Laser spot thermography and Pulse thermography – comparison of performance for non-destructive testing of composite structures

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ABSTRACT
Laser spot thermography (LST) is a sub-domain method in active thermography that uses a laser as the heat source. The method allows for precise control of the beam shape, pulse duration, and delivered energy. Therefore, this technique can be applied, especially for delicate structures where testing conditions must be maintained precisely. The following work includes the introduction of a laser spot thermography technology demonstrator that was designed and constructed at AGH UST. The paper presents laser thermography laboratory experiments along with the developed procedure for automatic defect identification. The measurements were used to establish an automatic procedure and algorithm for automatic defect identification based on regression methods.

1. INTRODUCTION

1.1. Non-destructive testing

Non-destructive testing (NDT) methods are processes aimed at determining the physical state of the sample without damaging it. These methods allow material discontinuities to be detected. In other applications, it can be used to measure physical properties. NDT includes many testing methods such as visual and optical testing, usage of ultrasonic waves [1,2], electromagnetic testing [3], thermographic [4] or radiographic [5,6] measurements, liquid penetrant imaging, magnetic particle inspection [7,8], acoustic emission, magnetic resonance imaging, near-infrared spectroscopy or optical microscope testing. [9] Some of these methods can be used only for specific materials (e.g.: magnetic particle inspection requires ferromagnetic material as an inspection object), while the others are designed to detect particular types of damage (e.g., liquid penetrant imaging helps to find narrow surface cracks under low contrast conditions).

1.2. Thermography

Thermography is one of the most versatile nondestructive methods. [10] It bases on the fact that everybody that has a temperature over 0 K emits radiation. The wavelength and intensity of emitted radiation depend on temperature and are described by the Planck radiation equation. For room temperature, the maximum intensity of emission lies in the infrared (IR) part of the electromagnetic spectrum. Imaging in IR allows measuring the temperature of a specimen in

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a contactless way. Temperature distribution gives useful information about the investigated material. Different variants of thermography are used, based on the best-expected results. The most common division of thermographic methods is shown in figure 1.

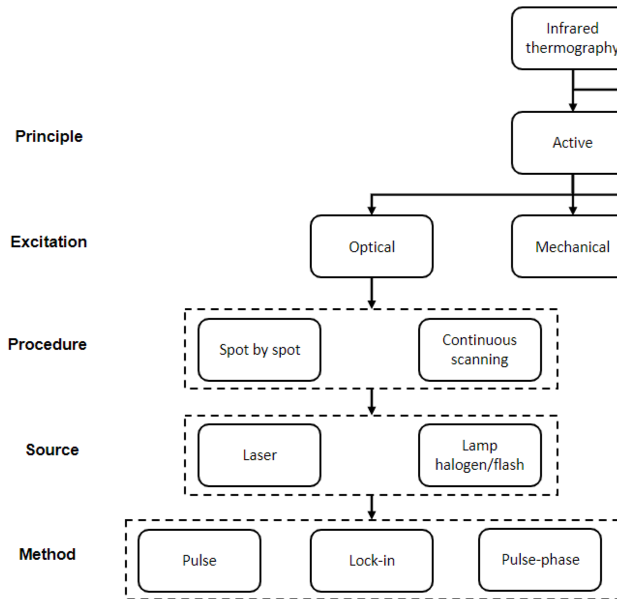


Figure 1. Thermographic techniques split with an indication of division criteria.

In active thermography external thermal irradiation is required and can be done in optical (laser or halogen lamp), mechanical (ultrasound excitation) or another way [11]. This paper presents the results of a comparison of two methods of optical excitation in active thermographic measurements with the use of Thermal Signal Reconstruction (TSR) in the data processing phase. Recently, machine learning based methods started to be used in automatic procedures of damage detection. [12,13] Pulse thermography (PT) uses flash lamps as an excitation source. Unlike LST, PT is a full-domain method that allows making fast investigation of large areas, without precise control over surface temperature. The paper compares the quality of the data obtained with the LST method using the PT method and also evaluates material conditions with the use of data clusters.

2. MOTIVATION FOR RESEARCH

Deployment of different methods in active thermography is the way to continually keep improving the quality of results compared to different methods. This paper focuses on the advantages that can be introduced by laser spot thermography. To explore this approach to thermography, Laser Spot Thermography was verified by Pulse Thermography to collate its efficiency and consistency of findings. Comparison of outcomes can provide information which solution is the best to be applied. Conversion of obtained data to the same format allows using the same clustering algorithms that were developed to find damaged or modified areas of examined material.

3. EXPERIMENT STANDS:

3.1. Inspected sample

To conduct experiments specimen has been prepared. All the measurements are performed on rectangle sample with flat-bottomed indentations. The specimen is presented in figure 2.

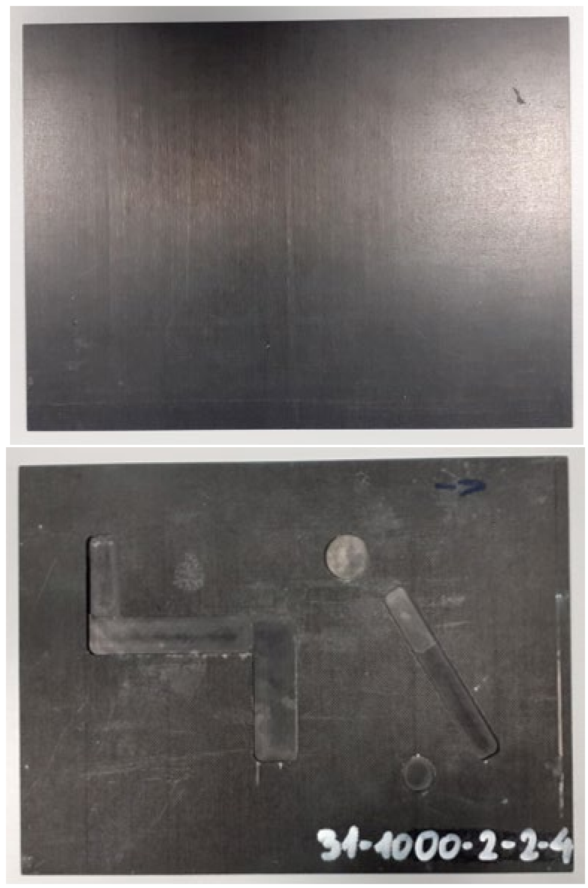


Figure 2. Front and rear view of the inspected sample. On the back of the sample flat bottom indentations are present.

Carbon fiber reinforcement polymer (CFRP) is used as a material for the specimen. In general, CFRP composites can be damaged by relatively light impacts causing invisible damage. [14] Geometric dimensions have been taken with a caliper so that results obtained with the presented methods could be verified. The total dimensions of the sample are 200 x 150 mm, and its thickness equals to 3 mm. The depth of the holes varies from 1 mm to 2.7 mm. The exact depths are presented in figure 3. Different depths on the sample are useful to inspect the sensitivity of methods. Measurements are carried with the flat side of the sample faced to the IR camera.

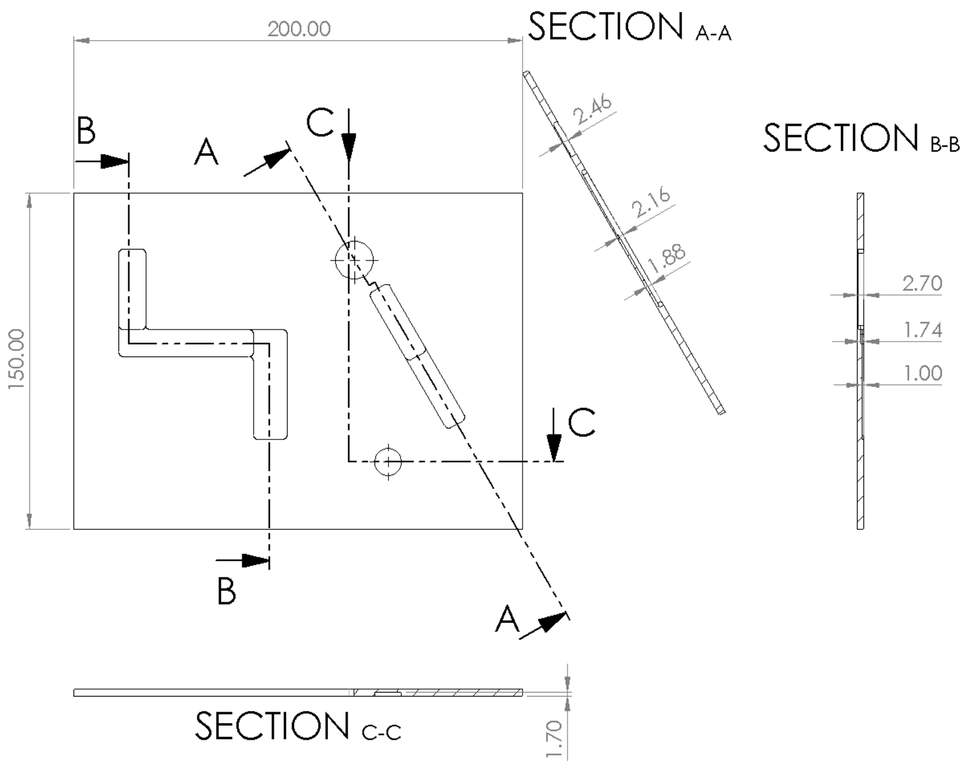


Figure 3. The depth of each indentation is marked on section views.

3.2. Laser spot thermography - experiment stand

Experiment stand for LST is prepared at AGH-UST in Cracow, Poland. Because of multiple measurement cycles due to the chosen method and the narrow field of view of the camera, it is necessary to move the specimen precisely between each acquisition cycle. To fulfill this requirement two-axis Standa 8MTL1401-300 positioner is provided. As an excitation source laser LIMO120-F400-DL808-AV5-A is used. Its nominal power is equal to 120W, and the center of the wavelength spectrum is at 800 nm (close IR). Control and synchronization are done by real-time computer PXIe. Another computer - a PC with a Windows operating system is used for data processing and manual initiation of the acquisition process. An infrared camera (FLIR A655sc with 640 × 480 pixels resolution, 50 fps framerate, and spectral band ranging from 7.5 to 14 µm) is used to record the temperature field at the surface of the sample. Figure 4 presents the arrangement of the components in the laboratory.

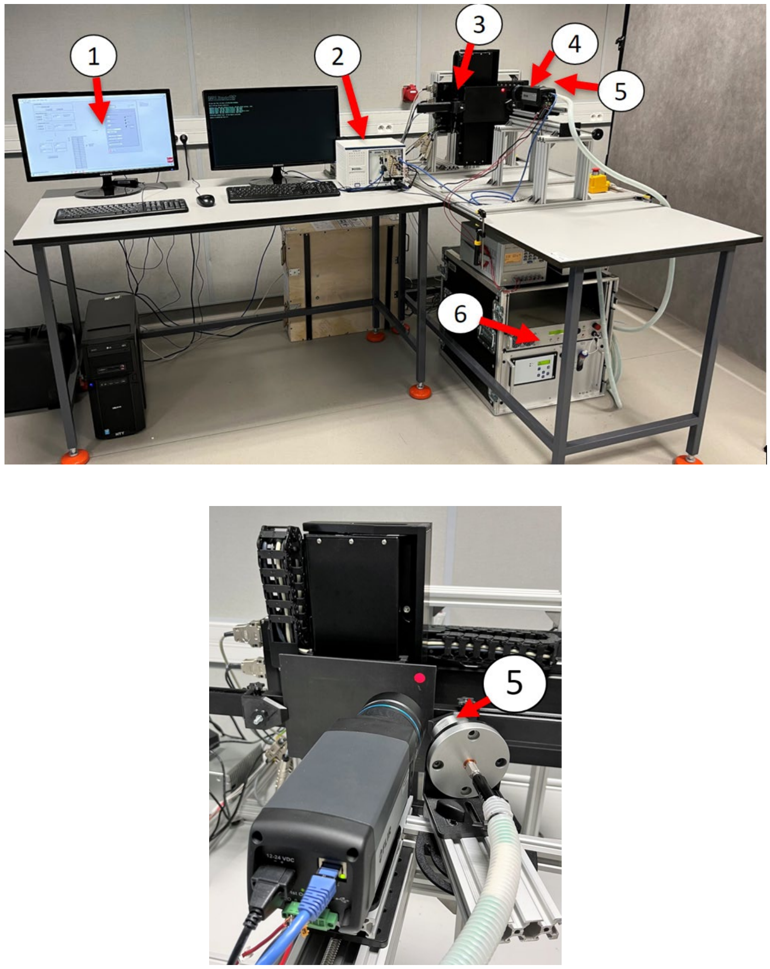


Figure 4. Test stand for laser spot thermography. Marks in the picture: 1) PC, 2) PXIe, 3) Positioner, 4) IR Camera, 5) Collimator, 6) Laser source.

3.3. Pulse thermography – experiment stand

For pulse thermography, experiment data is also acquired by a computer. Two 1 kW halogen Hedler lamps are used as the form of excitation. Lamps are placed 75 cm from the surface of the sample with a 35 cm distance between halogens. The camera was placed between the lamps 53 cm from the sample surface. To control the process of gathering data and to perform proper actions timely, a controller coordinating the behavior of the lamps is used. It had been prepared in advance by one of the authors of this paper. Excitation time was set to 3 seconds, while acquisition time was 15 seconds. The arrangement of each element is shown in Figure 5.

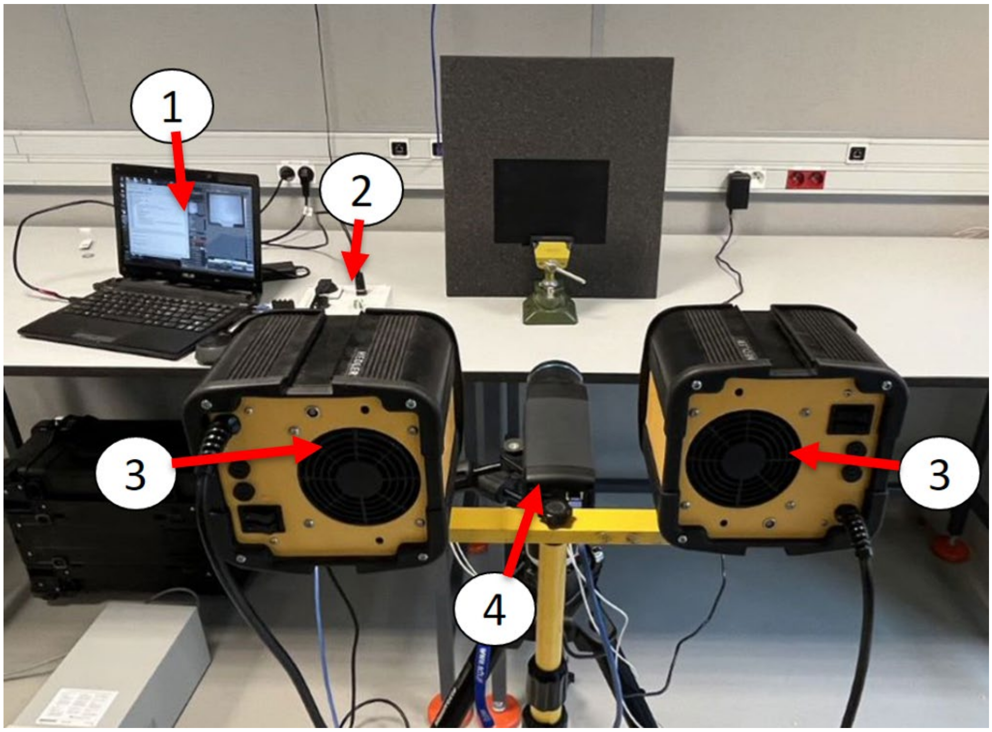


Figure 5. Test stand for pulse thermography. In the picture marked: 1) PC, 2) Controller, 3) Halogen, 4) IR Camera

4. EXPERIMENT PROCEDURE

To obtain useful data, the recording sequence should contain 3 segments. They are necessary since all of them provide a complete set of information about the sample that can be extracted in post-processing operations. Recording background is the first of them. It enables a user to get information about the temperature of the surface of the specimen before the experiment and later analyze the change of temperature instead of the actual temperature value. Its duration is 0.2 s which makes it the shortest part of the recording. The second acquired part of the recording is the heating sequence. Data obtained in this part is not used in this paper, but it can provide valuable information about material properties [15]. The last fragment is the sequence recorded during the cooling phase and the parameters extracted for this time courses are a matter of further analysis. All stages are marked with colors on the example signal in figure 6.

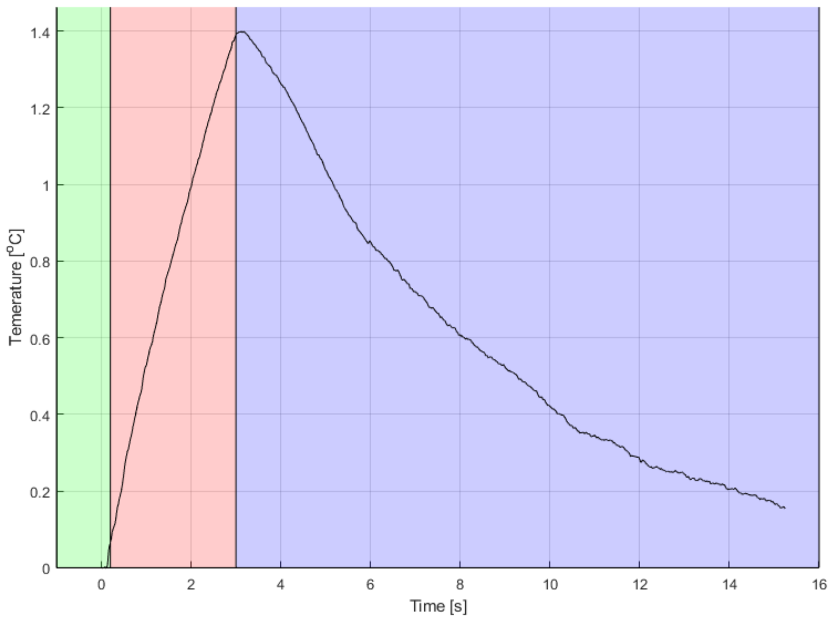


Figure 6. Three stages of thermographic measurements. The green rectangle is marking the background establishment, red –the heating period, and blue – the cooling phase.

4.1. Laser Spot Thermography - acquisition procedure

Laser Spot Thermography is one of the possible approaches in the non-destructive investigation. The measurement system requires sequential excitation of different points at the surface of the specimen. The recorded thermographic sequence is saved with corresponding coordinates and analyzed later. One of the key attributes of LST is the small field of view and high spatial resolution. According to the fact that the white noise is present in each measurement, the redundant spatial resolution can be reduced in order to decrease the influence of white noise. Reduction is made by averaging signal inside a chosen region of interest. Typically, a single inspection requires recording hundreds of measurement points to get reliable results. The scheme of the procedure is shown in figure 7. To investigate the examined specimen, a sequence consisting of 800 points is recorded. It covers 62% of the specimen area. The recorded sequence contains a 0.3 s record of the background, 0.8 s record of the heating phase, and 4 s record of the cooling phase.

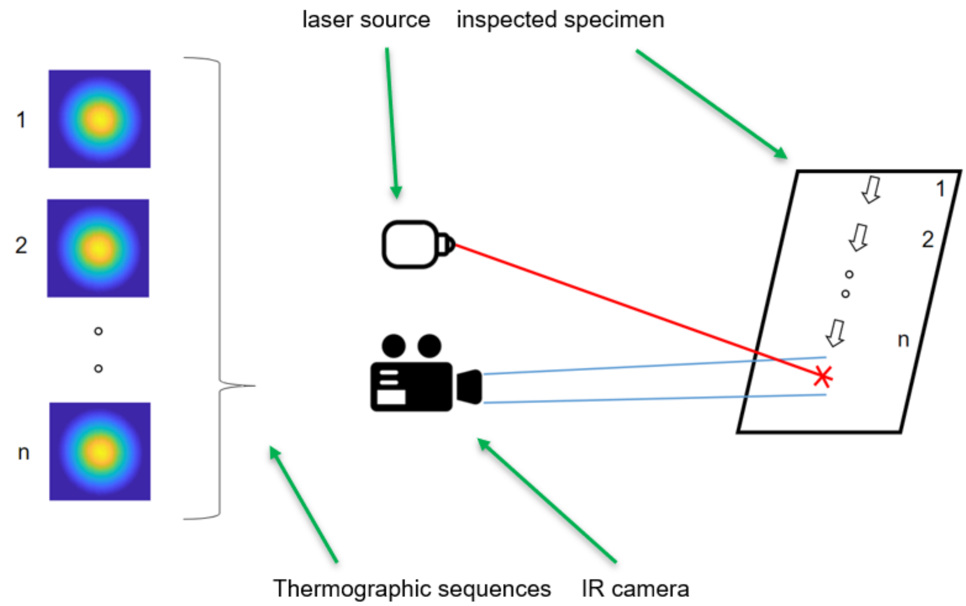


Figure 7. Scheme of Laser Spot Thermography process. It requires a series of measurements with specimen displacement.

4.2. Pulse thermography - acquisition procedure

Pulse thermography (PT) is probably the most widely used technique for non-destructive thermography measurements. It is based on full-field excitation with short excitation time. Thermographic frames are obtained during the passive cooling of the sample. [16] The maximum duration of the heating impulse varies between the investigated samples due to its material properties. In general, the lower the thermal diffusivity of the material, the longer the excitation can be considered a pulse. For composite materials such as carbon fiber reinforced plastic (CFRP), a maximum pulse duration of 5 seconds is allowed. [17]

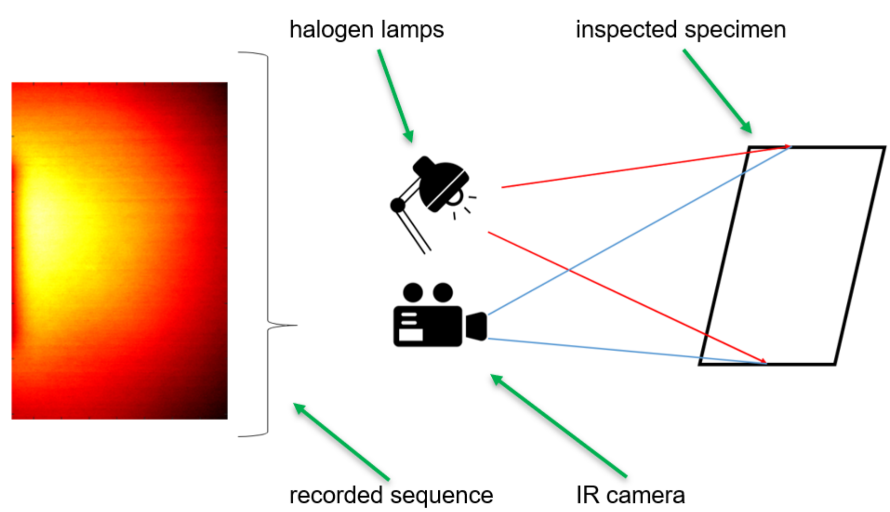


Figure 8. Scheme of Pulse thermography process. The inspected area is in the camera field of view at once.

The recorded sequence is 15 s long and contains a 0.3 s record of the background, a 3 s record of heating, and an 11.7 s record of the cooling stage.

4.3. Thermal Signal Reconstruction – signal processing procedure

Thermal Signal Reconstruction (TSR) is a method that is based on fitting a curve to the obtained data. The curve is described by a simple equation, that allows for further analyses. This approach minimizes the temporal noise of the signal and allows for further processing without generating additional noise. Most often, a fitted equation is a low-order polynomial or sum of exponential functions. [18] The method has been shown to have a significant effect on noise reduction and allows for the detection of deeper defects in materials. However, with a longer acquisition time, lateral diffusion may affect the quality of the fitting. This method was originally developed for PT. Classic TSR usage is based on fitting the exponential curve to the recorded signal and its derivatives. [19]

Instead of the typical TSR algorithm, further operations have been done with the implementation of the data clusters. This machine learning based approach is recently explored to make fully automatic damage evaluation systems [20-23]. There is a wide variety of data clustering methods presented by Jane et al. [24] In general, clustering can be divided into two categories - hierarchical and partitional. Partitional clustering can be performed with the deployment of inner alia square error or mixture resolving whereas hierarchical clustering is based on assumption that the individual components of the mixture density are normally distributed. In this paper, both types of clustering were applied. Clustering is done with three different methods: hierarchical clustering, which is the hierarchical clustering method, K-means, which is square error partitional clustering and Gaussian mixture, which is a mixture resolving partitional clustering.

The processing of Pulse data was done using MATLAB software. The processing algorithm starts with the region of interest (ROI) constraint; then, the background subtraction operation is performed. The image is divided into a grid of small subregions within which the signal is averaged to reduce random noise. The operation was carried out for subregions with dimensions of 1x1 px. (without averaging) and 5x5 px. Next, the parametric curve given with equation (1) is fitted to the averaged signals using a minimal square optimization algorithm. As an outcome, four parameters are obtained.

$$T(t) = a \cdot e^{b \cdot t} + c \cdot e^{d \cdot t} \tag{1}$$

An example of the signal time course and the associated curve for a pixel is shown in Figure 9. The signal processing of the LST data was performed in Python. Firstly, the laser spot center was found, then rectangle-shaped ROI was designated with 80x80 px. dimensions and center in the middle of the laser spot. The signal within the ROI is averaged to reduce random noise. Next, the parametric curve (1) is fitted to the averaged signals using a python script library. As a result, four parameters of course are obtained.

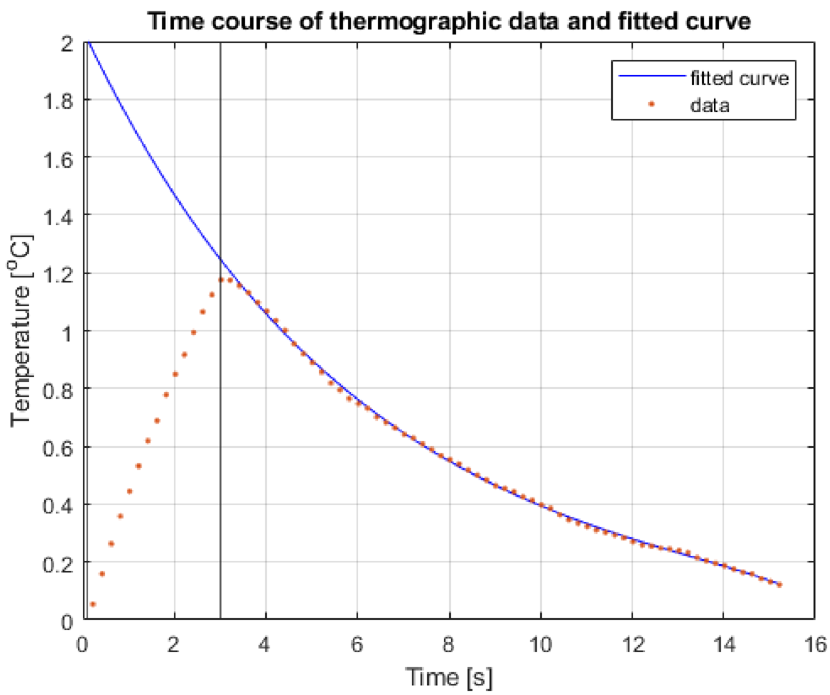


Figure 9. Time course of relative temperature (orange dotted) and fitted exponential curve (blue line). Temperature course is obtained in pulse thermography. Vertical lines divide the course into 3 stages.

Parameters from each measurement point, in both methods, are clustered with the following algorithms: K-means, hierarchical clustering, and Gaussian mixture with the use of the Python seaborn library. Finally, the images are reconstructed and presented in figures in the next chapter.

5. RESULTS

Figure 11. presents the results of measurements obtained with the LST technique with the use of K-means clustering. Clustering was performed with the use of 4 variables obtained in the TSR process, and the number of clusters varied from 2 to 6. The best values were obtained for 4 clusters.

Figure 12 shows the results of clustering the data, obtained in pulse thermography, with the use of the Gaussian mixture procedure. Data is clustered with the use of 4 parameters and as for LST, the best results are obtained for 4 clusters. This method was chosen since it provides the best results for pulse thermography among all methods listed in this article. As opposed to laser spot thermography, K-means didn't provide as accurate outcome as Gaussian mixture.

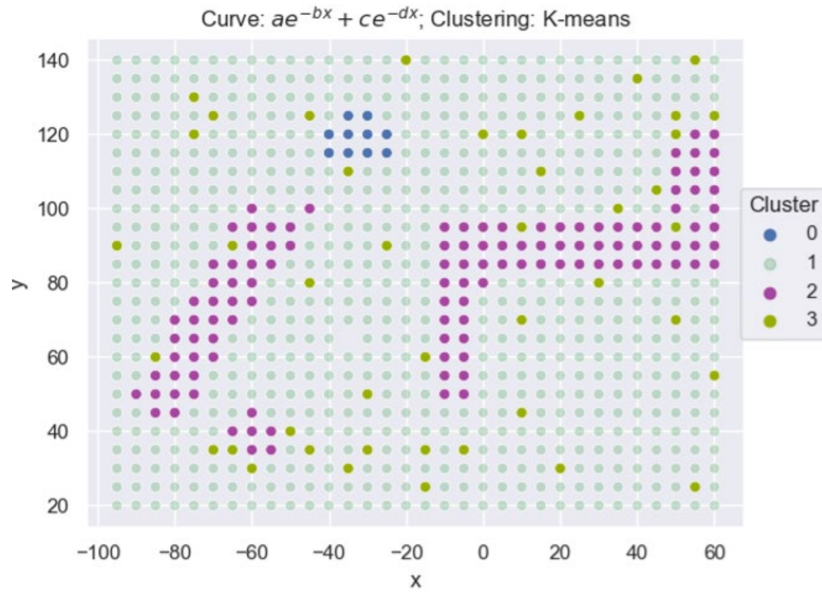


Figure 11. Results of processing data obtained with the LST method. Clusters 0 and 2 correspond to the damaged area, while cluster 1 represents healthy material. Areas with ambiguous results are represented by cluster 3.

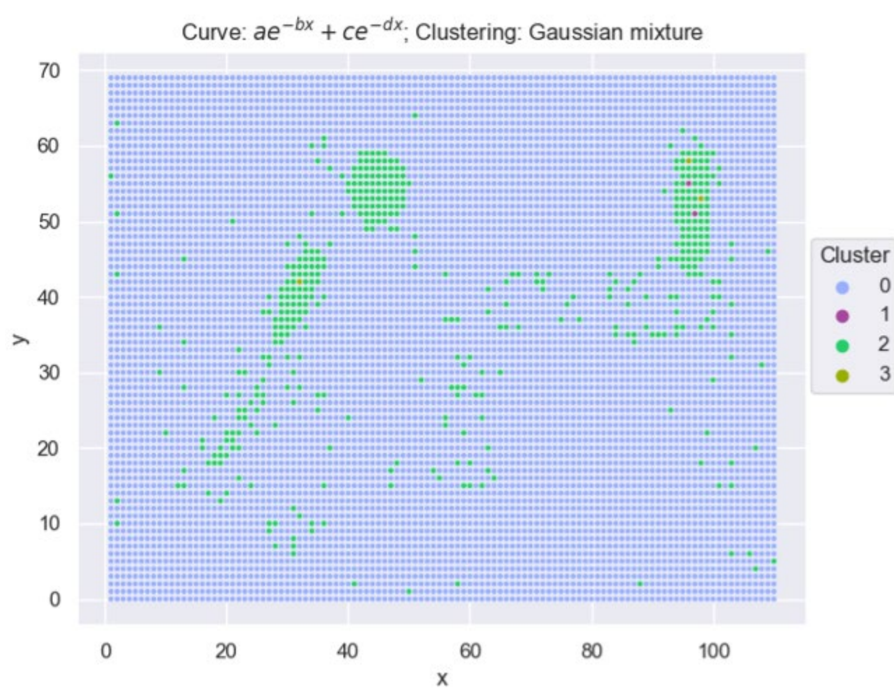
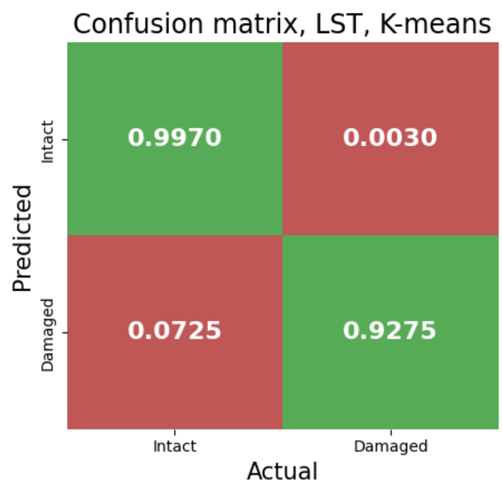
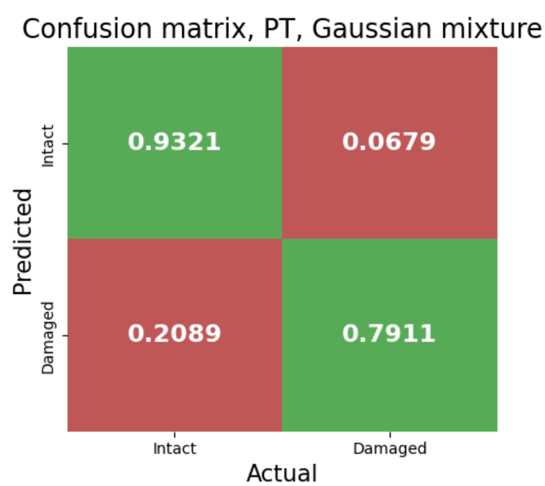


Figure 12. Results of processing data obtained with PT method. Clusters 1, 2, and 3 correspond to the damaged area, while cluster 0 represents health material.

The comparisons of the results are presented in confusion matrixes in figure 14, and selected statistical measures are shown in table 1.



(a)



(b)

Figure 14. Confusion matrixes were obtained with LST and PT classification results.

Table 1 shows the comparison between results gained with the use of these two methods.

Measure:	LST	PT
Sensitivity	0.9846	0.4198
Specificity	0.9851	0.9863
Precision	0.9275	0.7911
Accuracy	0.9850	0.9229

Table 1 Statistic measurement of data from LST and PT. The best values are highlighted in green. Pulse thermography has a slightly higher specificity than laser spot thermography. The other measures presented such as sensitivity, precision, and accuracy are better for LST.

6. CONCLUSION

CFRP specimen was successfully investigated with laser spot thermography. As a verification method pulse thermography was used. Data obtained in both methods was processed using thermal signal reconstruction method and clustering techniques. Laser spot thermography presented higher effectiveness which has been proven by statistical measures. Pulse thermography acquisition time was significantly lower than laser thermography (51s vs 3h 15min). This study has demonstrated that clustering can be used as a high-accuracy evaluation method.

ACKNOWLEDGMENTS

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