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Cooling rate VS temperature to establish thermographic prediction model in surface cracks in steel

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ABSTRACT:

The inspection of steel welds is an important task to ensure the integrity of structures and machines. The inspection process presents two main objectives: ensure that welds meet the geometrical specifications established in the international standards, and analyze the existence of flaws. The most critical flaws to be detected during welding inspection are cracks, because their propagation under stress conditions can cause the collapse of the welded structures or the failure of the machines with welded elements. The technological requirements in nondestructive testing (NDT) for the inspection of surface cracks should not be as complex as the requirements for detection of internal cracks. However, the technique used must be efficient enough to ensure the full detection of surface defects and imperfections, including those of difficult visual detection such as little surface cracks or internal cracks open to surface. Active thermography presents an enormous detection potential for surface cracks in welding: allowing the depth estimation of the crack from the processing of the thermographic data. For this aim, the thermographic test can be designed either to evaluate the absolute temperature after heating (as a thermal stimulation of the material towards the increase in contrast between different zones of the crack) or to evaluate the cooling rate during the cooling posterior to this heating. In this contribution, a comparison between the two methods mentioned for crack evaluation is raised. The results of temperature and cooling rate for the same crack are respectively correlated with the depth data of the crack obtained from a macro-photogrammetric procedure.

1. Introduction

Within the defectology of welded materials [1, 2], the study of the cracking process presents great importance to guarantee the safety of vehicles, structures and machines. The cracking process is critical because it may result in the failure and full collapse of the different welded structures. Therefore, the characterization of the type of crack and its evaluation are important towards the prediction of the direction of propagation and, thus, the possible type of failure.

Nowadays, active thermography technique is being consolidated as an effective and safe NDT (Non-Destructive Testing) technique. Its main advantages regarding other techniques are its speed and simplicity of application to structures under poor environment conditions [3]. During active thermography tests, the specimen is subjected to a thermal excitation. Continue or pulsed excitation sources are tasked to induce an artificial excitation of the electrons of the atoms of the material in order to show surface or subsurface defects, imperfections or discontinuities. There are different methodologies based on active thermography depending on the following aspects: type of heating, arrangement of the sample and the heating or excitation source, and size and shape of the thermally excited area [4]. This technique has been established nowadays like a NDT for the detection of internal defects in composites materials such as CFRP [5]

The excitation sources can be either optical [3,6] or non-optical as eddy current [7] or ultrasounds [8]. When the excitation source is pulsed, results can be analyzed either in the frequency domain (Pulse-Phase

Thermography, PPT) or in the time domain (Thermographic Signal Reconstruction, TSR) [4]. When the excitation source is continuous, results could be analyzed by contrast [9] or by time domain (cooling or heating rate) [10].

On the other hand, modern close range photogrammetry is an important optical technique that allows the generation of dense point clouds models and the complete study of complex 3D geometries using simple digital images. When photogrammetry is applied using a macro lens, small surfaces can also be modelled with high precision [11]. If the mentioned macro-photogrammetric procedure is applied to a crack in a steel welded union, the extraction of a dense point cloud of the cracking zone with a reduced error is possible, including depth data of the crack.

Small cracks open to surface are difficult to detect visually without help, and thus impossible to measure. Furthermore, the crack can be internal with a small opening to surface, sometimes undetectable within the visible spectrum. On the other hand, the traditional gadgets used to measure cracks do not allow the thorough and accurate measurement of the depth of little cracks.

In this contribution, authors propose the comparison between two thermal parameters used to predict the depth in little surface cracks: absolute temperature [12] and cooling rate [13]. Statistical parameters of the correlation between infrared data (temperature) and depth values will be compared with the statistical parameters of the correlation between cooling rate and depth values for the same crack in order to discuss the most adequate model for the aim.

2. Materials and Methods.

2.1. Materials.

A welded plaque of low carbon steel (120 mm x 70 mm) with a thickness of 7.5 mm was chosen as subject of the inspection (Fig. 1). The plaque has been welded with Tungsten Inert Gas welding (TIG), presenting butt-welding with edge preparation in V. The weld (Fig. 1) has a small crack open to surface (Fig. 1) in the adjacent zone to the face of weld, oriented parallel to the longitudinal axis of the weld, and consequently denominated as toe crack according to the international quality standard [1]. Cracks open to surface in steel frequently present abrupt and heterogenic regions. Their causing mechanism is known as cold cracking due to the stresses provoked by the increase in hardness in the zone, mainly due to the transformation of austenite to martensite during the cooling phase after the welding process.

In order to implement the thermal analysis, a thermographic camera is used. The infrared (IR) camera used for this work is a NEC TH9260 with 640 x 480 Uncooled Focal Plane Array Detector (UFPA), a resolution of 0.06 ºC and a measurement range from -40 ºC to 500 ºC. Prior data acquisition, the thermographic camera is geometrically calibrated using a calibration grid based on the emissivity difference between the background and the targets, presented in [14].

For the macro-photogrammetric three-dimensional reconstruction, a Digital Single Lens Reflex (DSLR) commercial and non-professional camera Canon 500D is used. The optics used for image acquisition is a Sigma 50 mm macro lens.

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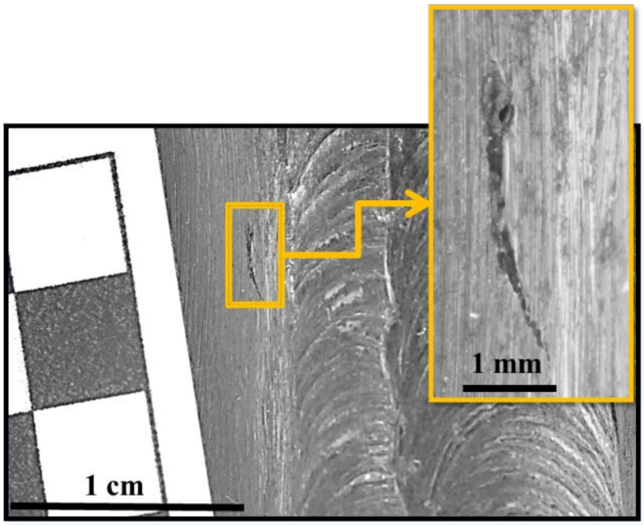

Fig. 1: Steel weld and crack studied ("toe crack" typology according to [1])

2.2. Methodology

First, the steel welded union is slightly heated until 45 ºC. When the welding reaches the required temperature, in that time, the procedure is divided in two sections (Fig. 2). For the study of temperature, a single thermal image is acquired in cooling time 0 s [12]; while for the cooling rate study, the cooling is monitored during 300 s [13]. For both cases, the thermal images obtained (one for the first case and a sequence for the second) are rectified in order to scale to the real geometry and correct any perspective effect introduced by the lens, allowing the establishment of a mathematical correlation between temperature or cooling rate, and depth values.

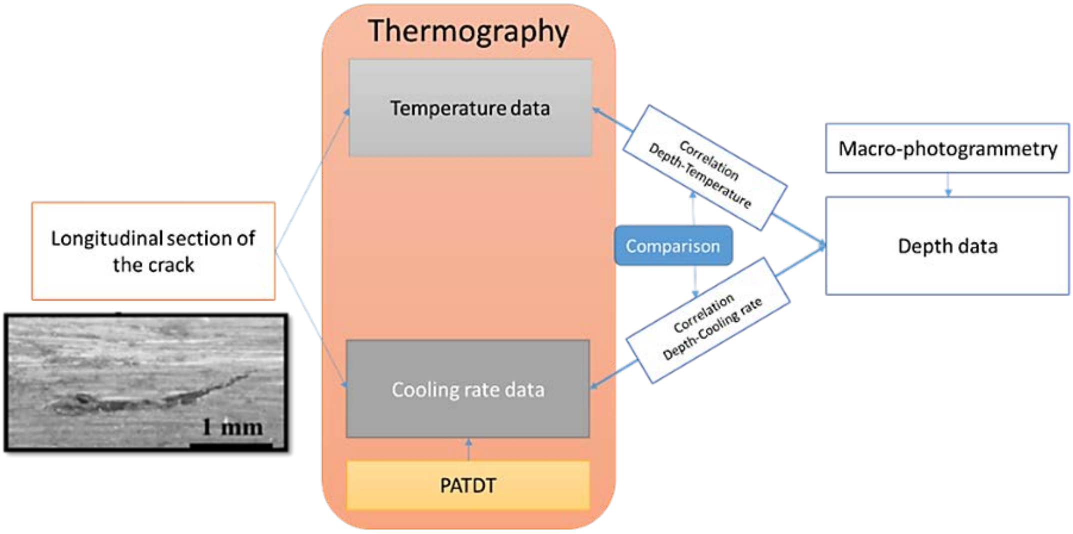

Fig. 2. Left: surface crack under study. Right: Methodology used to study the quality of the correlations depth-cooling rate and depth-temperature through their comparison.

The 3D point cloud of the crack (Fig. 3) is extracted by means of close range macro-photogrammetry following the procedure established in [11]. This procedure allows the generation of models with a precision of tenth of millimeter. It could be summarized in the following steps: the first step is the acquisition of photographic images with a DSLR non-professional camera following a semispherical trajectory centered on the crack and keeping a constant distance between the lens and the object. Once images are acquired, they are first subjected to the automatic determination of their individual spatial and angular positions, regardless the order of acquisition and without requiring initial approximations or camera calibrations. Then, a dense 3D point cloud is automatically computed, so that each pixel of the image renders a specific point of the model of the weld. When the point cloud is generated, it is sectioned following the transversal direction (Fig. 3).

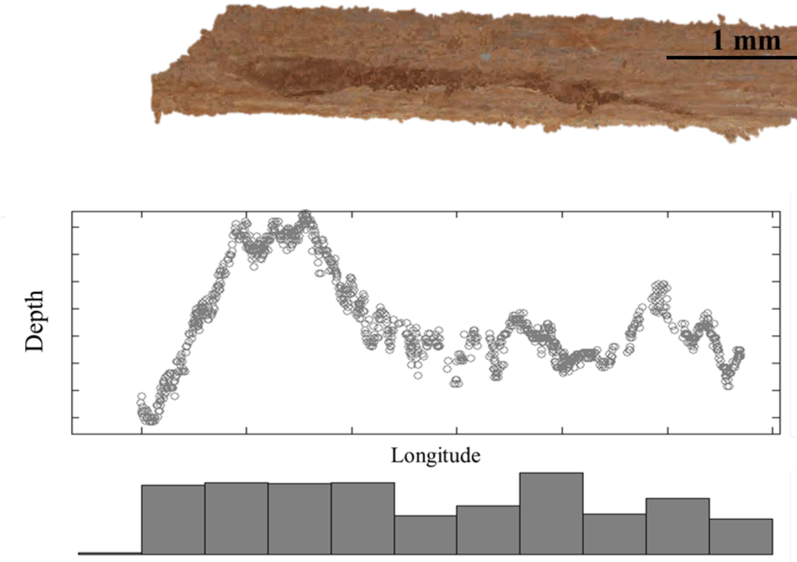

Fig. 3. Top: Reconstructed macro-photogrammetric point cloud of the crack. Middle: Section of the point cloud following the longitudinal section. Top: Histogram of points, showing the homogeneity of point density.

2.2.1. Rectification of thermal images

The rectification process is important to give a real 2D metric to the thermal images in order to compare the values of temperature with the depth extracted by photogrammetry through the longitudinal section of the crack.

The procedure used for the rectification of the thermal images is exposed in [15]. The first step consists on the extraction of the temperature matrix for each thermographic image: each component of the matrix contains the temperature value of each pixel. These are corrected on an emissivity basis, using as reference the temperature values measured at the beginning of the test (end of heating period) with the contact thermometer.

Once the temperature values are corrected, the matrix is subjected to a rectification algorithm. The core algorithm of image rectification is the plane projective transformation, ruled by equations 2 and 3:

$$X = \frac{a_0 + a_1 x' + a_2 y'}{c_1 x' + c_2 y' + 1} \quad (2)$$

$$Y = \frac{b_0 + b_1 x' + b_2 y'}{c_1 x' + c_2 y' + 1} \quad (3)$$

Where X, Y are the rectified (real) coordinates of the element, x' and y' are the pixel coordinates in the image, and a_0, a_1, a_2, b_0, b_1, b_2, c_1, c_2 are the mathematical coefficients of the projective matrix that encloses rotation, scale, translation and perspective. To solve the system of equations, the knowledge of the coordinates of at least 4 points in the object is the only requirement for the determination of this projective matrix, as well as the calibration parameters of the camera.

2.2.2. Analysis of temperature from a single thermal image

The methodology to extract the temperature data of the crack is established in [12]. It consists on the extraction of the pixel submatrix corresponding to the crack from the single raw thermal image. Each pixel of this submatrix indicates the absolute temperature for this point. The map of temperatures for the crack is shown in Fig. 4 and it is similar to the geometry of the crack (zones with more depth present higher temperature after the heating). A temperature profile $(T_1, T_2, \ldots, T_n)$ is extracted through the longitudinal section of the crack (Fig. 4).

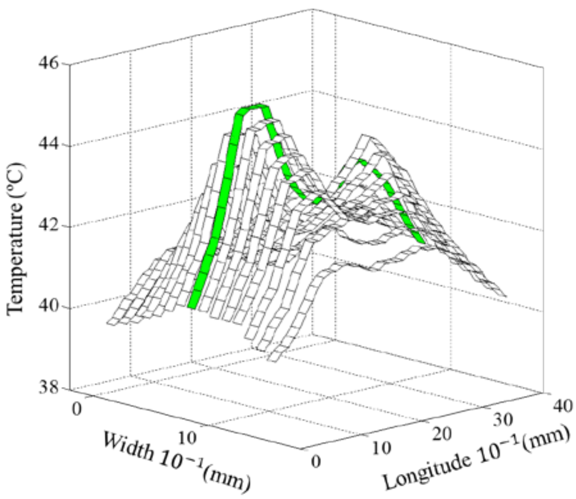

Fig. 4. Temperature map for the surface crack with the longitudinal section selected for the correlation of thermal and depth data highlighted in green.

Temperature values along the crack will be correlated with the depth data obtained from the macro-photogrammetric model for each point of the section.

2.2.3. Analysis of cooling rate from a temporal sequence of thermal images: Design of algorithm Pixelwise algorithm for time-derivative of temperature (PATDT)

For the analysis of the cooling rate in the crack, the Pixelwise Algorithm for Time-Derivative of Temperature is applied [13]. The PATDT algorithm is based on the analysis of the cooling rate of the heated steel according to Newton's Cooling Law [10, 16]. This Law indicates that temperature decreases exponentially during the cooling. This procedure uses the monitoring of the cooling for the detection of defects without using complex processing algorithms like those indicated in the introduction section.

The PATDT [13] applies Newton's Cooling Law for each pixel of the thermal image using an exponential fit model for the temperature-time data of each thermal image of the sequence (Fig. 5). Using this approach, a cooling rate function *Q(t)* is established for each pixel as time-derivate of the temperature function, *T(t)*. It allows the computation of a new matrix with the same dimensions as the thermal matrix, through the introduction of the integrated average cooling rate $Q\_(i,j)$ on each *i,j* position of the matrix, resulting on a cooling rate matrix. This matrix allows the establishment of a cooling rate map of the crack. Finally, the difference between the cooling rate in the zone with no crack (cooling for $0\ mm$ depth of crack, Q_a) and the cooling rate for each point of the cooling rate matrix (Q) is extracted (relative cooling rate, $Q_a - Q$ [13]). In this way, relative cooling rate indicates the difference of cooling rate for each point with respect the cooling rate in the no-cracking zone. When this value is high for a determined zone of the crack, the cooling rate is low.

As done with temperature values, relative cooling rate will be correlated with the depth data obtained from the macro-photogrammetric model for each point of the longitudinal section.

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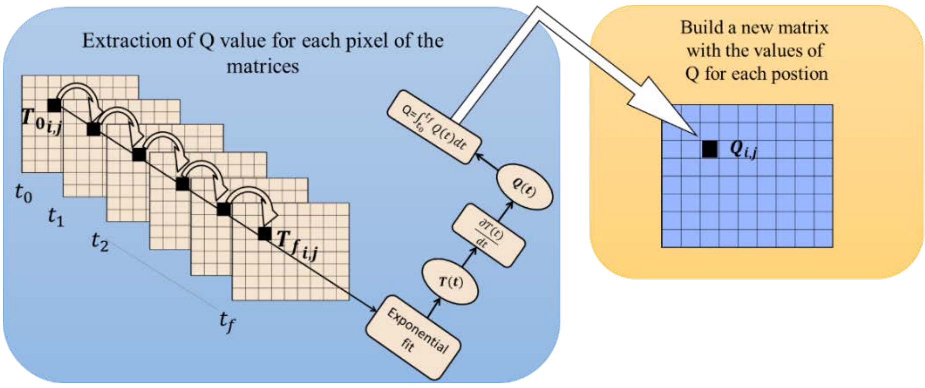

Fig. 5. Steps followed by the global time-derivative algorithm. After data acquisition and rectification, the exponential model is applied for each (*i,j*) position with the values of temperature for each time instant. As a result, a temperature function is obtained and the time-derivate of the temperature function is the cooling function, which is averaged for each position of the matrix, obtaining a matrix of cooling rates.

2.3. Data correlation

When depth data are extracted from the macro-photogrammetric point cloud [11], the correlation between each value of the cooling rate matrix and the depth for each point is calculated for each value of the longitudinal section $(x_1, x_2, \dots, x_n)$ (Fig. 6). Results of temperature and results for cooling rate are independently correlated with respect to the depth of the crack. The statistical goodness results for both correlations will be calculated.

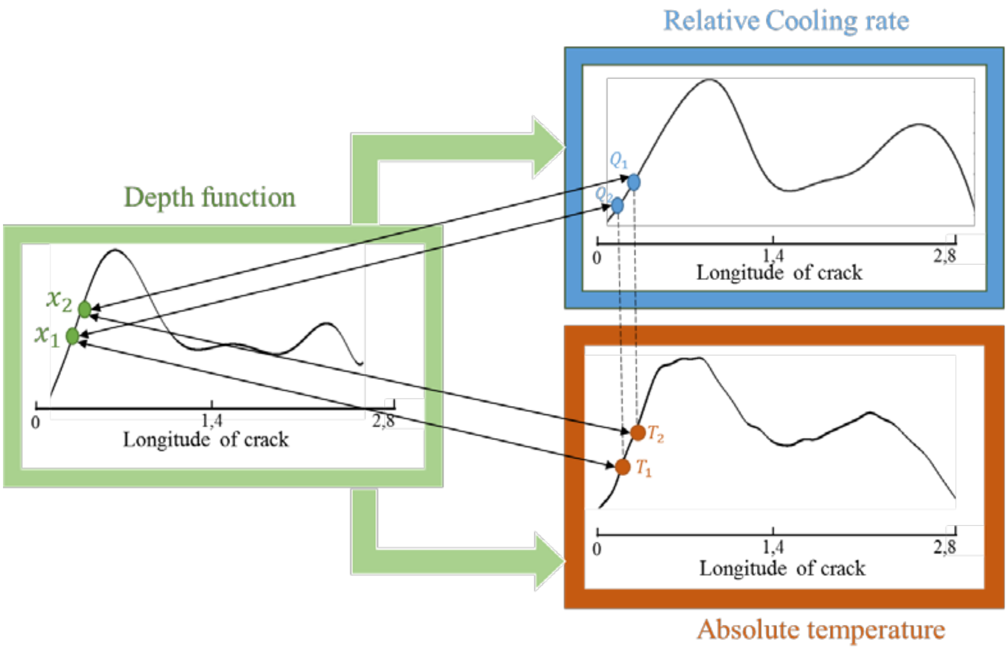

Fig. 6. For the computation of both correlations, the geometrical depth values obtained with macro-photogrammetry (left) are correlated with the cooling rate data (right-top) and absolute temperature data (right-bottom) through the longitudinal section distance values $(x_1, x_2, \dots, x_n)$.

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3. Results

Both correlations will be subjected to a statistical analysis towards the determination of their statistical quality and the identification of the optimal option (Fig. 7, Fig. 8): temperature-depth correlation VS cooling rate-depth correlation. The maximum depth of the crack is 0.19 *mm*; the temperature in this maximum depth point is the highest (around 44ºC) while the cooling rate is the lowest (highest relative cooling rate, implying that the material in the area takes longer to cool).

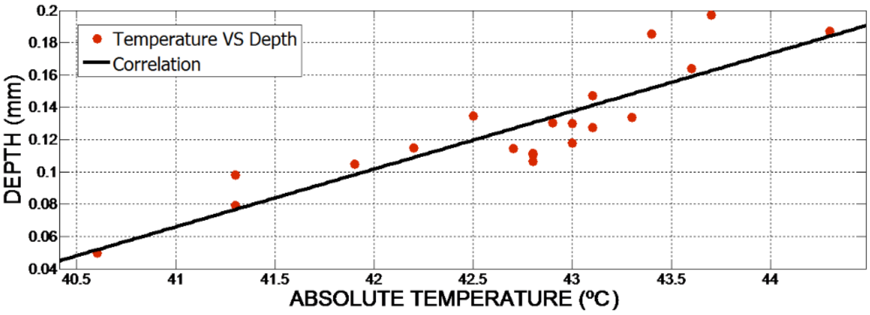

Fig. 7. Correlation between temperature and depth values. Red points represent depth and temperature for each 3D point in the longitudinal section of the crack.

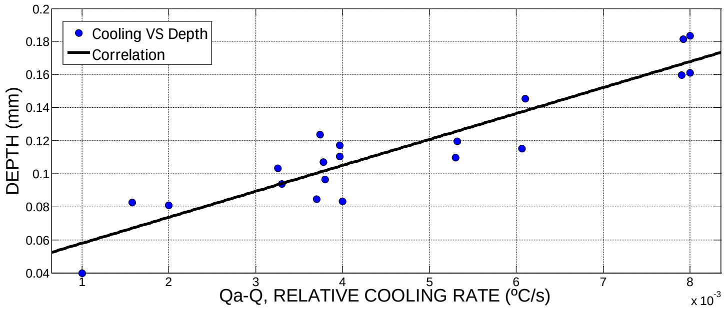

Fig. 8. Correlation between relative cooling rate and depth values. Blue points represent depth and relative cooling-rate for each 3D point in the longitudinal section of the crack. When the relative cooling rate is higher, the cooling of corresponding zone is lower.

The root mean square deviation (RMSD) is a good scale-dependent measure of precision for a prediction model. RMSD and R^2 are obtained for the both correlations analyzed. The RMSD for cooling rate-depth correlation is 20% lower than the depth-temperature correlation. This means that the cooling results could present a better statistical adequacy in comparison to the temperature results (Table 1) for the prediction of depth of the crack.

Table 1.Results of RMSD for both correlations under study.

Statistics parameters of goodness: **Cooling rate-Depth VS Absolute Temperature-Depth**		
	RMSD *(mm)*	R^2
Temperature distribution study	0.0174	0.77
Cooling rate distribution study	0.0141	0.86

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4. Conclusions

The prediction of depth for surface cracks in welding unions using infrared thermography is possible through the study of the temperature distribution along the crack, as shown in [12]. This is an important step because the measures for depth into the crack are of the order of tenths of millimeter, increasing the complexity of the inspector's task for the measurement of small depths with the inadequate tools currently used. In this study, a new thermographic study based on the comparison of absolute temperature data and cooling rate data to predict the depth of surface cracks in welding is introduced. In this way, both depth-prediction procedures based on infrared thermography have been compared in order to study the adequacy of the approach based on cooling rate [13] with respect to the temperature approach. Results show that the RMSD is 0.003 mm higher for the cooling rate correlation than for the temperature correlation, while the R^2 of the first correlation is closer to 1, implying a better correlation. Thus, the depth prediction from cooling-rate data gives a better statistical adequacy than the prediction established from temperature values. This preference could be principally due to the effects of emissivity and infrared reflexes, which do not present an important effect on the cooling rate study because the parameter is analyzed as a function of time, allowing the compensation for the previous effects. As a conclusion of this preliminary study, the cooling rate approach allows the better correlation of depth data into the crack and it could be a great advantage to design accurate prediction models for depth in surface cracks. Further research would perform the study in a wide selection of cracks of different typologies and in different steel materials, for the deeper understanding of their heating and cooling physics and extraction of correlation models towards the use of infrared thermography as quantitative inspection technique.

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