(03-044) - Detection of anomalies in stainless steel containers by means of infrared thermography

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Infrared thermography is a non-destructive testing technique widely used in industrial applications. In this study, the ability to detect anomalies in stainless steel containers using infrared thermography is analyzed. The vessels evaluated consist of an external coil welded on its lateral surface whose function is to heat or cool the vessel, depending on the needs. The objective of this study is to identify problems in the weld joint between the coil and the vessel by means of infrared thermography. Low emissivities and specular reflections of metal surfaces make it difficult to detect thermal patterns associated with possible anomalies. Thus, this study demonstrates the need to shield the area near the surface of the container to be analysed by thermography to avoid specular reflections and to favor the detection of thermal patterns on the surface.

Keywords: Infrared thermography; specular reflections; low emissivity; metals; anomaly

Detección de anomalías en cubetas de acero inoxidable mediante termografía infrarroja

La termografía infrarroja es una técnica de ensayos no destructivos ampliamente utilizada en aplicaciones industriales. En este estudio se analiza la capacidad de detectar anomalías en cubetas de acero inoxidable mediante termografía infrarroja. Los recipientes evaluados constan de un serpentín externo soldado en su superficie lateral cuya función radica en calentar o enfriar el recipiente, según las necesidades del producto. El objetivo es identificar problemas en la unión de la soldadura entre el serpentín y el recipiente mediante termografía infrarroja. Las bajas emisividades y los reflejos especulares que presentan las superficies metálicas dificultan la detección de patrones térmicos asociados a las posibles anomalías. Así, este estudio demuestra la necesidad de apantallar la zona cercana a la superficie de la cubeta que se va a analizar mediante termografía para evitar reflejos especulares y favorecer la detección de patrones térmicos en la superficie.

Palabras clave: Termografía infrarroja; reflejos especulares; baja emisividad; metales; anomalía

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Agradecimientos:

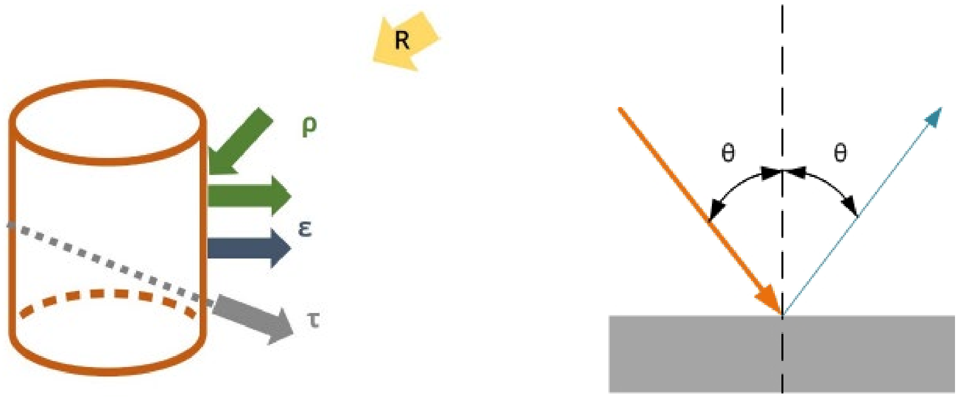
1. Introduction

Metallic materials are widely used in the industry because of their features, they are long-lasting, non-corrosive, inert and can be manufactured into different size and shapes. Specifically, in food industry, stainless steel containers are commonly used to store all kinds of foodstuffs since they are hygienic along with, they are resistant to both temperature and corrosion (Deshwal et al., 2019). In some cases, the needs of the product to be stored require additional external heating or cooling. For this purpose, one possibility is to weld a coil to the outer surface of the container through which a fluid at a desired temperature can circulate. In order to keep the product of interest warm or fresh, the heat transfer via conduction between the coil and the container must be effective. In this sense, the thermal conductivity of the container but also the contact between the coil and the container surface are of utmost importance. Welding is a very common method for joining materials, specifically metallic ones, however, during the process some problems can appear such as lack of contact or discontinuities, which can result in the eventual deterioration of the stored product. Due to the latter, it must be ensured that the welding has been accurately performed, confirming, therefore, a good thermal contact between the coil and the vessel. When evaluating weld-joints, several non-destructive techniques can be used such as ultrasounds, magnetic particles, radiography, or infrared thermography (Farley et al., 1998).

Infrared thermography is a non-destructive technique in which radiation emitted by body surface (at temperatures above absolute 0) is detected and captured by an infrared camera at a distance from it. Since it is a non-invasive technique, nowadays, it is being used in a wide range of areas such in the electrical field, mechanical applications, renewables, building survey but also in medicine or veterinary (Osornio et al., 2019). When an element is to be inspected, several thermography approaches can be distinguished (Vavilov et al., 2020). In the passive mode, objects to be tested undergo thermal changes on their own because of their normal operation and no additional thermal excitation is needed (Maldague, 2001). Some examples can be found in electrical connections, bearings failures, or injuries in medicine applications. In this sense, passive infrared thermography in many industrial processes such as predictive maintenance or manufacturing processes, may be essential to assess their proper operation. Conversely, when the object to be inspected presents the same temperature as its surrounding, the desired flaws cannot be located unless an external thermal excitation is performed (i.e., turbine blades, or composite materials used in aerospace) (Maldague, 2001). On the other hand, when evaluating infrared information, a distinction can also be made between the qualitative and quantitative approach. When the aim is focused on the thermal patterns of specific regions of interest and accurate temperature measurement assessment is not intended, a qualitative analysis is usually performed. However, when temperature variables within an image or a specific area are to be accurately determined, a quantitative approach must be performed. In these evaluations, the compensation parameters including emissivity, reflected temperature or distance must be considered (Vollmer et al., 2017). Although qualitative inspections may seem more straightforward, some considerations must be taken into account to avoid errors in the image's interpretation (Cañada et al., 2016)

When radiation reaches a body, it can partially be absorbed (α), reflected (ρ) or transmitted (τ) through it and when the outgoing radiation of a body is evaluated, it can be reflected and/or transmitted when coming from other sources (Figure 1a). Finally, the body can also emit radiation (Vollmer et al., 2017).

Figure 1: a) Fractions of radiation when the radiation abandons a body b) specular reflection in a reflecting surface.



a) **b)**

Moreover, energy conservation states that any radiation reaching a body can be reflected, transmitted through the object, or absorbed within the object and in case of opaque objects, that present nule tranmission, the emission and reflection of an object are complementary (Bergman et al., 2017).

$$\varepsilon + \rho = 1 \quad (1)$$

Particularly, for an opaque surface, the radiosity j_i (W/m^2) accounts for all the radiant energy leaving the surface.

$$j_i = \varepsilon \cdot \sigma \cdot T_{obj}^4 + (1 - \varepsilon) \cdot \sigma \cdot T_{surr}^4 \quad (2)$$

where ε is the emissivity of the object, σ is the Stefan-Boltzmann constant, T_{obj} [K] is the temperature of the body surface and T_{surr} [K] is the temperature of the surrounding surfaces. Hence, body surfaces with lower emissivity present higher values of reflectivity, which would lead to greater surroundings' influence. For this reason, thermal reflections play an important role when it comes to detect flaws based exclusively on thermal patterns. In this sense, the materials themselves, or their surface's characteristics such as the geometry or the surface finishing have a direct influence. Specifically, smooth surfaces such as glass, polished and/or varnished metals or wood are the ones that makes infrared inspections most challenging since they lead to specular reflections. In these situations, the reflections of objects around the element being inspected along with even the thermographers themselves may predominate over the thermal patterns associated with the inspected element itself. Figure 2 shows an example of such behaviour where the thermographers' reflections on a metal tank can be observed on the infrared image (Figure 2b).

Figure 2: Thermal reflections observed on an infrared image on a tank made of metal.

Thus, when performing qualitative thermography to detect specific thermal patterns associated to defects or failures, it is advisable avoiding thermal reflections.

In this paper, infrared thermography has been used to evaluate the bonding welding between the coil and the stainless-steel containers in order to detect points of poor cohesion.

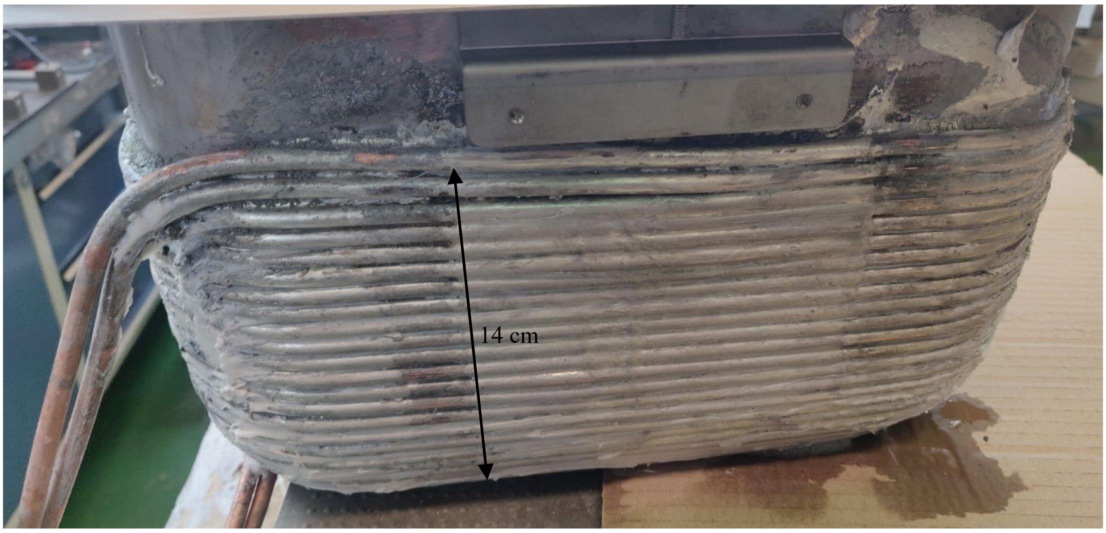
2. Objectives

The objectives of this study are therefore to demonstrate the feasibility of infrared thermography to detect faults in the coil welding of stainless-steel containers. Moreover, the limitations of such materials have been evaluated.

3. Methodology and case study

10 stainless steel containers were inspected. The size of the containers is 460 x 350 mm^2 and 203 mm deep. All of them presented an external coil (wrap double circuit with copper tube Ø6x1, total 11 turns plus outlets, 14 cm high) covered with aluminium adhesive tape welded in its outer surface. To illustrate the device in Figure 3 a typical stainless steel is shown.

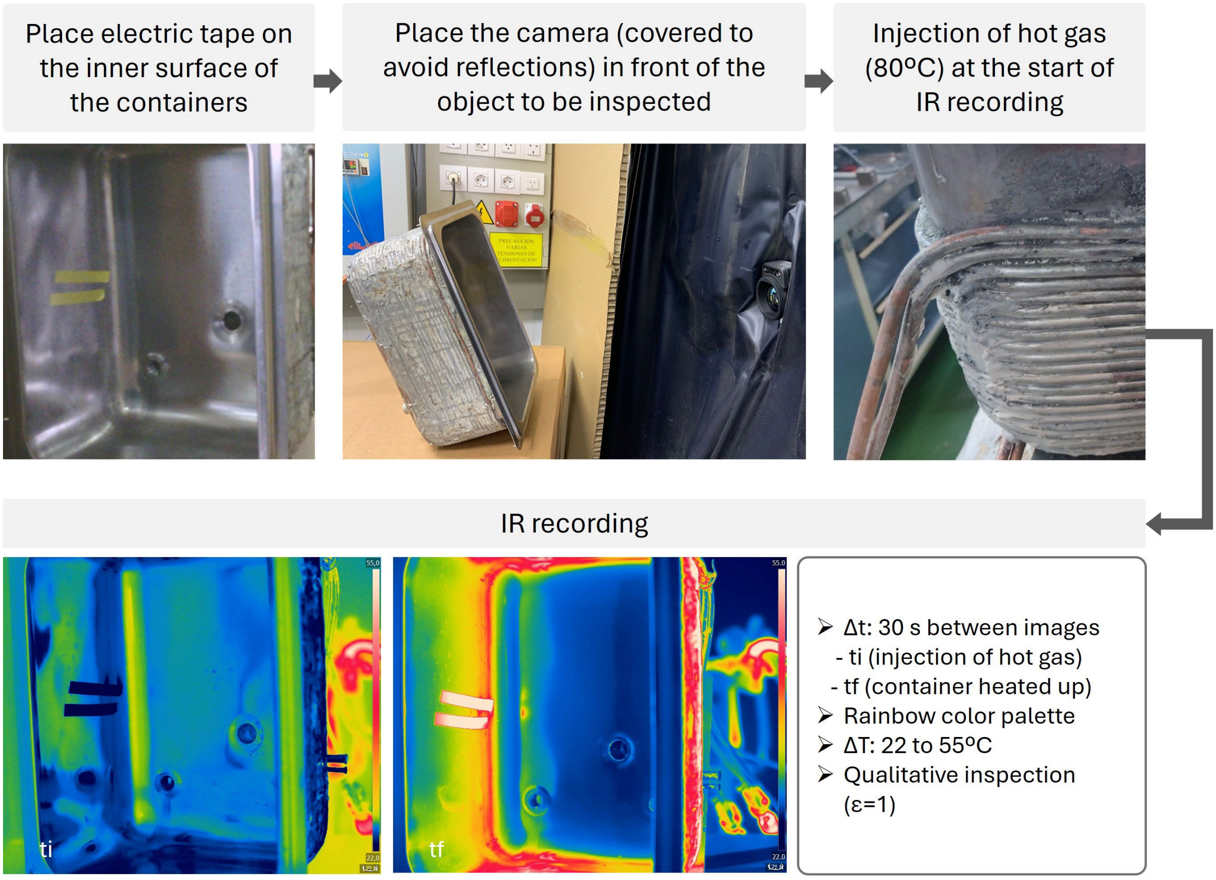
Figure 3: Outer surface of a container showing the welded coil



On the other hand, Figure 4 shows the methodology workflow followed in this work. All containers were inspected by means of infrared thermography. Thus, to achieve sufficient thermal contrast so poor contact point in the weld could be detected, containers were heated up by means of a hot gas (at approx. 80ºC) injected through the coil. If the welding was carried out correctly, the contact between the coil and the container would be good. In this situation, the heat transfer by conduction between the heated coil and the container would be good and consequently, when the inner surface of the container was inspected with the infrared camera, uniform heating would be observed. Otherwise, failure welds would mean poor contact and therefore conduction between the coil and the containers would not be as good. Consequently, in these cases, the infrared thermography images would show non-uniform heating on the inner surface and the coil would be separated for re-welding.

Infrared data were recorded using an infrared camera FLIR T1020 (FLIR Systems, Inc., Wilsonville, OR), working in the long wavelength range (8-14 μm), with a field of view (FOV) of 1020 x 768, a thermal resolution (NETD) of < 20 mK at 30ºC and measurement uncertainty of ± 2ºC of the overall temperature reading. All the inspections were carried out in a company responsible for production of ice-cream machines in València during March 2021.

Figure 4: Methodology workflow



Since the aim of the work did not involve the temperatures measurement, qualitative infrared thermography was performed. In this sense, thermal adjustments regarding emissivity and background temperature were established at 1 and 0, respectively. However, since the containers to be inspected presented several thermal reflections, some measures were envisaged to avoid them as much as possible. Thus, each container to be inspected was shielded using a cardboard. Moreover, the infrared camera along with the other elements concerning the inspection (even the thermographers), were covered by an opaque curtain as shown in Figure 5. Only the camera lens focusing the inside surface of the container was not covered.

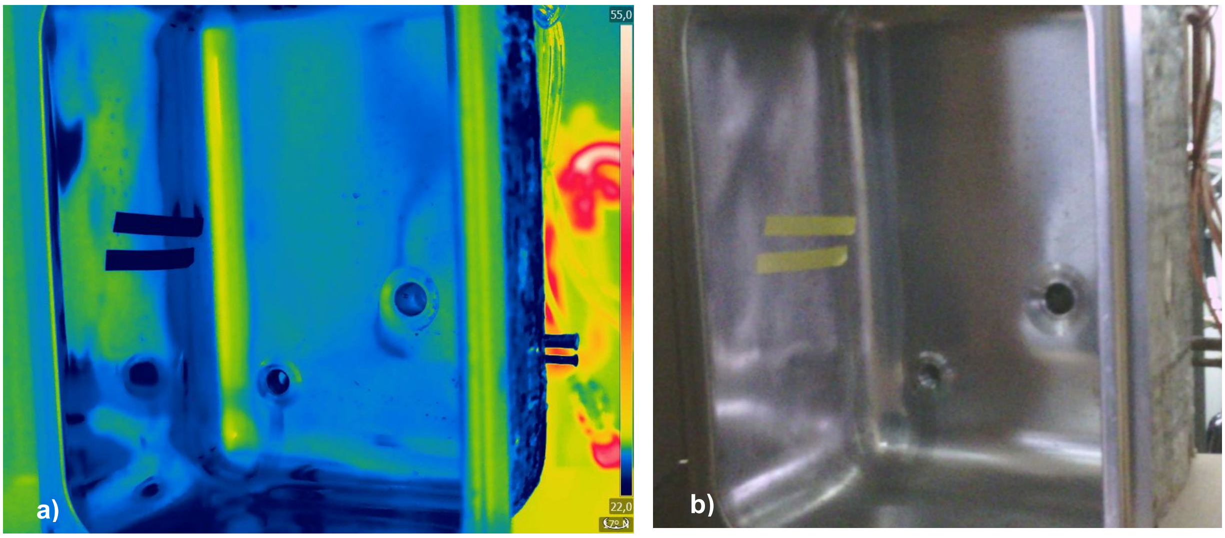
Figure 5: Set up of the infrared thermography inspections.

On the other hand, materials with fast thermal responses, such as metals, are usually monitored in transient state, that is, their thermal behaviour are evaluated as a function of time. To do so, the sample must be subjected to a significant thermal contrast and at the same time, the surface temperature must be recorded during a period of time. Thus, when the thermal pattern is considered as suspiciously irregular, it may be related to a defect area.

First, a container performing properly was inspected, acting as a reference one. Then, 10 tests on different containers suspected of malfunctioning were analysed. Thus, each infrared inspection concerned one container.

Periodic recording of infrared images every thirty seconds were made, starting from the injection of hot gas through the coil and lasting until the entire coil heats up. As shown in Figure 6b, the inner surface of the stainless-steel containers were inspected. A rainbow colour palette has been chosen to help the visualization of the thermal pattern (Figure 6a). The same range of apparent temperatures between 22ºC and 55ºC has been adjusted. Additionally, electric tape with high emissivity (and therefore, very few reflectivity) was placed on the inner surface of the container to show thermal patterns without being influenced by reflections.

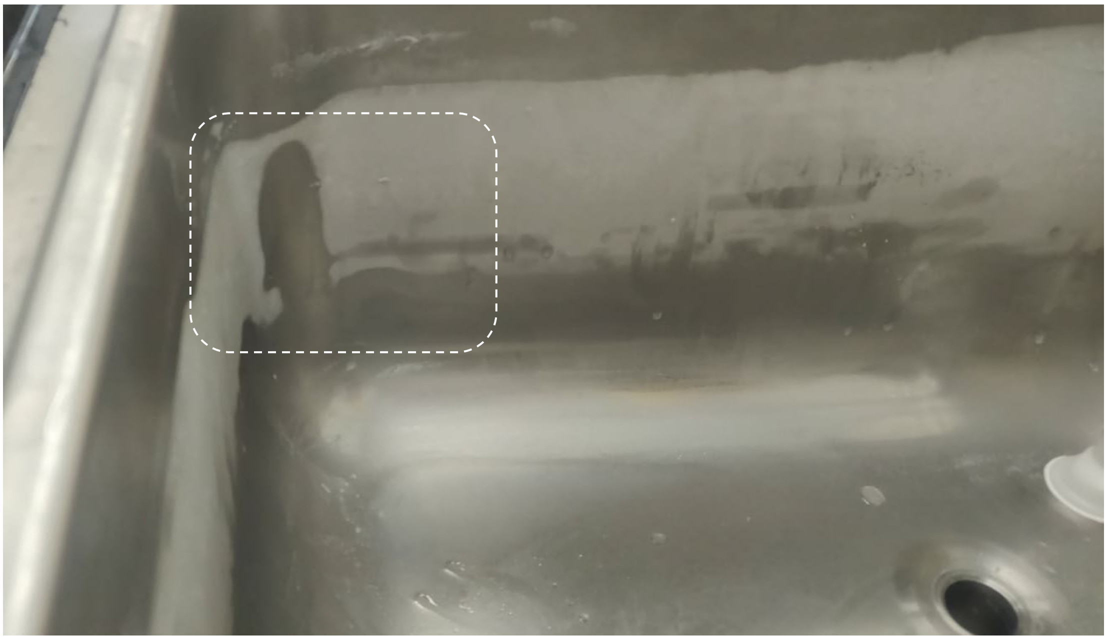
Figure 6: a) Infrared and b) visual image of the inner surface of a stainless-steel container at ambient temperature.



4. Results

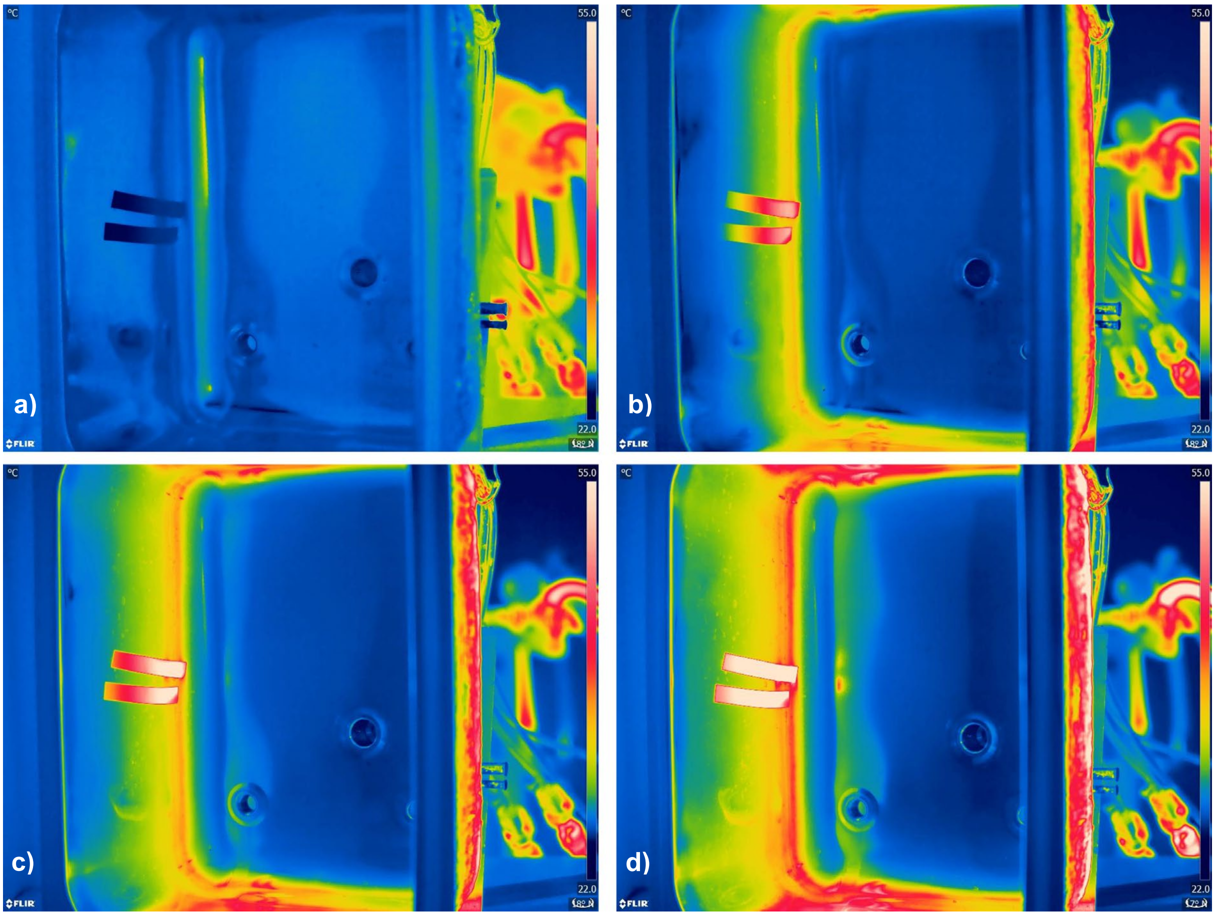
The reference container presenting the correct welding was the first one to be inspected. Then, ten containers suspected of presenting welding faults were analysed. In such cases, the manufacturer noticed that during the normal operation, in which cold gas is injected through the coil, the cooling inside the containers were uneven. Figure 7 shows an example of this situation. Certain areas of the inner surface present non-uniform cooling, which may mean a failure in the welding of the coil.

Figure 7: Stainless steel container in normal operation for storing ice-cream. Certain zones presenting uneven cooling can be observed.



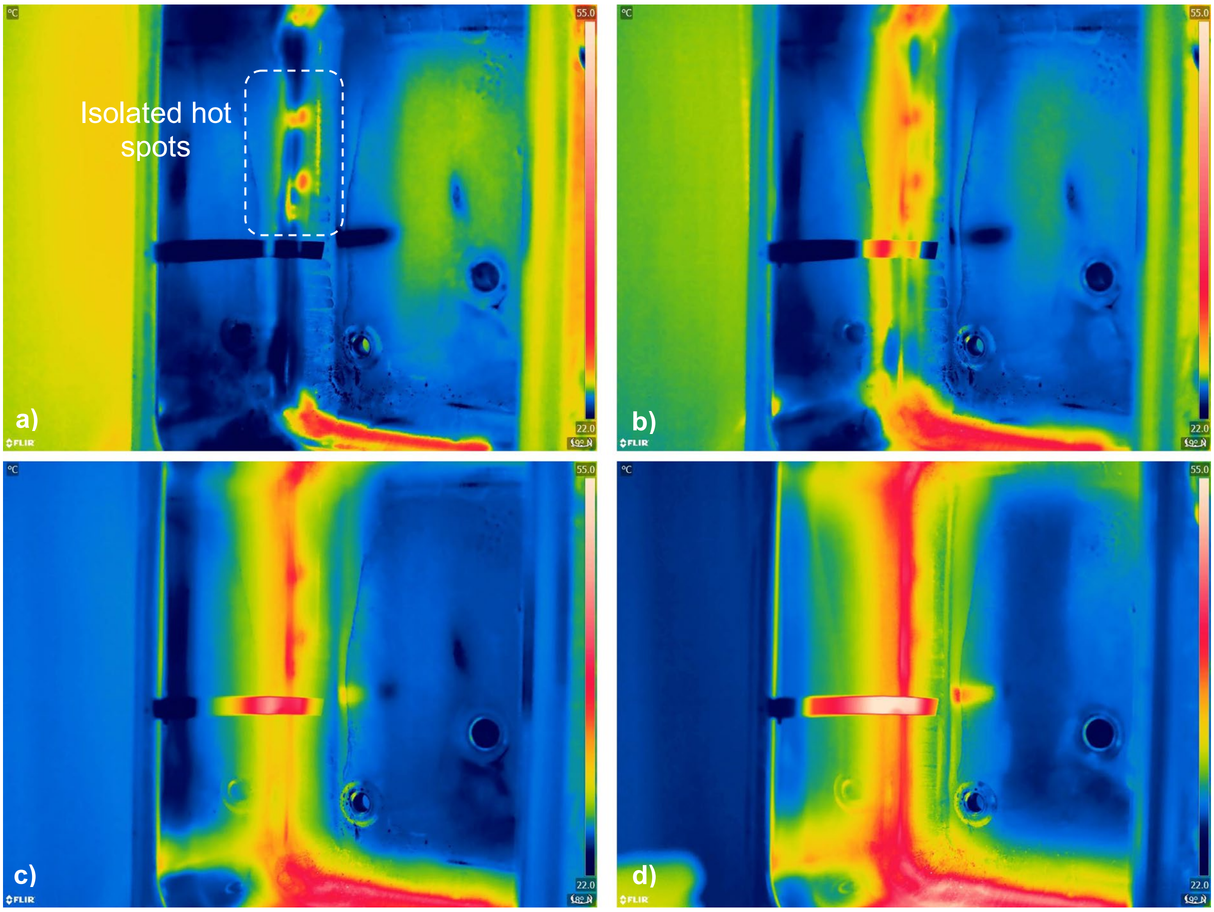
To have a baseline of proper operation, a container with its coil assumed to be correctly welded and with proper thermal contact was first inspected. As can be observed in Figure 8, from the first moment when the hot gas is injected through the coil (Figure 8a), and until 90 seconds after (Figure 8d), the thermal pattern corresponding to the heating of the coil is uniform. Additionally, the thermal pattern observed within the tapes placed on the inner surface, confirm such uniform warming. Hence it may confirm the appropriate thermal contact between the coil and the container and, therefore a correct welding.

Figure 8: Infrared images of the reference stainless steel container taken every 30 seconds right after the hot gas is injected into the coil (a).



Following the reference container, ten more containers suspected of presenting welding faults were analysed. Among them, a lack of uniformity in thermal patterns was detected in some cases. Figure 9 shows an example of a stainless-steel container with an uneven thermal response. In Figure 9a, already after the coil starts to be heated up, isolated hot spots appear in the inner surface instead of a continuous heating line corresponding to the first circuit tube. Besides, the adjacent inner surface corresponding to the narrowest one of the container already presents a more pronounced warming. About one minute after (Figure 9c), although the inner surface present a warm-up, it lacks uniformity.

Figure 9: Infrared images of a stainless-steel container taken after the hot gas is injected into the coil. After: a) 30 s b) 60 s, c) 90 s and d) 120 s.



Using the same infrared images on Figure 9, a complementary support tool has been applied in order to make it easier to detect the contact problems on the container (Figure 10). The mentioned tool, known as isotherm, highlights the desired temperatures interval within the infrared image. Thus, the original infrared image is displayed in gray palette and the isotherm, conversely in yellow, highlights only the areas within the image in the selected apparent temperatures. In Figure 10a) and b), specifically, the isotherms indicates the temperature intervals from 32.6 ºC to 35.6 ºC and from 35 ºC to 37 ºC, respectively. In this sense, it can be clearly seen that the heating up pace is irregular in the two different inner surfaces evaluated in the thermography inspection. On the one hand, as previously mentioned, the inner surface where the electrical plate is placed, presents a slower warming. When apparent temperatures reach 36 ºC, the adjacent surface has already overcome 45 ºC (Figure 10b). Moreover, warming on this surface is far from being uniform since, as it can be observed, there is an area comprised in the middle of the isotherm at a higher apparent temperature. Similarly, will occur when instead of hot gas, a cold gas would be injected through the coil in normal operation. As a result, there will be areas of the inner surface presenting irregular thermal patterns, and consequently, cooling the stored ice-cream in an irregular way.

Figure 10: Isotherm used on infrared images of a stainless-steel container taken a) one and b) 2 minutes after the hot gas is injected into the coil.

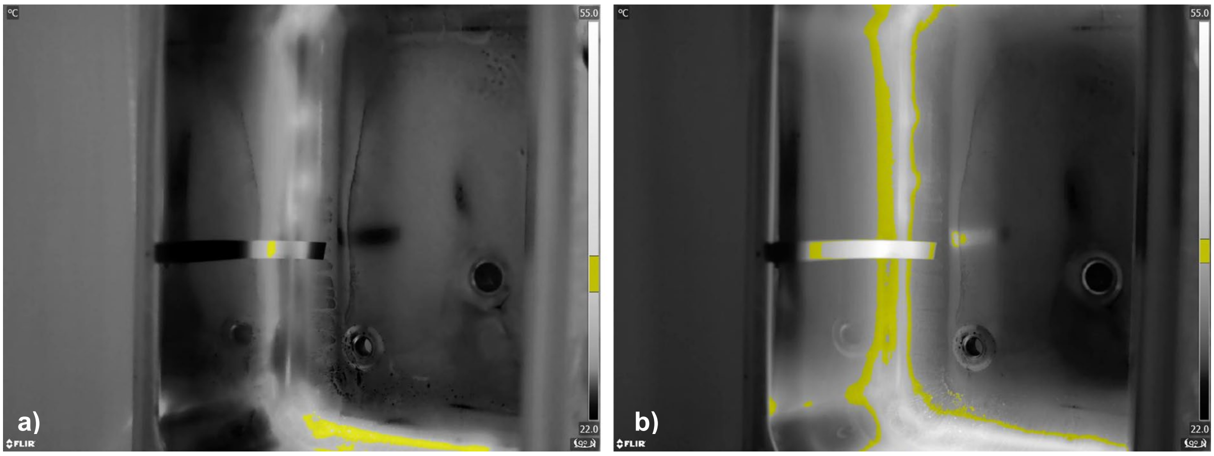
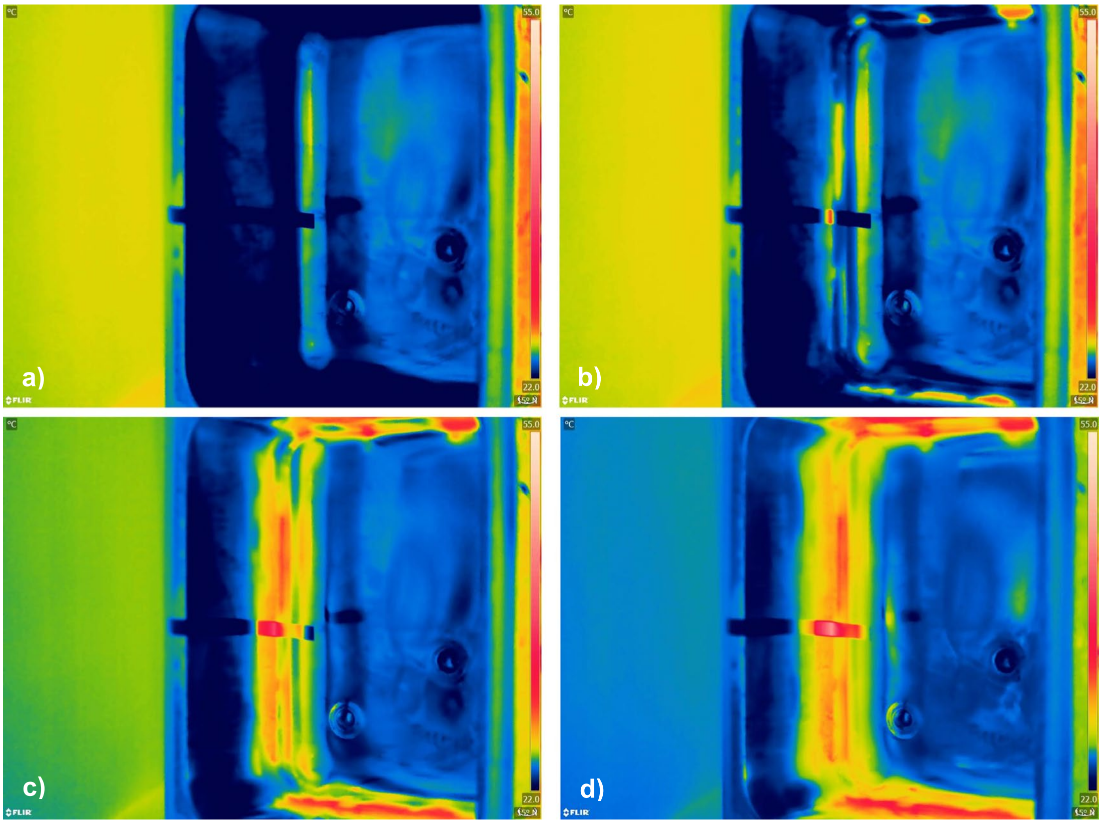


Figure 11 shows another example of a stainless-steel container with an uneven thermal response, in which infrared images acquired right after the injection of the hot gas into the coil and after 30, 60 and 90 seconds are presented. In this case, the inner surface corresponding to the one where the electric tape is placed shows at first a warming in form of a line, instead of spots. Nevertheless, subsequent infrared images reveal the irregular warming on the different surfaces of the container. Thus, in Figure 11 c) areas located near the corners present lack of warming, whereas central areas show better uniform heating. This latter effect seems reasonable since the welding of the coil at the corners would be more difficult. Therefore, the areas observed on the corners could correspond to poor contact areas due to welding failures.

Figure 11: Infrared images of a stainless-steel container taken a) right after the hot gas is injected into the coil and after: b) 30 s c) 60 s and c) 90 s.



5. Conclusion

The feasibility of infrared thermography as a support tool to detect weld discontinuities in stainless - steel containers has been demonstrated. Generating a sufficient thermal contrast (approx. 50ºC) in the container by means of a hot gas circulating through the coil, enable the observation of areas of irregular warming in infrared images which may indicate contact problems between the coil and the container.

Stainless steel is a material widely used in the ice-cream industry, however, due to its polished surface, it presents several thermal reflections, which makes infrared inspections a challenging task. Since this kind of materials, and specifically, this kind of polished surfaces may be a nuisance concerning the infrared analysis, it should be advisable to supress or to reduce them as much as possible. For this purpose, placing a shield over the element to be inspected has been proved to be necessary to visualize the desired thermal patterns without external influences (reflections). Additionally, using different colour palettes and tools such as the isotherm not only make a difference when interpretation is involved, but they also may avoid that several details would be overlooked.

Weld performance in steel containers for food industry plays an important role, since the existence of discontinuities or flaws may cause a reduction in the subsequent operation process, which may result in quality issues of the product stored. Therefore, infrared thermography has shown a feasible non-destructive technique for qualitatively evaluate coil welding in stainless steel containers.

6. References

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