Detection of internal corrosion by long-pulse thermography and digital image processing

Detección de corrosión interna mediante termografía de pulso largo y procesamiento digital de imágenes

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Abstract

This paper addresses the problem of internal pitting corrosion in metals. The approach to solving this problem is carried out by means of long-pulse thermography (step heating) and digital image processing, using the median filter in the pre-processing and the Fourier transform in the processing. The long pulse thermography technique is an excellent way of detecting corrosion in metals. According to the state of the art, most of the works reviewed detect only the presence of external corrosion. In the experiments plates of different thickness were evaluated, one of 2 mm and another of 8 mm; this is another point in favor since most of the reviewed articles only focus on a single sample. In the development of this project, the following lines of research have been identified: implementation of new digital image processing methods, improvement of the thermography technique using other energy sources to heat the plates in a shorter time, exploring other functions of image processing in programming languages, carrying out tests with plates of different thickness and size, measuring the percentage of corrosion.

Infrared thermography, Long pulse thermography, Digital image processing

Resumen

En este trabajo se aborda el problema de la corrosión interna por picadura en metales. El enfoque de solución de este problema se plantea mediante termografía de pulso largo (step heating) y procesamiento digital de imágenes, utilizando en el preprocesamiento el filtro de mediana y en el procesamiento la transformada de Fourier. La técnica de termografía de pulso largo es una excelente forma de detección de corrosión en metales. De acuerdo al estado del arte, la mayoría de los trabajos revisados detectan sólo la presencia de corrosión externa. En los experimentos se evaluaron placas de diferente espesor, una de 2 milímetros y otra de 8 milímetros; este es otro punto a favor ya que en los artículos revisados la mayoría sólo se enfocan en una sola muestra. En el desarrollo de este proyecto se han identificado las siguientes líneas de investigación: implementación de nuevos métodos de procesamiento digital de imágenes, mejorar la técnica de termografía utilizando otras fuentes de energía para calentamiento de las placas en un menor tiempo, explorar otras funciones de procesamiento de imágenes en lenguajes de programación, realizar pruebas con placas de diferente espesor y tamaño, medir el porcentaje de corrosión.

Termografía infrarroja, Termografía de pulso largo, Procesamiento digital de imágenes

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Introduction

Infrared thermography has evolved and is now widely accepted as a condition monitoring tool, where temperature is measured without contact (Talai *et al.*, 2016).

Corrosion detection is one of the main fields covered by Non Destructive Testing and Evaluation techniques in recent years and is the main problem for industries such as marine, petrochemical, aerospace, energy, automotive and others. There are different forms of corrosion in metals that could cause an unexpected or premature failure in the structure or component (Cadelano *et al*., 2016). For example, if a pipe or pipeline has a defect caused by corrosion, this can lead to leakage of the transported material, which would imply economic loss, environmental pollution and an area of risk for people nearby (Laaidi *et al*., 2011).

The hazardous condition of a corroded metal installation is difficult to assess by visual inspection, especially if it is an internal defect. The existence of corrosion can lead to accidents that have terrible technical, economic, environmental and social consequences (El-Amiri *et al*., 2017).

Thanks to significant improvements of the thermographic camera in the last twenty years, it has been possible to detect small cracks using an energy source with low frequency or short duration pulses (Shepard *et al*., 2004).

In this paper we will work with long pulse thermography (step heating), which has been successfully applied to evaluate defects in materials, achieving good efficiency (Kamińska *et al*., 2019).

Problem

Corrosion causes large economic losses in various industrial sectors, from infrastructure and transportation to production and manufacturing. A study conducted in the United States of America indicates that the annual direct cost related to corrosion is about $276 billion (Koch *et al*., 2010) representing approximately 3.1% of that nation's gross domestic product.

Globally, the direct cost of corrosion in countries is estimated to be between 3% and 4% of each country's gross domestic product (He *et al*., 2012).

Due to the constant maintenance of steel structures, the costs of corrosion are high. It is estimated that 20% of the steel consumed in Mexico is used to replace the material lost through corrosion (Corrosion, n.d.). In terms of safety, there are also costs due to accidents caused by corroded structures. In industries, it can cause temporary interruption of production, which represents large losses for companies.

This corrosion problem needs to be addressed by early detection.

In the following classical corrosion model, the factor known as general sensitivity to material loss is defined, which means that for every 1% increase in temperature in a corroded area, there is a 1% loss of material when $t \to \infty$.

$$\frac{\Delta L/L}{\Delta T/T} \approx 1 \quad (1)$$

Where $\Delta L/L$ is the loss of material and $\Delta T/T$ is the relative temperature which increases (Doshvarpassand *et al*., 2019).

Justification

Inspection is an important part of many maintenance processes to maintain the safety of system components (Gao *et al*., 2014) and thus the integrity of the personnel working in each area.

It is important to detect defects in equipment in industries, in order to prevent unwanted accidents, to avoid leakage into the environment and to maintain the operational limits of the system components (Gherghinescu *et al*., 2013).

The present research is carried out for the timely detection of corrosion in industries or companies, in this way accidents can be avoided and acted upon in advance. It should be noted that the type of corrosion to be studied is pitting and internal corrosion in A36 carbon steel. The long pulse thermography technique will be implemented only at laboratory level.

Related work

The works related to the topic addressed in this article are the following:

In (Shen & Li, 2007), the results show that infrared thermography is a reliable non-destructive method for the detection of defects produced by corrosion and erosion flow in a high temperature pipeline. The disadvantage of this method is the need to heat the pipes to change the temperature.

The authors (Wallbrink *et al*., 2007) present a quantitative estimation of defect size and depth using lock-in thermography on a 10 mm thick steel plate. With an excitation frequency of 0.02 Hz, the best thermal contrasts are found for the range of defects considered.

In this work (Marinetti & Vavilov, 2010), defects were simulated and material loss was modelled using the inversion formulae for both flash and square-pulse heating.

In (Liu *et al*., 2012) pulsed thermography is considered to rapidly quantify pitting corrosion in a pipe. A thermographic image processing procedure is proposed to extract corrosion information with phase congruency measurement and local binary fitting. The second principal component shows a good linear relationship with pipe metal loss.

In this paper (Vavilov e*t al*., 2013), hidden corrosion is detected in 1 to 2 mm thick steel containers that are used as temporary storage of radioactive waste.

(Xu *et al*., 2016), pulsed Eddy current thermography in combination with Principal Component Analysis provides an effective way to detect hidden defects in corroded steel bar. Step heating thermography was also used in the experiments.

In the article (Cadelano *et al*., 2016), infrared thermography was applied to detect corrosion in a real pipe segment with hot water inside the pipe at more than 90°C. The results show that the presence of water is better and can be considered as active thermography analysis.

(Li *et al*., 2017), this paper proposes a strategy to execute pre-processing and post-processing for surface defect detection based on the Eddy current pulsed thermography method. For preprocessing, it is used: Reconstruction of thermographic signals, Principal Component Analysis, Independent Component Analysis; for postprocessing, iterative thresholding, Otsu's method, slice histogram and iterative fitting are used.

In (Yang *et al*., 2019) proposed a method based on the combination of thermal image sequence reconstruction and first-order differential processing, used for noise removal and contrast enhancement respectively.

In the paper (Da Silva *et al*., 2020), an active thermography algorithm capable of detecting defects in materials was developed, based on the techniques of thermographic signal reconstruction, thermal contrast and physical principles of heat transfer.

The authors (Simonov *et al*., 2020), made a cube with plates of 2, 4, 6 and 8 mm thick, on the inner sides were simulated defects of different sizes, the experiment consisted in heating each plate at the same time with two halogen lamps of 1000 Watts each, the captured thermographic images were processed by Principal Components and Fourier Transform, also used the signal-to-noise ratio.

In this article we will work with the long pulse thermography technique (step heating), as it is an excellent technique for detecting internal corrosion in metals and has not been widely used.

Methodology

The proposed approach consists of five stages, which are shown in Figure 1 and described as follows.

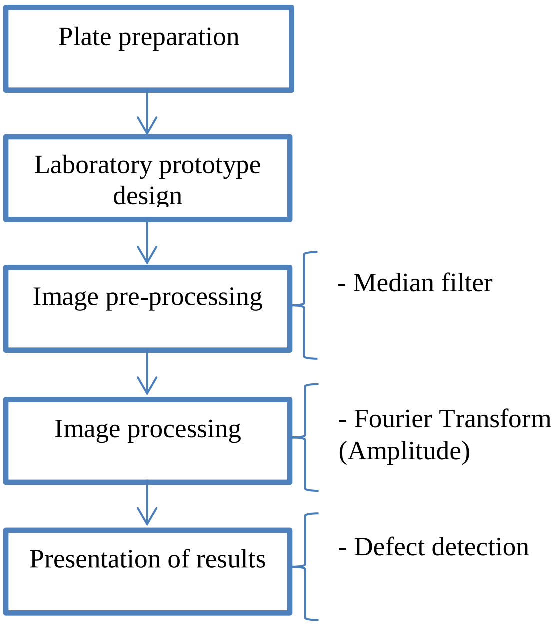

Figure 1 Solution approach for corrosion detection

Plate preparation

At this stage, A36 steel samples of size 15 centimetres wide by 15 centimetres long were prepared. Subsequently, holes of different diameters and depths were drilled in the central part of all the plates on the internal side, without going through the plate. Afterwards, salt water was added to the holes to cause corrosion, as well as residues of a corrosion rod, this process took about 3 weeks. As a next step, the plates were painted black on the outer side to improve the efficiency of the power source and reduce light reflection (Duan *et al.*, 2019).

The first plate, which will be referred to as plate 1, has a thickness of 2 millimetres and is shown in Figure 2.

Figure 2 (a) Plate 1 outer side, (b) Plate 1 inner side

Plates 2 and 3 have a thickness of 8 mm, as shown in Figures 3 and 4 respectively.

Figure 3 Plate 2 inner side

Figure 4 Plate 3 inner side

Laboratory prototype design

For the implementation of the prototype, two halogen lamps of 100 Watts each (Figure 5), a thermographic camera (Figure 6), the steel plates presented in the previous section and a computer were required. The thermographic camera was provided by the Polytechnic University of Altamira on loan.

Figure 5 100 Watt halogen lamps.

Figure 6 Thermographic camera

A classic design of the prototype and the way images are acquired is shown in Figure 7. In this figure, the number 1 represents the energy source, in this case a 100 W halogen lamp. The images are acquired by reflection, i.e. the thermal imaging camera and the energy source are placed on the same side of the plate, transmission is when the thermal imaging camera and the energy source are on opposite sides of the plate. Reflection mode is used for internal defects and transmission mode for deep defects. Number 2 is the steel plate, number 4 is the computer on which the images are processed.

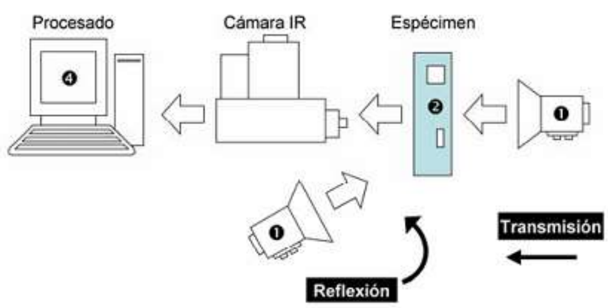

Figure 7 Prototype design *(Castanedo et al., 2014)*

Image pre-processing

Image pre-processing is very important, it is in charge of removing or filtering noise from the image so that it is ready for the next step, which is processing. In the experiments carried out, the median filter (Pratt, 1994) was used.

The median filter replaces each pixel of the image by the median of the pixels in the current filter region R, i.e.

$$I'(u,v) = mediana\{I(u+i, v+j)\} \quad (2)$$
$$(i,j) \in R$$

The median of a set of 2n+1 values $A = \{a_0, \dots, a_{2n}\}$ can be defined as the central value a_n after arranging A in an ordered sequence, which is,

$$mediana(a_0, a_1, \dots a_{n-1}, \boldsymbol{a_n}, a_{n+1}, \dots, a_{2n}) = a_n \quad (3)$$

Where $a_i \leq a_{i+1}$. Figure 8 demonstrates the calculation of the median size filter. $3 \; x \; 3$.

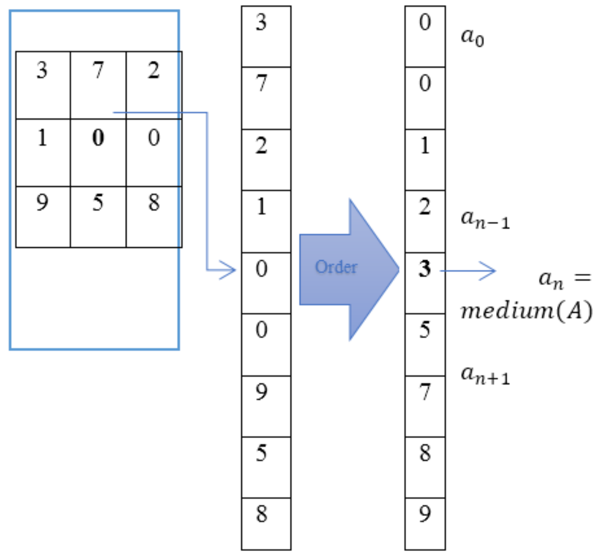

Figure 8 Median filter calculation

If the number of elements is even, then the median of the ordered sequence$A = (a_0, \dots, a_{2n-1})$ is defined as the arithmetic mean of the two central values a_{n-1} and a_n,

$$mediana(a_0, \dots \boldsymbol{a_{n-1}}, \boldsymbol{a_n}, \dots, a_{2n-1}) = \frac{a_{n-1}+a_n}{2} \quad (3)$$

Image processing

The Fourier Transform, which is used to decompose an image into its sine and cosine components, was used for processing. The Fourier transform plays a fundamental role in a wide range of image processing applications, including enhancement, analysis, restoration and compression. The basic theory given by Fourier states that:

– Periodic functions can be represented by the sum of sine/cosine functions of different frequencies, multiplied by a different coefficient.

– Non-periodic functions can be represented as the integral of sine/cosine multiplied by the weight function.

Digital images are used as input data. Thus, the discrete version of the Fourier Transform is used to convert a digital image into its frequency domain (Thanki & Kothari, 2018). This transform is known as Discrete Fourier Transform and given as:

$$F(u,v) = \frac{1}{MN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1} f(x,y)e^{-j2\pi\left(\frac{ux}{M}+\frac{vy}{N}\right)} \quad (4)$$

where $u = 1, 0 \ldots M-1$ y $v = 0, 1, 2 \ldots N-1$.

Presentation of results

In this section, the identification or detection of defects, i.e. the identification of internal pitting corrosion, is carried out.

Experiment 1: Evaluation of plate 1

Objective: To identify internal pitting corrosion on the 2 mm thick plate.

Procedure: The plate was heated by reflection with the two 100 Watt halogen lamps for a period of 120 minutes at a distance of 10 centimetres on the outer side, the side with no holes or corrosion. Subsequently, a sequence of images was taken of the plate on the same side with the camera at a distance of 22 centimetres. The images were then taken from the camera and copied to the computer to make a selection of the images using the camera software and obtain those where, by adjusting the temperature, the defects can be seen. The selected images were then preprocessed and processed in the IR View software, which is free and open source, developed in Matlab by Laval University. The median filter was chosen for the pre-processing and the Fourier transform by amplitude for the processing.

Results

The chosen thermographic image of plate 1 is shown in Figure 9. The result of the image using the median filter can be seen in Figure 10.

Figure 11 shows plate 1 when using the amplitude Fourier transform.

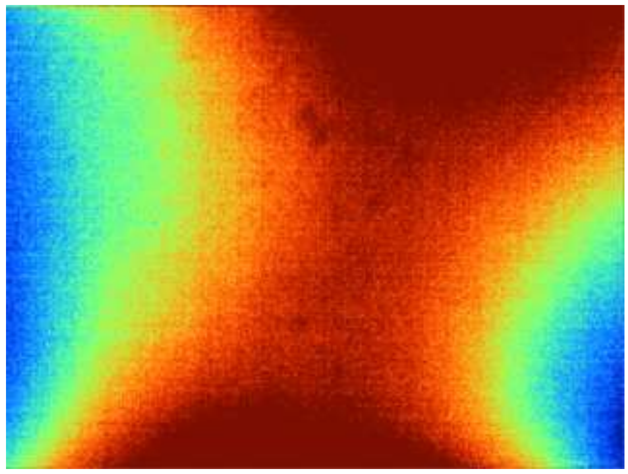

Figure 9 Thermographic image of plate 1

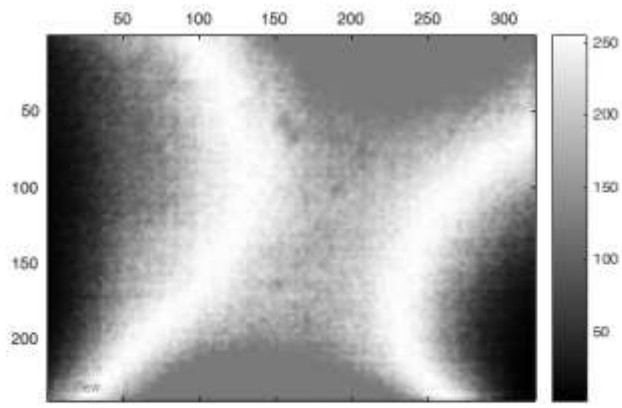

Figure 10 Plate 1 with median filter

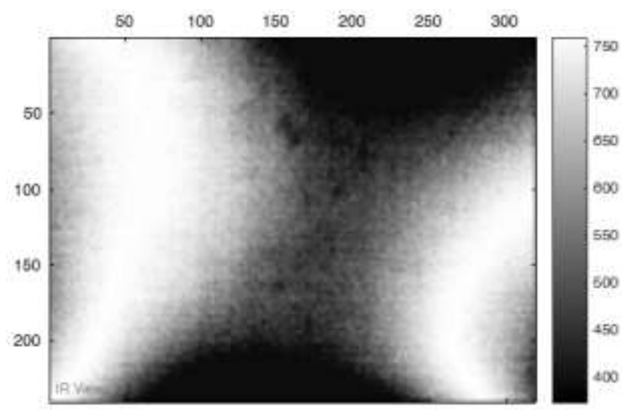

Figure 11 Amplitude Fourier Transform Plate 1

Experiment 2: Evaluation of plate 2

Aim: To find internal corrosion in plate 2 of 8 mm thickness.

Procedure: The power source was provided by two halogen lamps, placed 10 centimetres from the plate for 120 minutes. Several thermographic images were taken at a distance of 24 centimetres from the plate, a representative image was selected to apply the median filter and Fourier Transform by amplitude.

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Results

Figure 12 shows the thermographic image of plate 2.

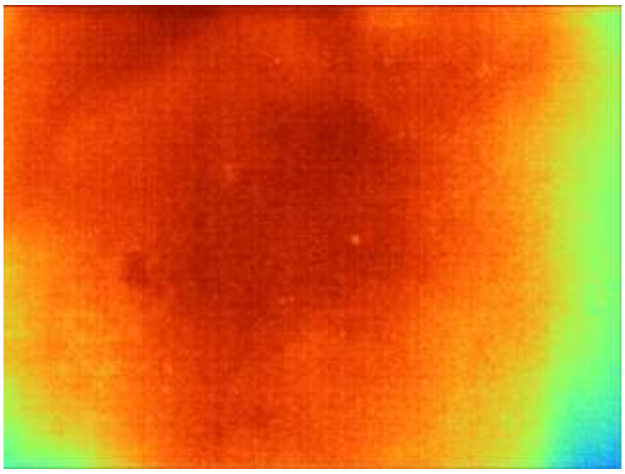

Figure 12 Thermographic image of plate 2

The thermographic image with the median filter is shown in Figure 13 and the applied Fourier transform is shown in Figure 14.

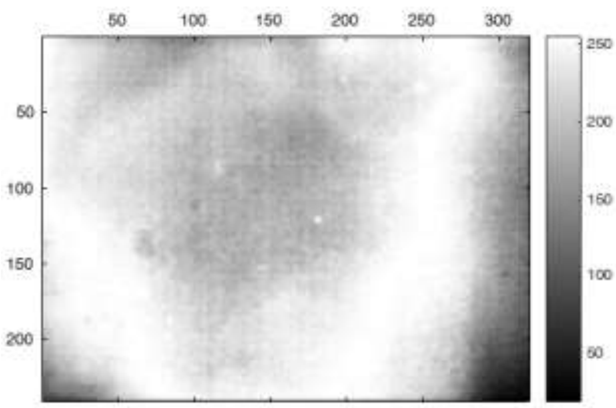

Figure 13 Plate 2 with median filter

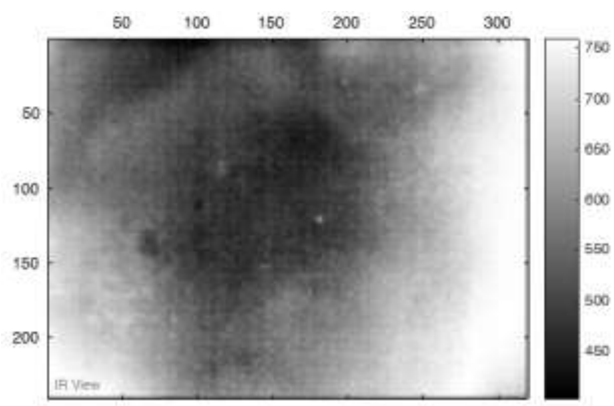

Figure 14 Plate 2 with amplitude Fourier transform.

Experiment 3: Plate evaluation 3

Objective: To detect internal corrosion in the 8 millimetre plate 3.

Procedure: Power was supplied to the plate with 100 W halogen lamps for 120 minutes at a distance of 10 centimetres, thermographic images were taken with the camera at a distance of 25 centimetres. The best image was considered and the median and amplitude Fourier transform filter was applied.

Results

The thermographic image, pre-processed and processed, are shown in Figures 15, 16 and 17 respectively.

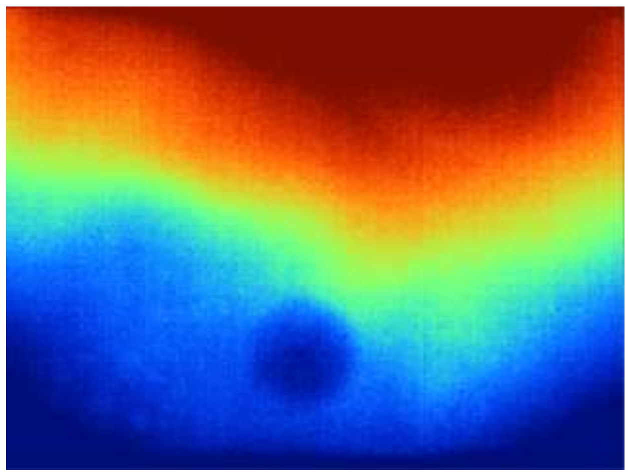

Figure 15 Thermographic image of plate 3

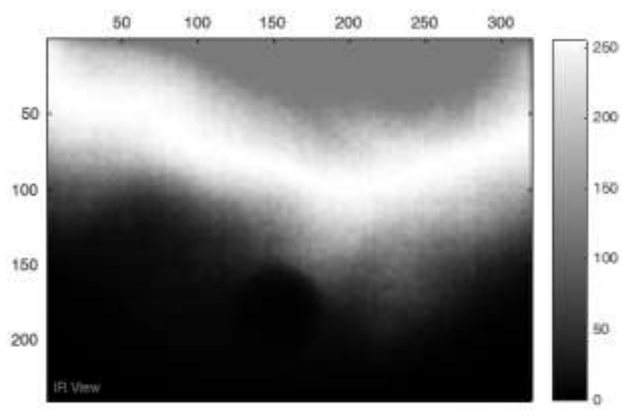

Figure 16 Image with median filter

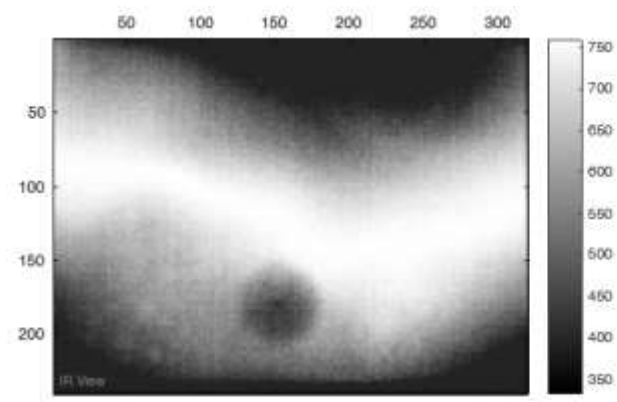

Figura 16 Fourier Transform Imaging

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Conclusions

This work proposes a new technique for detecting internal pitting corrosion in metals, which can be implemented in real situations such as in a pipe or container transporting a substance.

The following lines of research were identified for future work:

- Implementation of new digital image processing methods. The concern arises to explore and implement other image processing methods to improve the result of the processed image.
- Improve the thermography technique using other energy sources. Given that the source used is very low power, the aim is to improve this energy source in order to heat the plates in a shorter time.
- Explore processing functions in programming languages.
- Perform tests with plates of different thickness and size.
- Measure the percentage of corrosion. Find out how to measure the corrosion percentage.

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