IR Thermography for the Nondestructive Evaluation of the Protective Coating Coverage on Steel Substrates

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ABSTRACT

The infrared thermography (thermal imaging) is considered a flexible, non-contact, and non-destructive tool used to evaluate wide variety of coating attributes (e.g. appearance and protective attributes). This paper addresses the application of thermographic systems in evaluating the protective-coating coverage over steel substrates in two different painting industries. First case is the inspection of the ballast ship tanks coating for "Holidays" or missed coated spots. The second describes the development of an automated thermographic system, designed to inspect for: thin coating, coat cracking, and coat chipping of an anti-corrosive paint applied on automotive steel containers.

This work describes the theory of detection and the thermographic system design and implementation that include the hardware and the software development, where an in-house code is used to process the acquired data.

1- Introduction

Coatings are applied on material surfaces to provide two main attributes. (1) Appearance that relates to the color dimensions and the geometrical aspect that features haze and gloss. (2) Protection, represented by its ability to protect against corrosion. This protection is achieved by utilizing a primer layer that functions through insulating the substrate from surrounding conditions (e.g. weathering effects). In the case of corrosion, this insulation protects by breaking the corrosion cycle (i.e. Anode, Cathode and an electrolyte) by shielding the steel substrate from the electrolyte (e.g. salt water). Because insulation is crucial, coverage and integrity of the coating must be accurately inspected to ensure it will protect as it is designed.

Infrared thermography or, IRT nondestructive applications constitute the thermal mapping of material surfaces to investigate its facial and/or its subsurface status that may affect its performance. This is done using photonic or bolometric arrays sensitive in the (1-13 μm) band of the electromagnetic spectrum [1]. IRT has been successfully used as a real-time thermal machine vision system for detecting thin paint spots on automotive fuel containers in [2]. Further, it has effectively been used to detect latent corrosion in different steel structures including bridges [3] and petroleum reservoirs [4]. Furthermore, Infrared thermography has also been used to measure the thickness of different types of coatings such as Thermal Barrier Coatings (TBC) applied to turbine blades [5, 6]. This technique has two advantages as an inspection method for coated structures: (1) no contact with the surface, enabling it to be applied in wet and dry settings, and (2) area coverage enabling it to be applied in large structures such as, ships' ballast tanks and bridges [7].

Next two sections of this manuscript introduces two case studies for the IRT coating inspection; one is the real-time, on-line detection of thin paint spots on coated steel fuel containers in automotive production lines. The second relates to IRT application in evaluating ships ballast tanks' coat coverage.

2- Fuel containers inspection

In this work, the targeted products are automotive steel fuel containers coated with a single layer of a waterborne, anti-corrosive protective coating (150-400 µm in thickness). Those containers are mass- produced to serve as a safe fuel storage and supply source. For this case, the coating application problems to be detected were (1) thin paint (or spots missed, uncoated) and (2) chipping upon curing. Both kinds of defective application expose the substrate and thus may allow corrosion to begin if uncorrected.

The two current methods for inspecting these defectives are not optimal. Visual inspection by human operators is not continuous but relies on checks during certain time periods; industrial plant lighting conditions and the small size (~ 0.4 mm; see figure 1,a) of the defects make accurate inspection by the naked eye difficult. Visual inspection routines utilizing Charged Coupled Devices CCDs are also less than optimal for this application due to the rough surface profile (as shown in figure 2) and certain aspects of the surface geometry. Both of these factors cause light scattering that can mask defective spots.

The analytical study and the laboratory testing for this application are fully presented in [2], where a micro-bolometer infrared detector was used to scan the surface of the tank detecting the difference in thermal emission from the pinholes (behaving according to steel substrate thermal properties) and the well coated surroundings (emitting according to paint properties). This deviation is displayed in figure 2,b and quantitvely described later in the text.

Because, thermography requires thermal emission from the surface, the online deployment started with surveying the containers production cycle to decide where to install the system. Production lines for such containers use curing-ovens to cure and dry the coat film. Because these ovens operate at between $373-423K$, they can serve as a thermal stimulant, which eliminates the need for an external heating unit and consequently improves the system's reliability and compactness.

An industrial packaged thermal detector with 320×240 array and $60Hz$ acquisition rate (commercial name A40M, FLIR MA,US) can be installed at the exit of the curing oven. This detector scans the container as it comes out of the oven, and interfaces the acquired thermograms through $IEEE1394$ link to processing unit. The on-site results are shown in figure 3 . The processing logic is discussed in section 4.

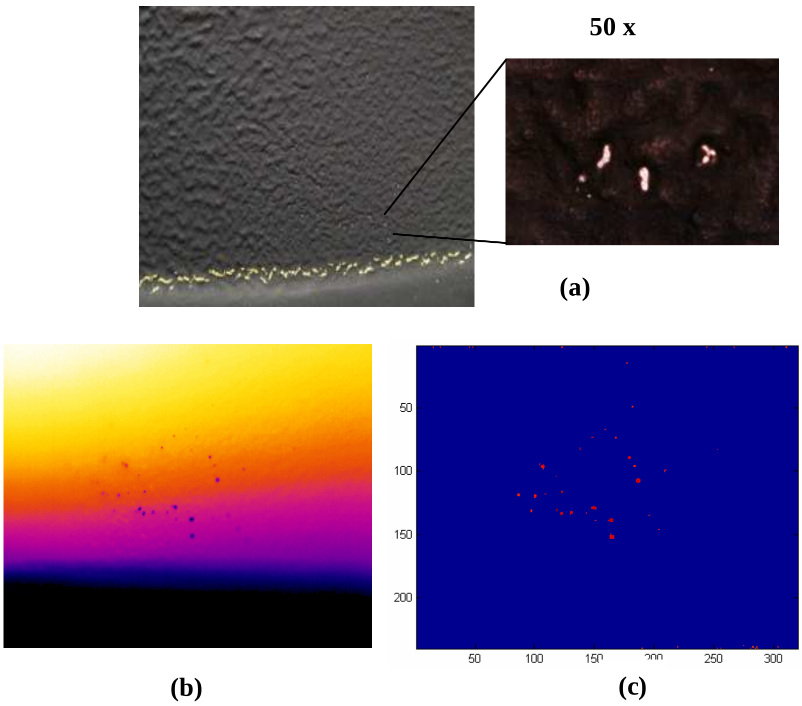


Figure 1. Visual, thermal and post-processed images of an under coated sample container: (a) Visual image for thin spots, and under 50-x magnification, (b) Thermal image of the field view in a, and (c) Processed image

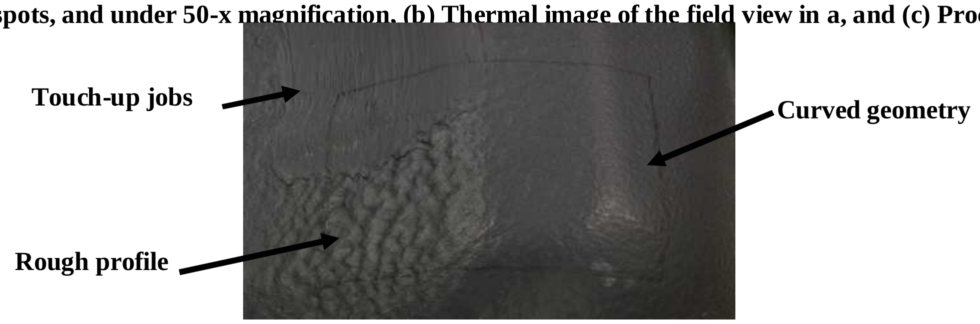
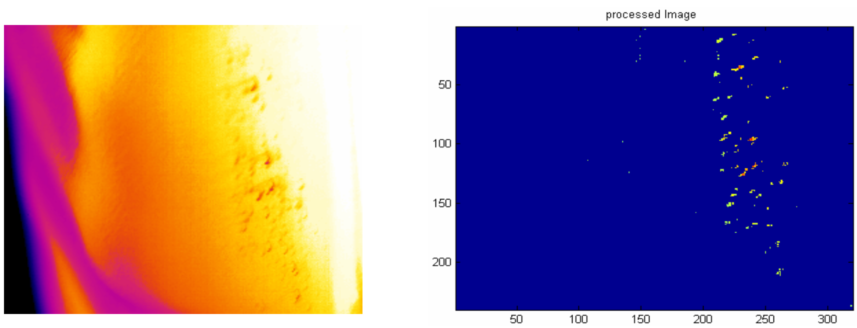


Figure 2. A color photograph showing surface profile of coated container

3- Ballast tanks inspection

This section focuses on the evaluation of newly coated ships' ballast tanks with marine primers that range in thickness from 125 – 250 microns. Oil tankers and other medium to large size ships use the ballast tanks to stabilize its floating equipments, by filling it with seawater. Corroded ballast tanks not only affect their own performance but also the safety of the whole ship.. While, currently used tools are applied in an on-site (e.g. wet sponge) and/or an off-site modes (e.g. wave tank introduced by Marintek, Norway)[8], it still require: (1) a dry paint film, which delays the inspection and separate it from the application step, even though, what is desired is to merge the inspection and application in a single step "do it right the first time", to (a) save time and effort and (b) facilitate an immediate correction because, the cost of a touch job is about $22/m^2. (2) Physical contact, this requires accessibility to corners and cervices that are considered most critical for corrosion initiation, while those tanks complicated geometries and uniqueness challenge this accessibility. Those two shortcomings, in addition to the recently issued regulations [9] that enforce more stringent standards on the finished ballast tanks' and the increase in ships sizes, the tankers size went from 100,000 dwt to 500,000 dwt in 10 years [10], motivate the development of a nondestructive, non-contact and real time tool to evaluate the paint deposition quality in terms of coverage and layer thickness.

Visible techniques in the form of machine vision systems or human naked eye inspection offer a contact less operation, however still inadequate for the detection of coating pinholes due to (1) variability and availability of environments lighting, as in dark tanks and (2) its sensitivity to the inspected surfaces' profile and geometry, due to its dependence on reflection. Those two factors hinder the repeatability and the reliability of this test. In addition, visual inspection is a facial technique not capable of providing thickness information.



(a) **(b)**

Figure 3. An on-site test result: (a) Thin coating targets detected at the exit of curing oven, and (b) Corresponding processed thermogram.

For the pinholes detection, we use a static mode of IRT through acquiring snap shot thermograms after heating the pinhole sample, this sample is shown in figure 4 and is prepared using drawdown blades on a 50 micron profile substrates. Two quartz-heating lamps with 400-watt intensity, installed along with the IR cam in a detection head figure 5, was used for 4 seconds, to heat the sample stimulating thermal emission. The pinholes behave according to the substrate properties i.e. $\kappa_{steel}, \rho_{steel}$ and Cp_{steel} , while the well coated surroundings have the thermal properties of the primer-coat. This creates the difference in the temperature reading across a missed coated region and another well-coated one, pictorially this is shown in figures 2,d and 8,c, and mathematically explained through the thermal mismatch factor or, the thermal reflection coefficient in equation (1), more details could be found in [11];

$$\Gamma = \frac{e_{coat} - e_{steel}}{e_{coat} + e_{steel}}, \qquad (1)$$

where, $e = \sqrt{\kappa \cdot \rho C_p}$ is the thermal inertia, the subscripts coat and steel refers to the use of the thermal properties (thermal conductivity κ , density ρ and specific C_p) of the steel and the primer-coat respectively.

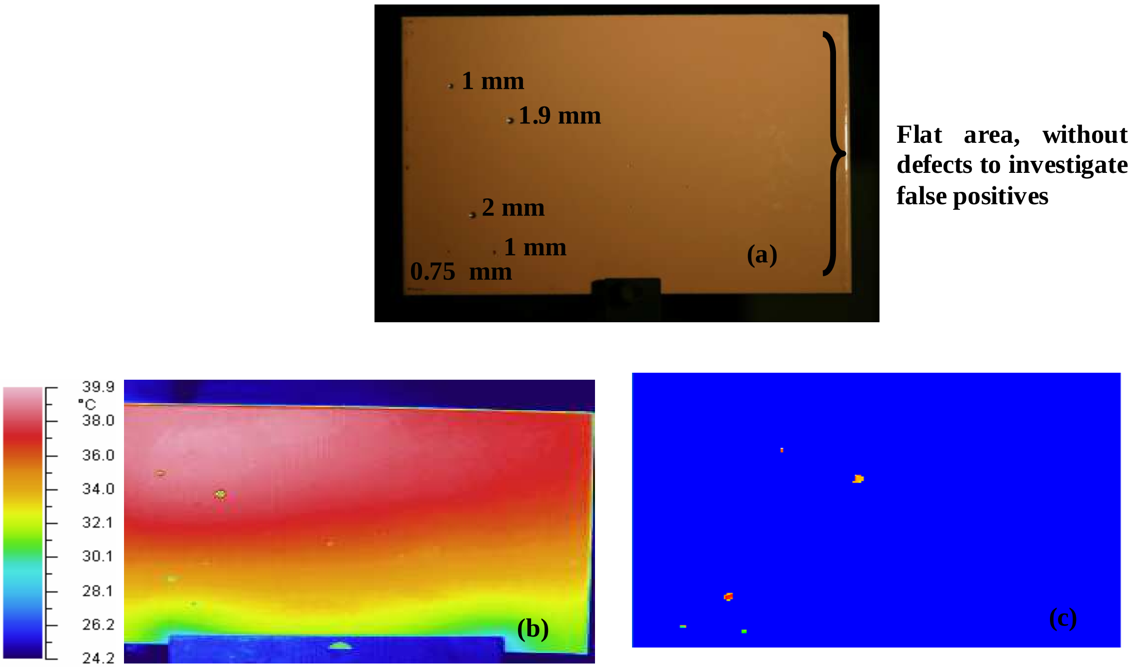


Figure 4, (a) Photograph of the pinhole sample, (b) Thermal pinhole image (thermogram), color-bar indicates temperature readings and (c) Processed thermal image.

4. Data analysis

Traditional image analysis routines are not suitable for processing the acquired thermal images or thermograms, because of the heating non-uniformities, which could be a result of the high tolerances in protective coat-film thicknesses, the touch-up jobs and surface profile and geometry. All of this creates non-uniform thermal maps. To provide a complete automated detection package, image processing software is required to isolate the defectives from their surroundings. In [12] we introduced a new image processing routine based on dividing the thermogram into localized neighborhoods. The size of the local neighborhood should be selected such that it will be larger than the defect and sizes sought and assure a stable temperature across the region, but small enough to be contained within the smallest area of non-uniformity (its definition dependant on the application at hand). A relative thresholding step follows, where each pixel in the thermal image is compared against the average of its surrounding neighborhood; if it passes the criterion in (2), its value is boosted with multiples of the difference from the average otherwise its value is set to zero.

$$\left| T_{pix} - T_{avg.} \right| \geq \eta \cdot \sigma_{surr(i,j)} . \qquad (2)$$

Where T_{pix} is the temperature of central pixel, $T_{avg.}$ is the kernel average temperature, η is a scaling factor dependant on the signal to noise ratio of the thermogram, and $\sigma_{surr(i,j)}$ is the standard deviation of pixels in the local neighborhood surrounding (i, j). To illustrate the effectiveness of this routine, we apply it to the thermogram shown in figure 1,b, 3,a and 4,b The results, in figure 1,c, 3,b and 4,c show that the code successfully removed the non-uniform heating effects while detecting the thin spots.

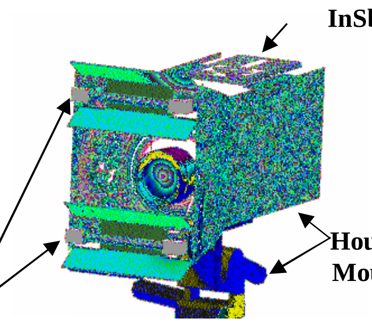


Figure 5, The detection head used for pinhole detection

To quantify the code performance, we utilize Tanimoto criterion (or, reveal ability $\mathrm{Re}v.$) described in equation (3), and first introduced in [13].

$$\mathrm{Re}v. = \frac{N_{real} - N_{missed}}{N_{real} - N_{false}} \qquad (3)$$

where, N is the number of defects and the subscripts $real, missed, false$ refer to real defects, missed defects and false positives found in the processed image. Applying this criterion to the processed images results in average of Rev. = 95 %. One should bear in mind that applying Tanimoto's criterion for a single image with limited number of defectives is considered highly conservative, and so any Rev. > 80% indicates effective processing.

4. Conclusion

This paper presented the infrared thermography capability in the non-destructive evaluation of coated surfaces in terms of paint coverage; detecting pinholes. The fast and area coverage attributes of thermography, enabled the development of a real time thin paint detection system suitable for industrial production lines. This work also, presented the novel, successful application of thermography in detecting "Holidays" or pinholes in marine coatings through the development of a mobile, compact detection head. The in-house code, enables those two systems to be applied in an automated fashion that enables, (1) objective judgment, (2) record keeping, and (3) ease of standardization of the inspection criteria.

Acknowledgments

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