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Cooling analysis of welded materials for crack detection using infrared thermography

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HIGHLIGHTS

- We propose a methodology to detect cracks in welds based on active infrared thermography.
- The method integrates thermal image analysis and study of the cooling data.
- Morphological characterization of defects is performed by contour lines processing.
- The method detects and characterizes cracks according to the quality standards.
- Two types of warming are used for the comparison of results.

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ABSTRACT

Infrared thermography offers a wide range of possibilities for the detection of flaws in welding, being the main difference among them the thermal excitation of the material. This paper analyzes the application of an inexpensive and versatile thermographic test to the detection of subsurface cracks in welding. The procedure begins with the thermal excitation of the material, following with the monitoring of the cooling process with IRT (InfraRed Thermography). The result is a sequence of frames that enables the extraction of thermal data, useful for the study of the cooling tendencies in the defect and the non-defect zone. Then, each image is subjected to a contour lines algorithm towards the definition of the morphology of the detected defects. This combination of data acquisition and processing allows the differentiation between two types of cracks: toe crack and subsuperficial crack, as defined in the quality standards.

1. Introduction

Welding is the metallurgical process most widely used worldwide for joining metals. Furthermore, the steel structure today is a strategic sector in Europe. The steel market in the EU is recovering gradually from the damage caused by the economic crisis, driven by improved activity in key markets [1] and forecasts are favorable due to the fact that metallic structures can be recycled and reused, highly valued aspects in the current economic situation.

Tests on weld can be destructive or non-destructive (NDT). Already in 2004 [2], made a comparison between destructive methods like macrography and Vickers test and non-destructive test like lock-in thermography, concluding that there must be a synergy between both types of tests, each of them supplementing the other.

The application of NDT to the study of welded elements is particularly relevant because of the requirement to welding to ensure safety in structures and machine elements; therefore, non-destructive techniques have been the object of numerous investigations in the last 30 years. However, the latest research shows the need of finding a technique for the detection of faults in welding that can be easily applied on site without causing any damage or malfunction to the machine or the structure.

The NDT methods recognized by international standards (ISO) are radiographic test, ultrasonic test, magnetic particle, eddy current and liquid penetrant. Among them, ultrasonic inspection and radiographic (X and gamma ray techniques) are officially regulated in Europe [3,4]. Comparative studies between these methods are presented in [5,6]. These techniques offer the possibility of automation, recording, viewing and verification of integrated inspection results, and they are also the most precise, versatile and sustainable testing methods; however, these techniques also have their limitations: in the majority of cases, they are only able to detect the defect, presenting some difficulties for its geometric

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characterization and also, sometimes, to value it in accordance with the standard. Also these methods have difficulty to detect near surface defects. Due to these limitations, the combination of any of these techniques, ultrasounds and radiographic test, with infrared thermography has been already investigated for metals like aluminum [7]. Researchers conclude that this combination produces better results than optically stimulated infrared thermography to detect internal and close cracks, although they recognize that further research should be made.

The radiographic (X and gamma ray techniques) test allows the display of a graphical profile of the interior of the piece, as well as the precise location and measurement of defects; its disadvantages are the high cost of the technique, the need of complex cooling systems in the tube, the danger derived from the radioactivity, the requirement to generate high voltage at the cathode and the low-portability of the equipment. These facts limit the use of radiographic methods to specific circumstances. In addition, the defects that do not have air inside (like inclusions of material) are not shown in the radiographic image as clearly as other defects; furthermore this method presents difficulties for small volume weld.

The application of infrared thermography to the detection of defects began in 1960–1970, when electronics and optics systems in the infrared band started to be employed in aerospace and nuclear engineering. However, the bad operation characteristics of infrared systems in those years held back its development as NDT [8]. Currently, there are different thermographic techniques depending on the heating method. Passive thermography is based on the acquisition of thermographic images of the object under study without external heat supply. In some cases, the heating caused by the incident radiation from the Sun is used to analyze the behavior of the differential surfaces and to detect pathologies like humidity or insulation defects [9]. On the other hand, active thermography is based on the use of an energy source that enables the excitation of atoms in the material. The heat source varies according to the technique employed. So far active thermography has been implemented with surface heating by pulsed laser [10,11] and flashlamps [11–16]; also no optical heat sources [12] like mechanical vibration [13,14], acoustic wave excitation [15] and microwaves [17] have been applied in active thermography. Regarding its application as NDT method, active thermography not only allows the detection and characterization of pathologies and flaws in materials [18,19], but also enables obtaining thermophysical parameters of the objects such as thermal diffusivity and thermal effusivity [20,21]. Active thermographic methods can be applied in non-destructive testing of welding, to allow the early detection of defects in different types of materials and for quality control in predictive maintenance and prediction of faults in machines, structures and even for troubleshooting in electrical equipment [22].

The main advantage of active thermography in comparison to other non-destructive techniques, is the large surface area covered and the high rate of image acquisition [23], in addition to the possibility of providing information as complete as the own radiography or gammagraphy image together with the versatile ultrasound test.

The tendency of the research so far has been towards the application of the technique of infrared thermography as NDT only in laboratories with sophisticated heating mechanisms aforementioned, which are difficult to apply in external environment; for this reason the European standard does not contemplate the IRT technique as another NDT method. However, recent studies have discussed the possibility of applying the heat source in the weld installation place. [17] have researched the application of heat with a microwave open source directly in the weld. It is a high thermal efficiency source, portable and which allows heating in a short time, but it is also an expensive resource, which requires a rigorous security study and presents difficulties to be used in Europe due to the safety standards for microwave heating systems [24].

The main objective of this paper is to validate a test procedure with a single, viable, safe, inexpensive heat source, which is also easy to use in outdoor environments, enabling the assessment of defects in accordance to European quality standards [25]. The proposed methodology consists on monitoring the cooling of the material after subjecting the steel to a small, continuous and homogeneous thermal excitation (lower heating at 70 °C); this thermal excitation is performed from two different positions regarding the front face of the welding: frontal and back heating. This difference in heating constitutes the core of the two methodologies analyzed. Image processing is performed with algorithms aiming at the applicability of the methodology to most existing scenarios.

The objective is to design a NDT procedure that allows the extraction of different thermal parameters and, according to them, obtain the defect situation in the weld and its characterization. For this purpose a thermographic camera is used and a heater with Joule effect is applied as excitation source. This heater is selected due to its characteristics of being accessible, safe, ergonomic and easily portable. When thermal data are obtained, the post-processing is implemented: first, a study based on temperature-isolines is performed in order to detect the defects and, once defects are detected, the cooling rates of both the defect and the healthy area are studied in order to analyze the trends in each area.

This paper is organized as follows: Section 2 presents the theoretical background of the paper; Section 3 describes the equipment involved in the essays, as well as the testing methodology; Section 4 includes a detailed data analysis for the detection of the cracks present in the weld; finally, Section 5 explains the conclusions reached after this study.

2. Theory

Newton's cooling law defends that intensity of heat energy transfer depends on the temperature difference between the different physical systems that interact [26]. Newton's cooling law (Eq. (1)) sets proportionality between the heat transferred to the environment by a body with higher temperature during its cooling Q (J) and the temperature difference (°C or K) between the material (T) and the environment (T_a). Starting with the definition of specific heat, c, of Eq. (2) and Newton's cooling law (Eq. (1)), the derivative of the temperature versus time, or what is the same, the cooling rate equation can be defined (Eq. (3)).

$$\frac{\partial(Q)}{dt} = -\alpha A(T - T_a) \tag{1}$$

$$c = \frac{1}{m}\frac{\partial Q}{dT}; dQ = -mcdT \tag{2}$$

$$\frac{\partial(T)}{dt} = -k(T(t) - T_a) \tag{3}$$

Being:

$$k = -\frac{\alpha A}{mc} \tag{4}$$

The solution to the cooling rate equation (Eq. (3)) for standard initial conditions is an exponential function with time as an independent variable (Eq. (5)), where T_0 is the material temperature at the initial time.

$$T(t) = T_a + (T_0 - T_a)e^{-kt} \tag{5}$$

The constant k (Eq. (4)) is associated to the material and geometry of the exposed surface, the constant depends on the heat