be captured from using the 45° lense. The PE scale is only presented in Figure 38 because it helps to isolate more the background equipment that seem to be revealed a lot in the APE scale creating more clutter to the image.

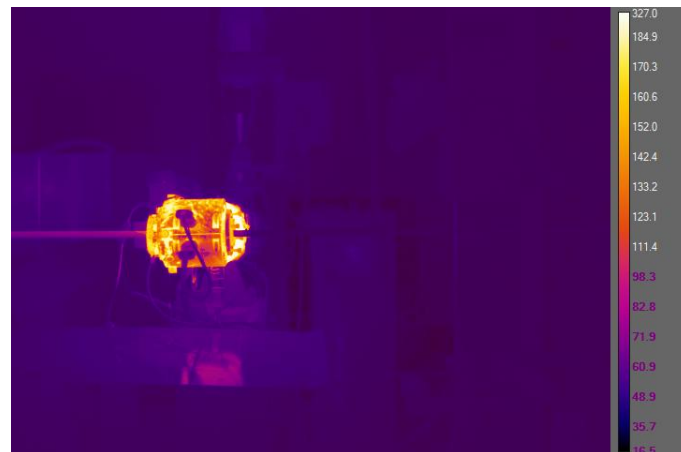


Figure 38: Glue application on inner pipe layer, frame 76 of K7 at  $t= 6s$  on PE scale

### Acquisition K8

Acquisition K8 captures the right side of the gluing extruder as the inner pipe layer enters the die in order for the glue to be applied. This acquisition's purpose was to see if any defects on the inner layer pipe can be captured before the application of the glue. In retrospect, the pipe has already passed through a water cooling stage after it exits the 1<sup>st</sup> extruder, making any potential hot spots not detectable or at least less colder.

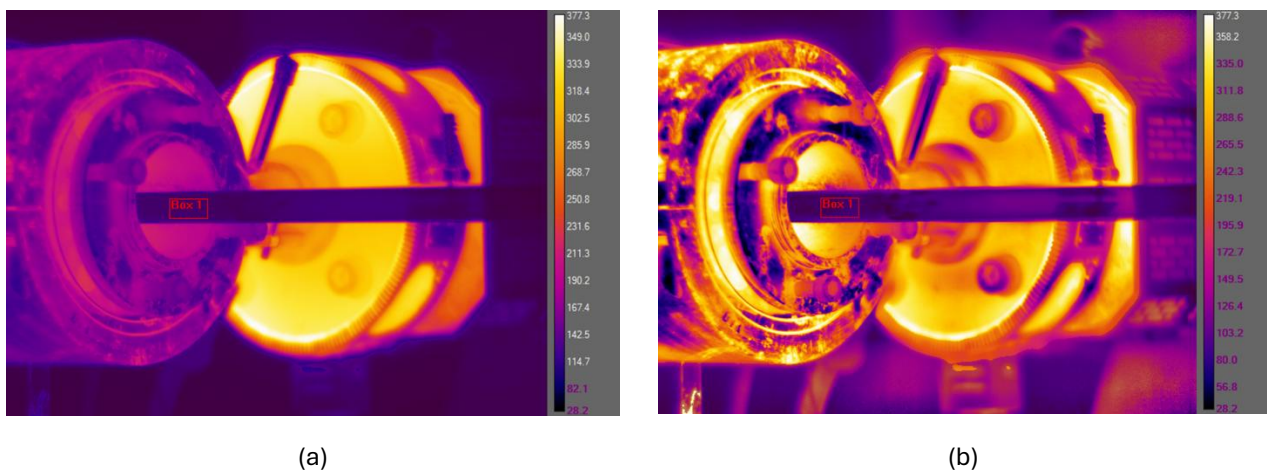


Figure 39: Frame 4252 of K8 at  $t= 86.5 s$ . (a) PE scale and APE scale (b) showing the right side of the gluing extruder as the inner layer pipe enter so glue can be applied

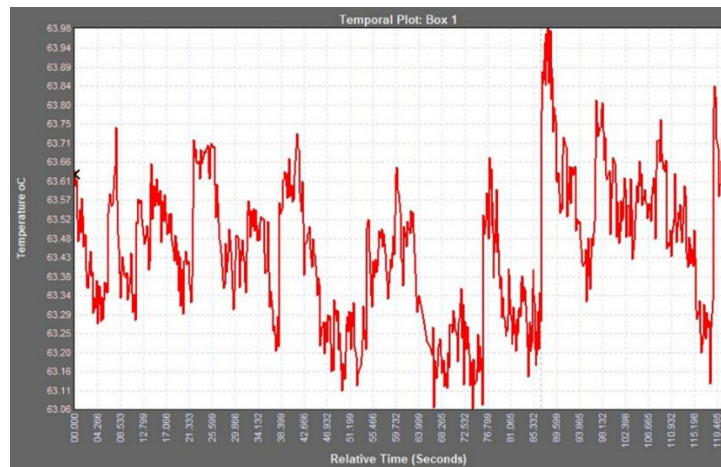


Figure 40: Temporal  $\Delta T$  diagram for the inner pipe layer entering the glueing application

### Acquisition K9

Acquisition K9 captured the welding process of the aluminium layer that has been rolled into a cylindrical shape around the inner pipe layer. This acquisition mostly focused on the part of the welding torch and the electric spark. It needs to be noted that this acquisition creates certain challenges because it incorporates temperature ranges that are covered by different temperature camera calibrations. Specifically, only high temperature calibrated cameras can see the temperature range that are available in this case. Hence, a 300- 2000 ° C calibration was used. This also created other issues because lower temperatures are not visible hence why Figure 41 is mostly dark.



(a)



(b)

Figure 41: Frame 640 of K9 at  $t= 12.5$  s on PE scale without ROI (a) and with ROI (b) showing the TIG welding process

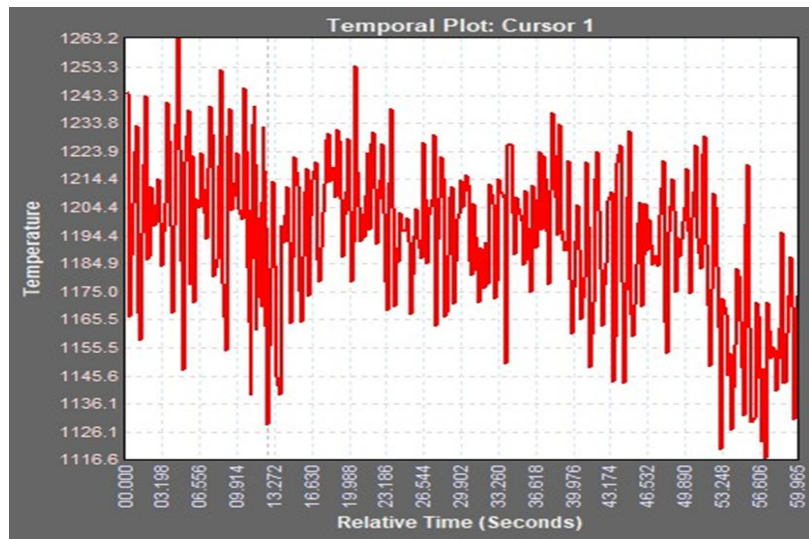


Figure 42: Temporal  $\Delta T$  diagram of the of the electrical arc from the TIG welding process

### Acquisition K10

Acquisition K10 is similar to K9 with the main difference of having a different temperature calibration profile of the camera at 100- 650 ° C in order to focus more on the lower temperature ranges of the weld and the pipe. In this analysis, the ROI has been placed next to the electric spark at the butt weld. This time due to the different calibration, the APE scale provides the outline of the thermal signature of the equipment.

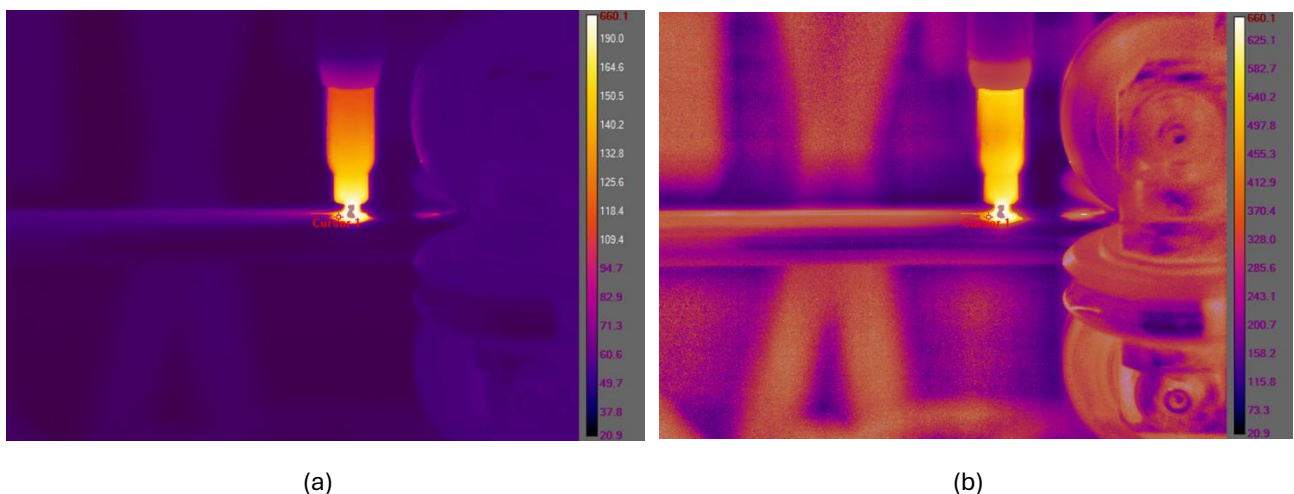


Figure 43: Frame 640 of K10 at  $t= 12.5$  s on PE scale (a) and APE scale (b) showing the TIG welding process

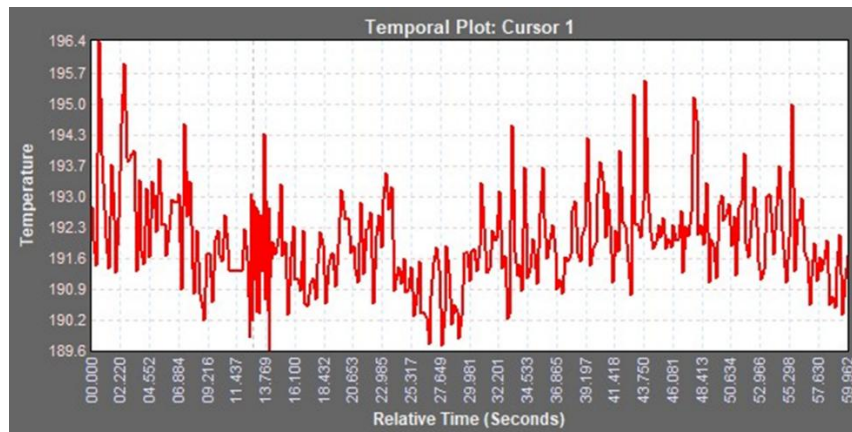


Figure 44: Temporal  $\Delta T$  diagram of the of the butt weld from the TIG welding process

### Acquisition K11

Acquisition K11 is the same as K9 and 10 with the difference of using a 45° lens. No significant difference is observed. The main conclusion from this acquisition is that for the welding processes a close up lens (15°) is more useful when monitoring the weld itself is of interest rather than the machinery. In addition, closer distances to those should have been used.

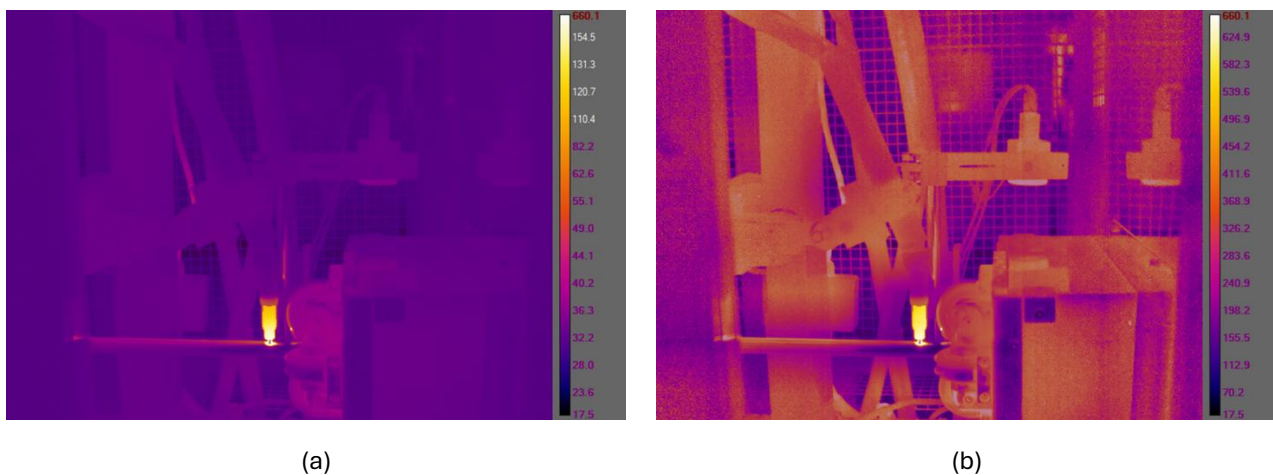


Figure 45: Frame 640 of K11 at  $t= 12.5$  s on PE scale (a) and APE scale (b) showing the TIG welding process

### Acquisition K12

Acquisition K12 captures the pipe after the aluminium cover has been welded and after it has past the eddy current device that is used for quality control of the weld seams. It needs to be noted, that during the acquisition no defects were recorded by the production line's quality control. A line ROI (Figure 46 a) was drawn in the middle of the seam line to check whether any significant temperature deviations in time can be detected. No significant deviations were recorded (Figure 47).

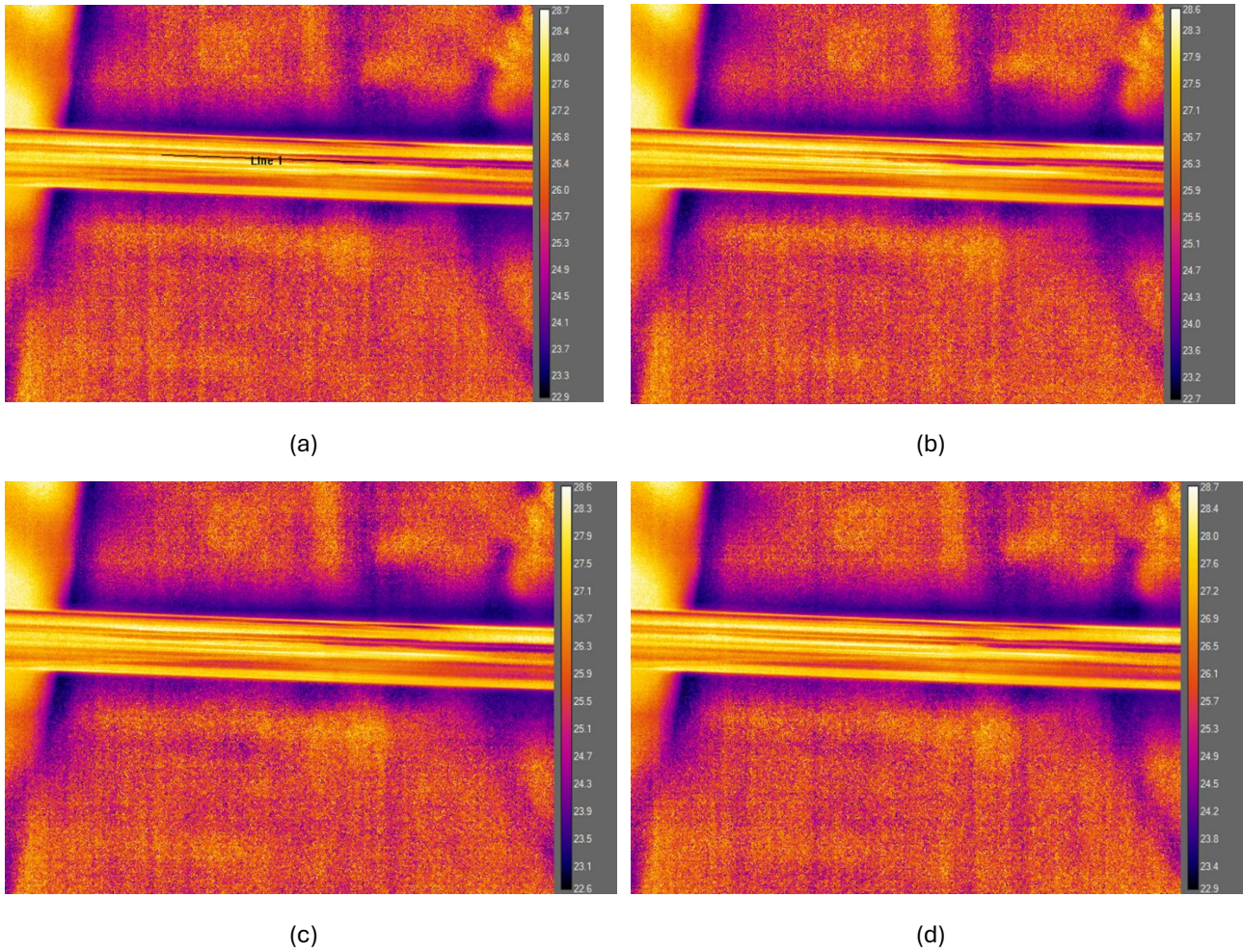


Figure 46: Different frame of K12, frame 530 (a), 2175 (b), 2247(c), 3935 (d) on APE scale following eddy current inspection

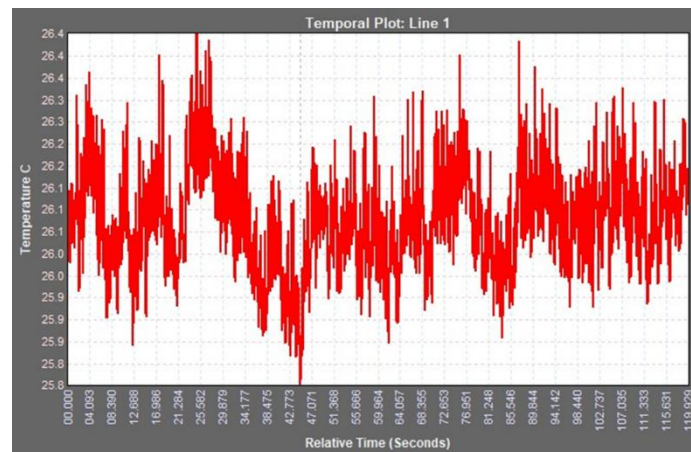


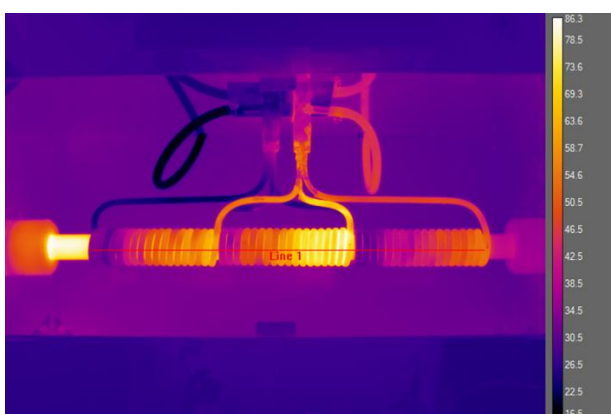
Figure 47: Temporal  $\Delta T$  diagram of line ROI on the seem of the butt weld

### Acquisition K13

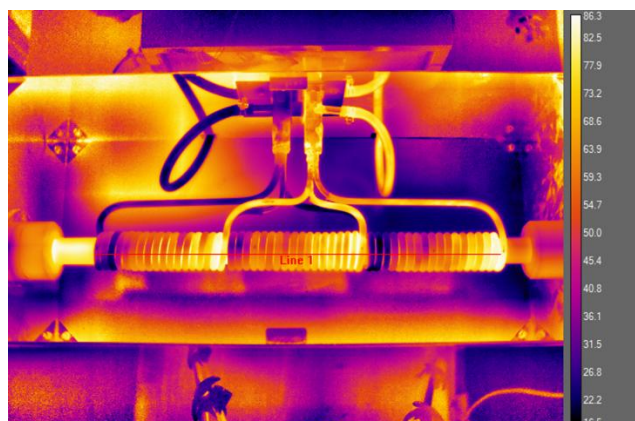
Acquisition K13 captures the induction coil machine that activates adhesion of the lower pipe layer to the aluminium core. This acquisition required to lift the acrylic lid that covers the coil (Figure 48). Hence, the duration of the acquisition could only be short (60s). A line ROI was drawn on the coil to capture the variation of the mean temperature across the coil. The thermal images (Figure 49), and profile plot (Figure 50) show that the temperature across the coil are not uniform. These non-uniformities are also not attributed to the burnt areas of the coil's sleeve. The continuous dip and peaks in the profile plot of Figure 50 are attributed to the shape of the coil itself, since there are small gaps in between. In addition, despite the fact of the non-uniform heat of the coil, the temporal plot shows that the mean temperature across the ROI does not vary significantly which means that the process control is normal. Another larger ROI was also drawn (not provided here) showing the same temperature curve. This finding was also validated with K-FLEX maintenance department.



Figure 48: Induction coil



(a)



(b)

Figure 49: Frame 2427 of K13 at  $t = 48.5$  s on PE scale (a) and APE scale (b) showing the induction coil

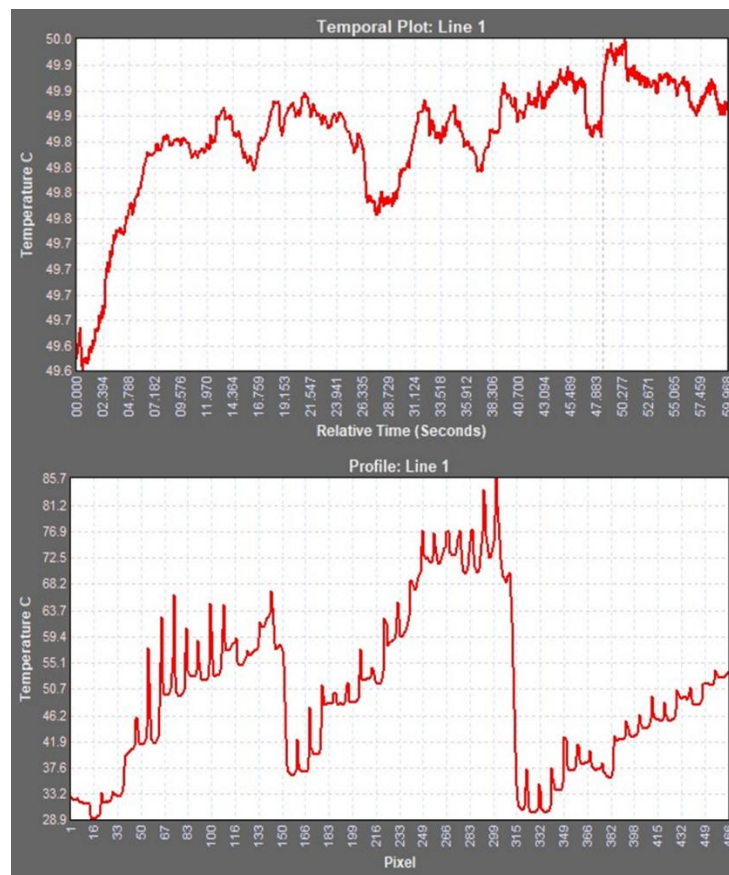


Figure 50: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 2467 in K13

### Acquisition K14

Acquisition K14 is almost identical to K13 in terms of setup with the difference that the camera was repositioned. As expected the images are identical with the only difference that the mean temperature fluctuations are different in this acquisition. The profile plot also shows the same temperature variations and range across the coil.

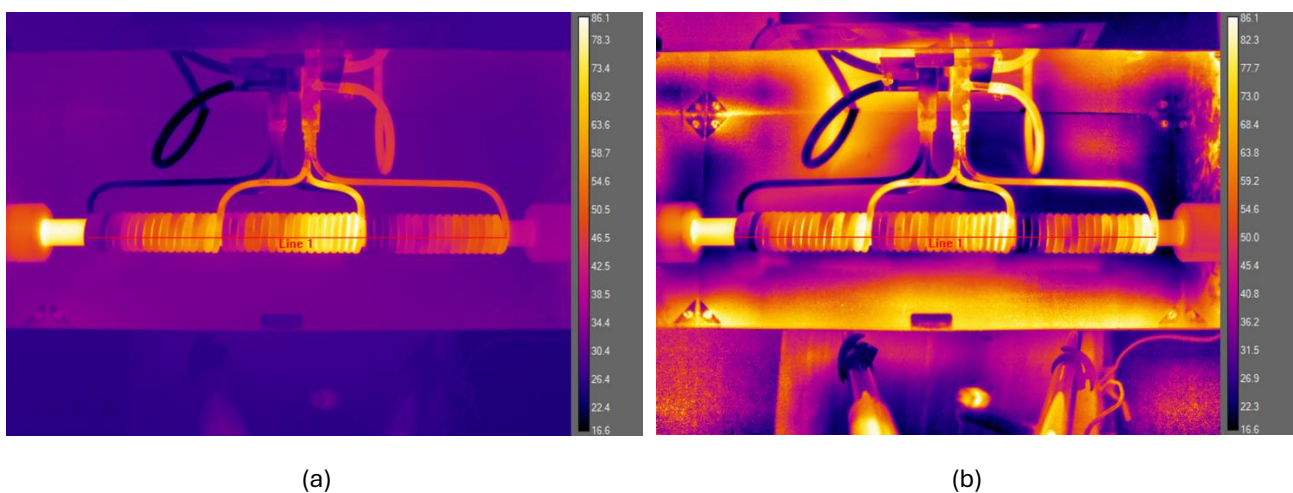


Figure 51: Frame 583 of K14 at  $t= 11.3s$  on PE scale (a) and APE scale (b) showing the induction coil

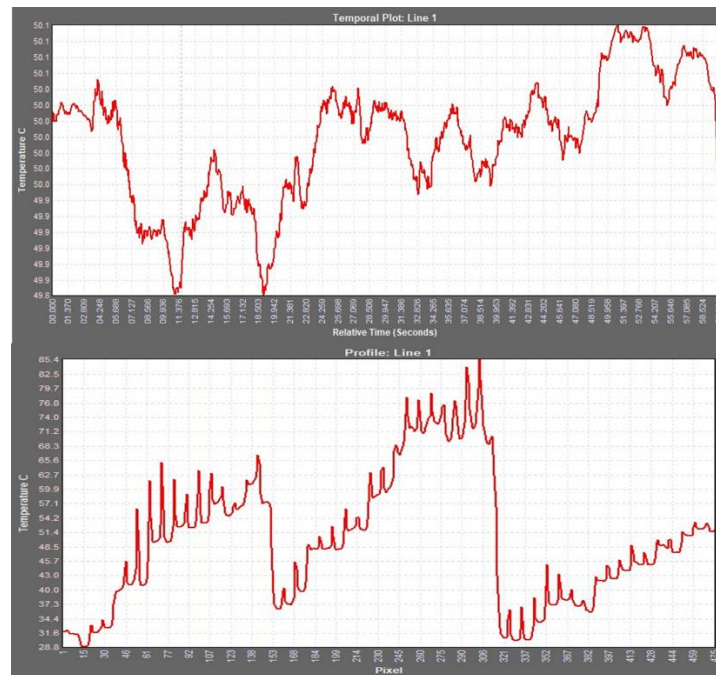


Figure 52: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 583 in K14

### Acquisition K15

Acquisition K15 captured the right side of the 2<sup>nd</sup> extruder die head where the inner layer pipe covered with the aluminium core enter from the right side of the head and are covered with the top layer as they exit on the left side. This station is located after the induction coil. In this case an acquisition was taken to check the thermal image of the die head and the pipe. The oval shaped hot spots on the die head are due to the paint cover that has faded on the top and bottom surfaces. A box ROI was drawn on the pipe as it exits the die head to see any mean temperature variations (see Figure 54).

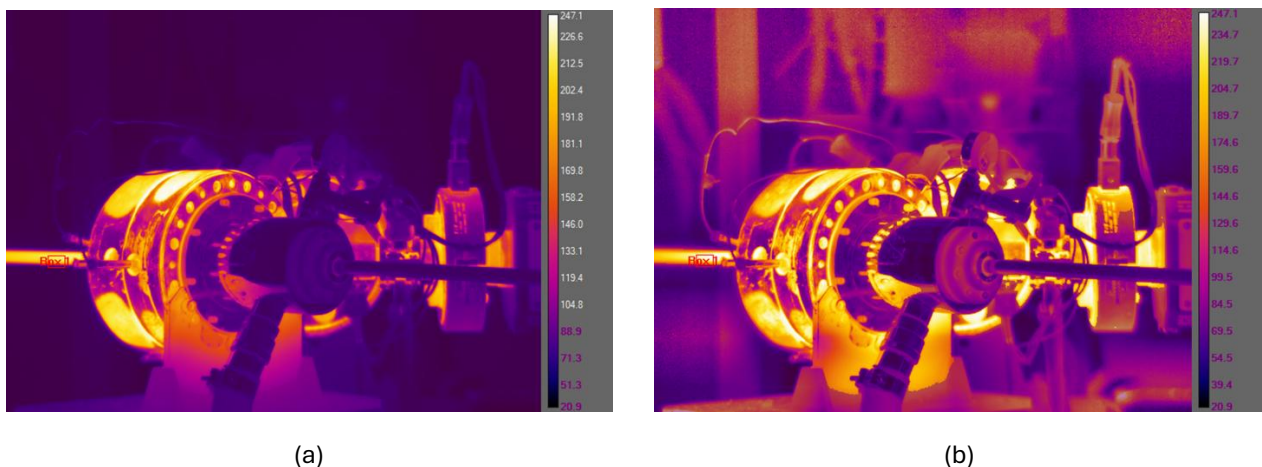


Figure 53: Frame 2701 of K15 at  $t= 54s$  on PE scale (a) and APE scale (b) showing the right side of the 2<sup>nd</sup> extruder

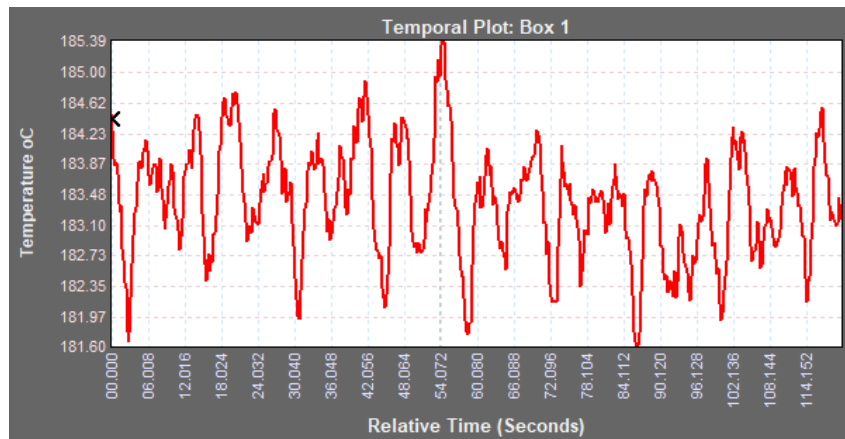


Figure 54: Temporal  $\Delta T$  diagram of the of the box ROI on the outer layer as it exits the die head

### Acquisition K16

Acquisition K16 captured the left side of the 2<sup>nd</sup> extruder die head. This acquisition did not provide any different results. However, it allows to capture the die head's left side that is more significant since it is the section where the extrusion occurs and the outer pipe layer is applied. No significant mean temperature variations have been captured on the  $\Delta T$  diagram (Figure 56) on the product itself as it exits the die.

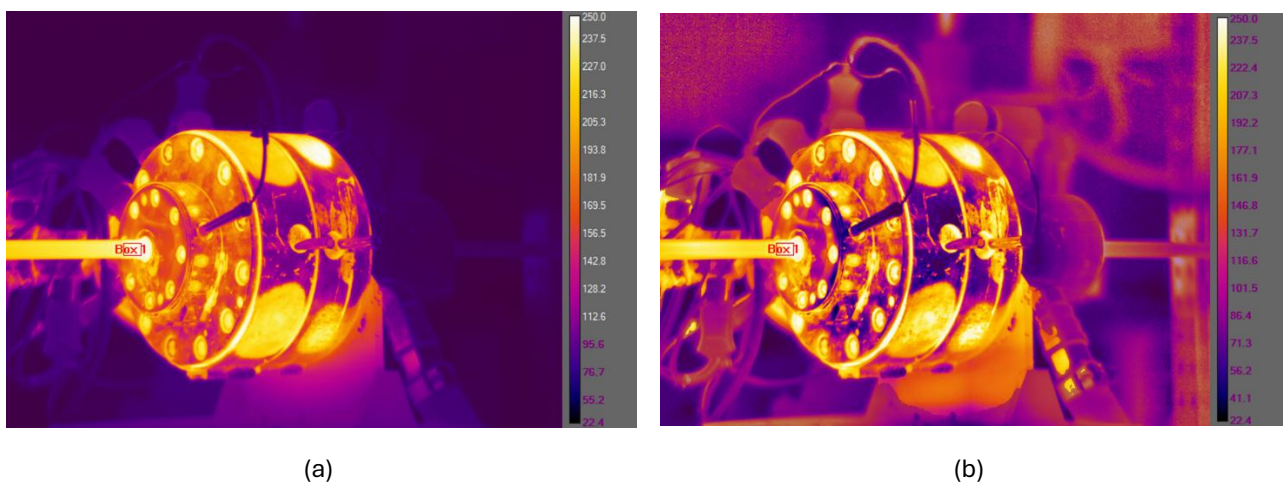


Figure 55: Frame 2604 of K16 at t= 52s on PE scale (a) and APE scale (b) showing the right side of the 2nd extruder

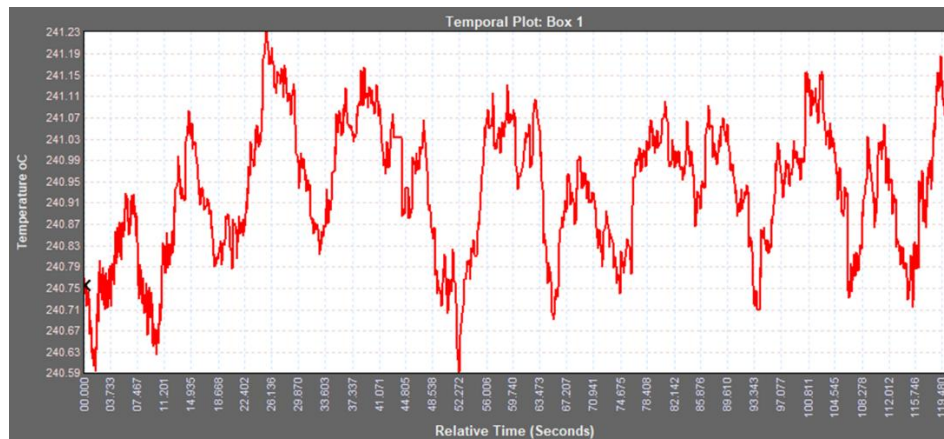


Figure 56: Temporal  $\Delta T$  diagram of the of the box ROI on the outer layer as it exits the die head from the left side

### Acquisition K17

Acquisition K17 captures the outer layer of the pipe from its top side after it has been extruded. This acquisition was carried out after the 2<sup>nd</sup> extruder's head from K16. The thermal images show the line ROI that was drawn on the surface of the pipe (Figure 57a). In Figure 57 the butt weld on the aluminium core creates this worm like line on the outer layer of the pipe that has just been extruded around the core. This line (visible only in the IR spectrum) disappears after the pipe has cooled down. The profile plot of the pipe in Figure 58, shows that the right side of the pipe is hotter due to its proximity to the extruder while the left side becomes colder as the pipe moves towards the last parts of the production line where cooling and winding into coils occurs.

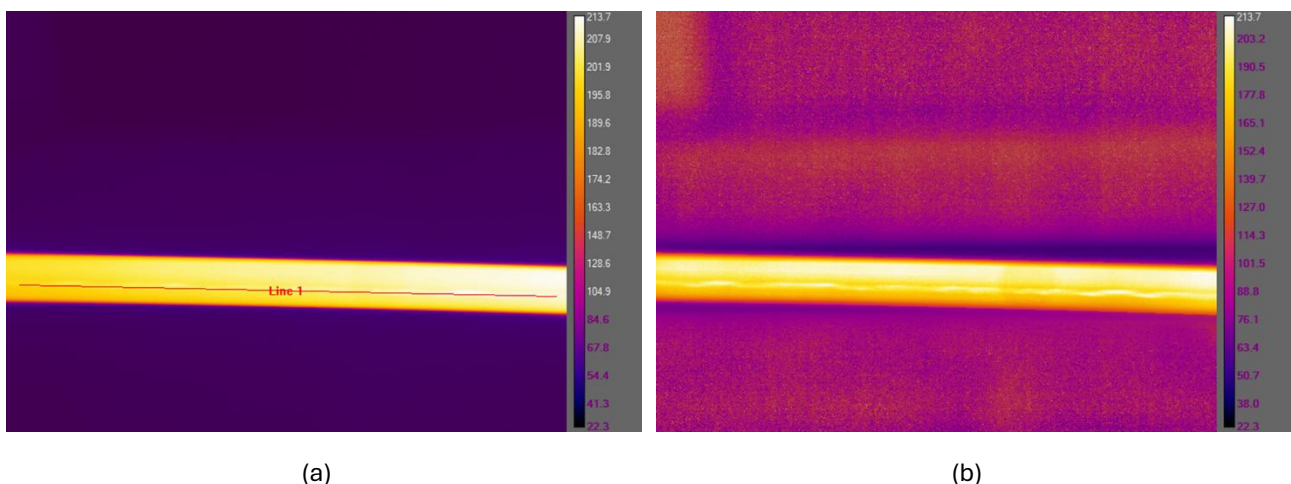


Figure 57: Frame 1658 of K17 at t= 32.8s on PE scale (a) and APE scale (b) showing the top layer pipe's surface

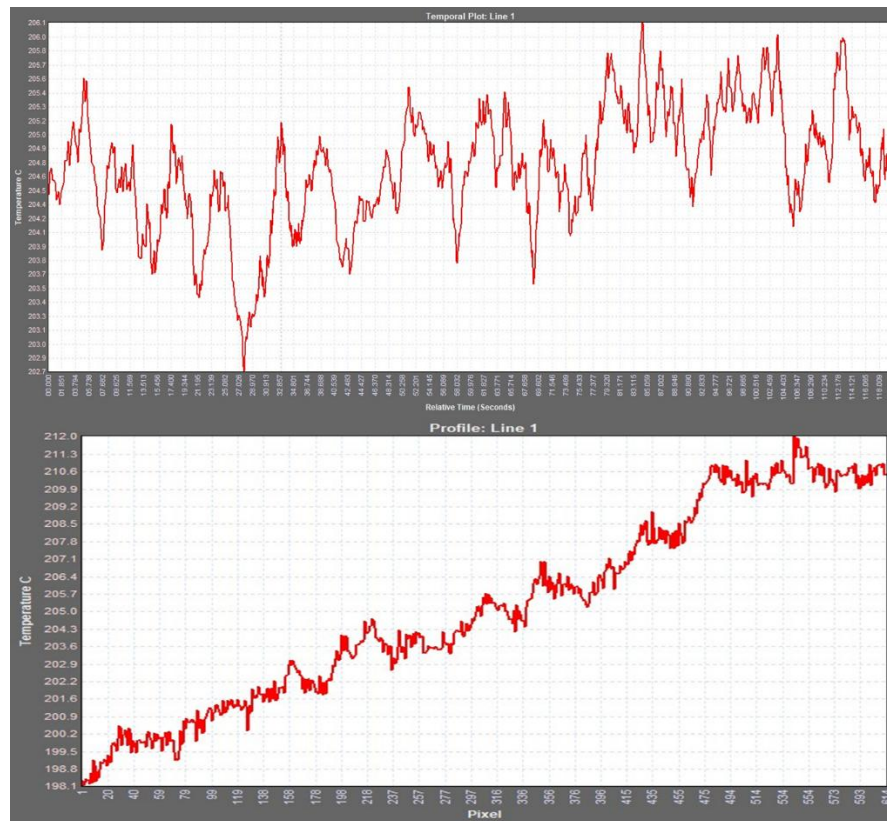


Figure 58: Temporal  $\Delta T$  diagram (top) and profile plot (bottom) for frame 1658 in K17

### 5.3.1 Brief observations from K-FLEX acquisitions

- The acquisitions on K-FLEX's PERT II pipe production line show that thermal imaging of the different parts of the production is feasible. The main area of interest at the moment was the induction coil and the product as it exits the final extruders or after the induction coil itself.
- However, with the introduction of the microwave system the main areas of interest would be to image the pipe as it exits the station including after the final extrusion of the upper pipe layer.

## 6. Proposed preliminary approach for the predictive maintenance platform

The key aim of the approach that will be used is to deliver a methodology for a predictive maintenance tool that can monitor key parameters of the heating systems and provide an early warning system of abnormal behaviour of the machinery. This approach will use passive infrared thermography as a monitoring mechanism of the products and or parts of the machinery.

To fulfil this task, as demonstrated in the previous sections, thermal images have already been collected from different locations of ARTIGO's and K-FLEX's production lines. These thermograms will be treated as images and ground-truth. CERTH will develop and validate an AI pipeline that first removes reflection-like artifacts from the thermograms. In addition, new thermal acquisitions, that will be carried out in the next project phase from ARTIGO and K-FLEX, will be used to evaluate if they significantly differ from trusted ground-truth thermograms. The goal is not to enhance images for appearance but to improve reliability downstream while maintaining thermal structure, hotspot shape, and value for operational decisions. A two-stage approach is suggested and described below.

In operational deployment, these techniques constitute stages of a processing pipeline. The first stage applies removal of reflections preprocessing, where the models are compared on laboratory-created thermograms with controlled reflection scenarios against clean reference images. The best-performing model is selected based on structural similarity and thermal fidelity. The second stage addresses anomaly detection, in which the captured, normally operating, industry thermograms are encoded into visual embeddings and used to build a normality model. This way, each new thermogram can be compared to the baseline and classified as normal, faulty, or outlier, based on its deviation from the learned distribution.

### **Stage1: Reflection-removal preprocessing**

**Input repository:** Laboratory thermograms with controlled reflection/artifact scenarios and clean or accepted reference thermograms will be created. Additionally, existing thermograms that were presented in this deliverable as well as new acquisitions from ARTIGO and K-FLEX will be used and combined with other sample images.

**Proposed candidate models that can be applied:** XReflection/RDNet (or equivalent) is suggested as the dedicated SIRR toolbox (Wan et al., 2017) while dereflection any image (DAI) or equivalent models will be applied for diffusion-prior dereflection (Wan et al, 2017; Yang et al. (2025); XReflection, 2025). A transformer-based visual restoration model will be used for a baseline comparison.

**Why compare dereflected images:** Single-image reflection removal is an ill-posed image-restoration task. Current literature emphasizes real-world gaps, dataset dependence, and the need for benchmark metrics.

A systematic review by Amanlou et al. (2022) confirmed that current approaches are benchmarked using SSIM, PSNR and perceptual metrics on controlled datasets with ground truth, and identifying dataset

dependence and real-world generalisation as key open challenges. It is noted that these SIRR methods originate primarily from the visible-light domain; their adaptation to thermal infrared imagery, where the radiometric model differs fundamentally from optical reflections, is an active area of investigation within this project.

**Outputs:** For each thermogram, a cleaned image, an artifact/residual map (where available), and metadata containing processing model, parameters, and version will be generated.

**Selection metrics.** Quality metrics such as PSNR<sup>13</sup>, SSIM<sup>14</sup>, LPIPS<sup>15</sup>, MAE/RMSE<sup>16</sup>, hotspot temperature-delta preservation, edge/shape preservation, and no-false-change behavior are some indicative inference metrics that will be applied (Dosovitskiy et al. 2020; Oquab et al. 2023; Fanchiang et al. 2022). This approach will become the standard preprocessing step for future inference thermograms.

## **Stage 2 - Similarity and anomaly detection**

**Ground truth base:** Thermograms collected from the aforementioned sources, under normal or accepted operating states, will be treated as ground-truth. These will be grouped according to machinery, camera, distance, emissivity settings, and operating conditions.

**Embedding models:** Vision Transformer (ViT) (Dosovitskiy et al. 2020) and DINOv2 (Oquab et al. 2023) will encode pre-processed thermograms into robust visual embeddings. The latter will allow to find similar images and thermal patterns as well as to cluster relevant data.

**Generative baseline:** Variational autoencoders (VAEs) will be used to learn the thermal distribution of normal thermograms. A resulting high reconstruction error or low latent likelihood will indicate a potential anomaly in the thermogram. Fanchiang et al. (2022) demonstrated this approach on power transformer thermograms, where a VAE-based generative adversarial network trained exclusively on normal-state thermal images produced pixel-wise residual maps that effectively localised overheating faults, achieving improved anomaly accuracy and AUROC compared to conventional detection methods. Their work validates the principle that a generative model trained only on normal thermograms can identify anomalous thermal patterns without requiring labelled fault examples, which is directly applicable to the industrial scenarios considered here.

**Inference output:** Thermogram will be processed to deliver: similar ground-truth images, a similarity and anomaly score, a calibrated confidence range, and an optional heatmap/localization of the regions causing divergence.

**Decision rule:** Thresholds will be established for anomaly detection based on the analysis of the validation data. Specifically, the bottom 90% of error scores will be considered as 'normal' behaviour, while scores between the 90th and 97.5th percentile will be treated as suspicious. Finally, any scores above the 97.5th percentile will be considered as true outliers. To ensure accuracy, recalibrations will be carried out based on site and asset class that is monitored.

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<sup>13</sup> Peak Signal-to-Noise Ratio

<sup>14</sup> Structural Similarity Index

<sup>15</sup> Learned Perceptual Image Patch Similarity

<sup>16</sup> Mean Absolute Error / Root Mean Square Error

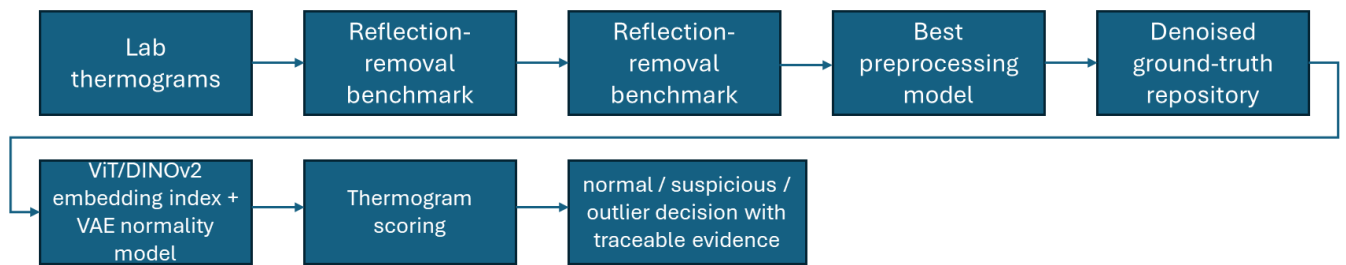


Figure 59: Proposed reflection removal and anomaly detection workflow

## Conclusions

D 7.2 presents the first stage of the research that has been carried out to develop the proposed predictive maintenance platform. The main first step was to understand what the aim of the platform would be and how it can be implemented. This was defined that the purpose of the platform would be to thermally image certain parts of the production lines of the two companies and use those images as ground-truth to compare them with future images taken when the new processes will be implemented in order to detect thermal anomalies, in the product or the machinery, using image processing and ML techniques. The detection of these anomalies would potentially indicate either issue in the process control or with the machinery itself and create an alert.

Therefore, the first step of the research involved visiting ARTIGO and K-FLEX facilities to familiarise with their production, manufacturing processes and the environment where thermography is going to be applied. Both visits provided valuable insight into the processes, but further visits will be required to acquire more images. Based on the acquisitions that were taken, the ARTIGO case seems to be more challenging due to the low emissivity of the rotocure drums and the limited access to sections of the rotocure where the product is visible to be thermally imaged. In addition, to these corrections, de-reflection pre-processing is suggested to digitally remove hot reflections from the image. In contrast, in the K-FLEX case, although the heating coil was imaged including other parts of the production line, with the introduction of the microwave heating process, the focus would have to be shifted to the product as it exits the heating process and moves towards the final extruders where the final PERT layer is applied.

These visits also provided insight into how thermography is going to be applied in order to collect more accurate temperature data from what was currently recorded using further emissivity calibrations. In the ARTIGO case, potential use of thermally insulating the IR camera with an enclosure, might be required in order to move the camera closer to the heating elements of the rotocure.

## Further work

Apart from the proposed development of prediction maintenance platform through various image preprocessing and processing techniques, future work will include research on the use of IR optical filters. The topic of IR filters in thermography with the aim of removing thermal reflections, is difficult and requires experimentation while literature is limited. In addition, another topic that will be researched is to the potential use of borescopes or endoscopes. This approach is based on identifying the actual potential use of such devices and whether they can provide any additional images that can be used to enhance prediction.

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