engineering proceedings

MDPI

Proceeding Paper

Improvement of Anticorrosion Coating Thickness Measurement Using Multi-Wavelength Lock-In Infrared Data Processing †

Tatsuhito Morimoto, Yuki Ogawa *, Takumi Sakata, Daiki Shiozawa and Takahide Sakagami

Department of Mechanical Engineering, Kobe University, Kobe 657-8501, Japan; 229t368t@stu.kobe-u.ac.jp (T.M.); 217t327t@stu.kobe-u.ac.jp (T.S.); shiozawa@mech.kobe-u.ac.jp (D.S.); sakagami@mech.kobe-u.ac.jp (T.S.)
* Correspondence: yogawa@mech.kobe-u.ac.jp; Tel.: +81-78-803-6128
† Presented at the 17th International Workshop on Advanced Infrared Technology and Applications, Venice, Italy, 10–13 September 2023.

Abstract: Steel structures are usually coated with anticorrosion coatings. Authors have developed a detection method of coating deterioration by infrared measurement. The mid-wavelength infrared camera captures both the reflection from the coating surface and the emission due to temperature rise of the coating. It is possible that the two components cancel each other out. We proposed a multi-wavelength lock-in infrared data processing that performs lock-in processing using time-series data of only the infrared reflection and emission components at different sensitivity wavelengths as reference signals. This method can separately detect the infrared reflection and emission components and quantitatively evaluate the coating thickness.

Keywords: anticorrosion coating; preventive maintenance; infrared thermography; active lock-in measurement; nondestructive evaluation

Citation: Morimoto, T.; Ogawa, Y.; Sakata, T.; Shiozawa, D.; Sakagami, T. Improvement of Anticorrosion Coating Thickness Measurement Using Multi-Wavelength Lock-In Infrared Data Processing. *Eng. Proc.* **2023**, *51*, 11. https://doi.org/10.3390/engproc2023051011

Academic Editors: Gianluca Cadelano, Giovanni Ferrarini and Davide Moroni

Published: 26 October 2023

1. Introduction

Bridges are indispensable to the social infrastructure of transportation systems. Proper maintenance management is required to prevent corrosion, the main cause of deterioration of the bridges. Multiple-layered anticorrosion coatings are applied to prevent damage to steel bridges caused by corrosion. The corrosion resistance of anticorrosion coating gradually deteriorates over time, it is desirable to repaint the coating before it deteriorates significantly. In the case of multiple-layered coatings, it is necessary to detect the deterioration of the outermost first layer at an early stage. Kishigami et al. [1] developed an evaluation method for the deterioration of anticorrosion coatings using the near-infrared spectral characteristics. Sakata et al. [2] also developed active self-reference lock-in near-infrared measurement method. This method can quantitatively estimate the remaining thickness of the first layer of anticorrosion coating, irrespective of the lighting conditions. However, the infrared spectral characteristics of the paint exhibit in the mid-wavelength and long-wavelength infrared regions. According to Planck's law, the infrared emission energy by a measurement object in the short-wavelength infrared region is very small. Thus, a near-infrared camera only captures the infrared reflection energy from the surface of the measurement object. In contrast, the mid-wavelength infrared camera also captures thermal infrared rays, which are emitted in response to the temperature of the measurement object. In the long-wavelength infrared region, this tendency is more pronounced. Thus, the infrared measurements in the mid-wavelength and long-wavelength infrared regions need to consider both infrared reflection and emission components. This study proposes a method to separately detect the infrared reflection and emission components. The proposed method quantitatively evaluates the coating thickness of the first layer of the anticorrosion coating even in the mid-wavelength infrared region.

2. Principle of Quantitative Nondestructive Evaluation for the Thickness of Coatings by Multi-Wavelength Lock-In Infrared Data Processing

When infrared energy is incident on an anticorrosion coating, infrared reflection, transmission, and emission occur in the first layer of the coating as measured by a mid-wavelength infrared camera. If the infrared energy transmitted through the second layer of the coating is set to 0, the infrared reflection energy from the entire coating, E_r is expressed by Equation (1).

$$E_r = \rho_1 E + \rho_2(\tau_1 E) - \alpha_1\{\rho_2(\tau_1 E)\} \quad (1)$$

where E is the incident infrared energy to the coating, ρ_1, α_1, and τ_1 are the reflectance, absorption, and transmittance of the first layer of the coating, respectively, and ρ_2 is the reflectance of the second layer of coating. Moreover, the infrared emission energy from the first layer of the coating, E_e is expressed by Equation (2).

$$E_e = \alpha_1 \sigma T^4 \quad (2)$$

where T is the temperature of the first layer of the coating and σ is the Stefan-Boltzmann constant. The absorption and transmission of the infrared rays, and the temperature of coating are affected by the coating thickness, it is possible to estimate the coating thickness by measuring the infrared reflection and emission energy. The infrared measurements in the mid-wavelength regions need to consider both infrared reflection and emission components. Thus, we considered that the difference in the coating thickness due to infrared reflection and emission energy could be quantitatively evaluated by separating and extracting the infrared absorption of the coating by the infrared reflection energy and the heat capacity of the coating by the infrared emission energy. The time-series data measured by the short-wavelength and the long-wavelength infrared camera capture the infrared reflection and emission energy prominently, respectively. Therefore, when only the infrared reflection component is extracted from the time-series data measured by the mid-wavelength infrared camera, the lock-in measurement is performed using the time-series data by the short-wavelength infrared camera as the reference signal, as shown in Figure 1. On the other hand, when only the infrared emission component is extracted, the lock-in measurement is carried out by the time-series data from the long-wavelength infrared camera as the reference signal. This method is called multi-wavelength lock-in infrared data processing. In this method, the infrared reflection and emission components of the time-series data of the mid-wavelength infrared camera were separated and extracted.

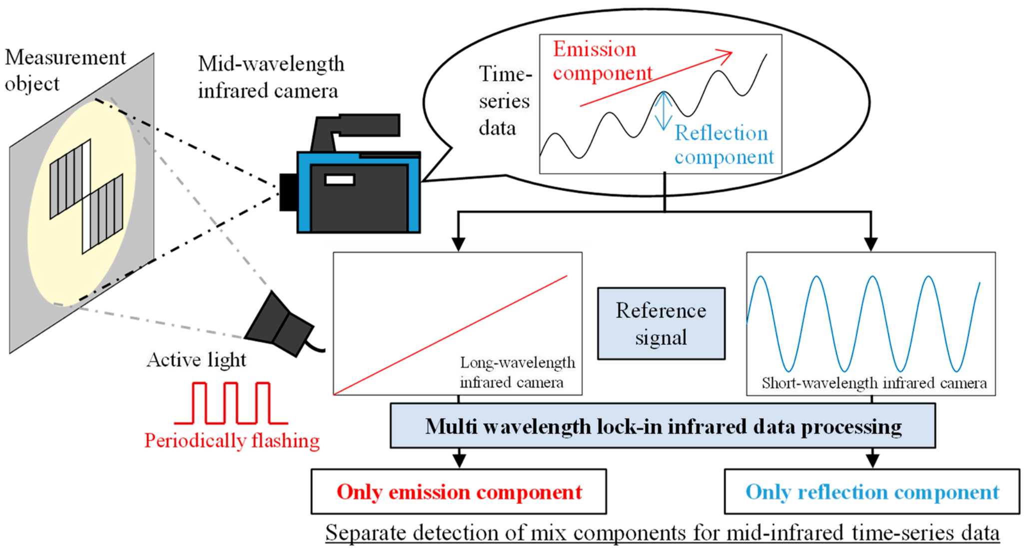
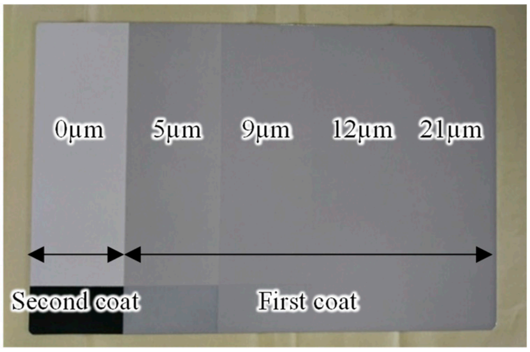


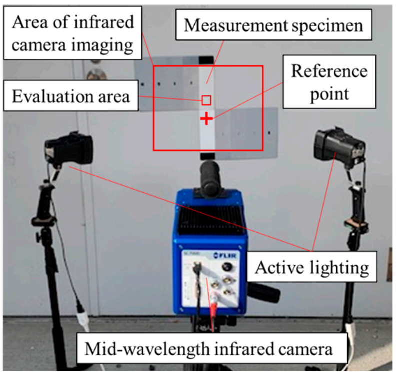
Figure 1. Illustration of multi-wavelength lock-in infrared data processing.

3. Experimental Method

The multi-wavelength lock-in infrared data processing was performed on a specimen consisting of a second layer of epoxy resin paint as a constant thickness and various thicknesses of the first layers of fluoropolymer paint on the steel plate, as shown in Figure 2a. The leftmost layer is the exposed second layer. The thicknesses of the various first coat was obtained using a cut-type thickness meter [2], the average coating thickness was appended in Figure 2a. A specimen of the same configuration was also prepared separately to obtain reference signals. Figure 2b shows the experimental setup of the active lock-in infrared measurement by the mid-wavelength infrared camera (SC7500 FLIR). For the reference signals in the different wavelength infrared regions, this study used a short-wavelength (SC7100 FLIR) and a long-wavelength infrared camera (SC7300L FLIR). A video light with a halogen lamp (VL-302 LPL Co., Ltd.) was used to provide periodic fluctuations in the infrared intensity of the measured object. A relay controller was generated to flash the video light as a pulse-shaped signal that repeated with a lighting time of 1.0 s and a lighting-off period of 1.5 s. The reference point was set in an area of the second coating of the reference specimen. The measurement specimen was shifted horizontally while maintaining the same evaluation area. The framerate of infrared camera was set to 100 Hz for all wavelength infrared regions to perform lock-in processing.



(a)

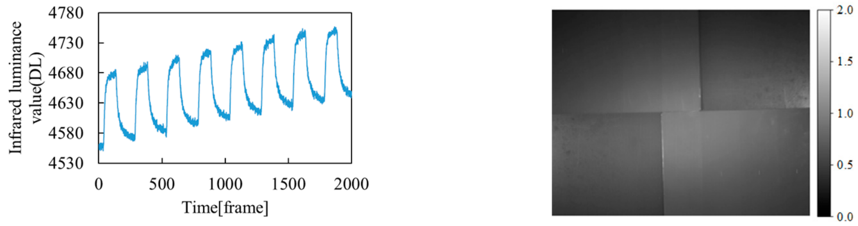


(b)

Figure 2. (**a**) Specimens with various coat thicknesses of anticorrosion coating; (**b**) Experimental setup of active lock-in infrared measurement by the mid-wavelength infrared camera.

4. Result and Discussion

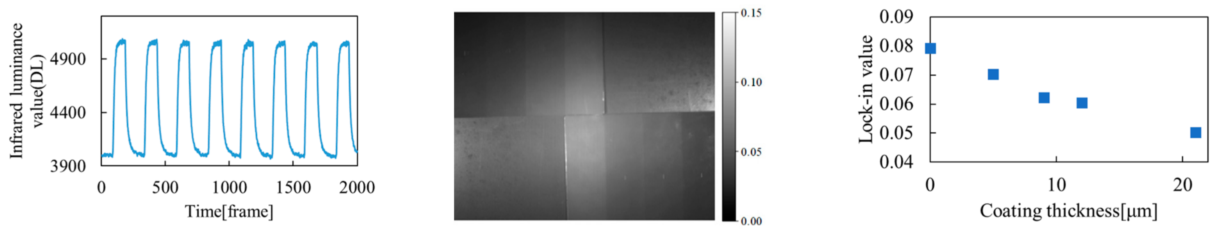
Figure 3 shows the results of the active self-reference lock-in infrared measurement [2] by a mid-wavelength infrared camera. The time-series data measured by a mid-wavelength infrared camera was a superimposed waveform of infrared reflection and emission components. In the self-reference lock-in processing image, the boundary between the first and second coatings can be confirmed, but it is difficult to distinguish the difference in the coating thickness of the first layer. In the case of thin coating thickness, the infrared reflection energy is larger, but the infrared emission energy is smaller. Thus, the total infrared energy is considered to be unable to detect differences in the coating thickness because the two components cancel each other out.



(**a**) (**b**)

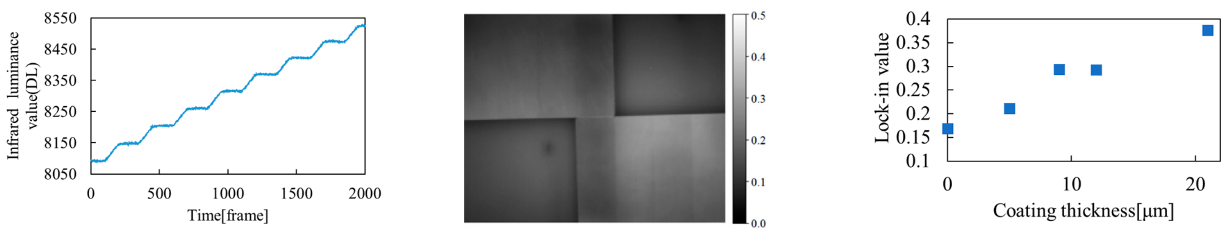
Figure 3. Experimental result of the active self-reference lock-in infrared measurement: (**a**) Time-series data of a mid-wavelength infrared camera; (**b**) Self-reference lock-in processing image.

Figures 4 and 5 show the results of the multi-wavelength lock-in infrared data processing to separately detect the infrared reflection and emission components of the time-series data of the mid-wavelength infrared camera, respectively. Figures 4a and 5a are the reference signal of short-wavelength and long-wavelength infrared cameras, respectively. The lock-in image, by the multi-wavelength lock-in infrared data processing with the reference signal of the infrared reflection components, reveals differences in the coating thickness of the first layer and shows the characteristics of infrared reflection, in which the infrared energy increases with thin coating thickness, as shown in Figure 4b,c. In contrast, the lock-in image of the emission components in Figure 5b,c shows the characteristics of the infrared emission, in which the infrared energy is smaller as the coating thickness becomes thinner. The above results indicate that the multi-wavelength lock-in infrared data processing can extract separately each component from the time-series data with superimposed infrared reflection and emission components, and the anticorrosion coating thickness can quantitatively evaluate based on the separately detected each component.



(**a**) (**b**) (**c**)

Figure 4. Result of the multi-wavelength lock-in infrared data processing of the infrared reflection components: (**a**) Time-series data of a short-wavelength infrared camera; (**b**) Lock-in image; (**c**) Relations of lock-in value and thickness of first layer.



(**a**) (**b**) (**c**)

Figure 5. Result of the multi-wavelength lock-in infrared data processing of the infrared emission components: (**a**) Time-series data of a long-wavelength infrared camera; (**b**) Lock-in image; (**c**) Relations of lock-in value and thickness of first layer.

5. Conclusions

In the active lock-in measurement of anticorrosion coatings by a mid-wavelength infrared camera, the infrared reflection and emission components are superimposed on the time-series data. We performed multi-wavelength lock-in infrared data processing using time-series data with significant reflection and emission components having different sensitivity wavelengths as reference signals. Consequently, the infrared reflection and emission components can be extracted from the measurement data of the mid-infrared camera, and the extracted data can evaluate the anticorrosion coating thickness.

Author Contributions: Conceptualization, T.M., Y.O., T.S. (Takumi Sakata), D.S. and T.S. (Takahide Sakagami); methodology, T.M., Y.O., T.S. (Takumi Sakata), D.S. and T.S. (Takahide Sakagami); software, T.M. and T.S. (Takumi Sakata); validation, T.M., Y.O., T.S. (Takumi Sakata), D.S. and T.S. (Takahide Sakagami); formal analysis, T.M. and T.S. (Takumi Sakata); investigation, T.M. and T.S. (Takumi Sakata); resources, T.M., Y.O., D.S. and T.S. (Takahide Sakagami); data curation, T.M., Y.O., T.S. (Takumi Sakata), D.S. and T.S. (Takahide Sakagami); writing—original draft preparation, T.M., Y.O. and T.S. (Takahide Sakagami); writing—review and editing, T.M., Y.O., D.S. and T.S. (Takahide Sakagami); visualization, T.M., Y.O., D.S. and T.S. (Takahide Sakagami); supervision, T.M., Y.O. and T.S. (Takahide Sakagami); project administration, Y.O., D.S. and T.S. (Takahide Sakagami); funding acquisition, T.S. (Takahide Sakagami). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by a Grant-in-Aid for Scientific Research (B) JP 21H01213 from the Japan Society for the Promotion of Science.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are not publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kishigami, S.; Mizokami, Y.; Sakata, T.; Ogawa, Y.; Shiozawa, D.; Sakagami, T. Detection of heavy-duty anticorrosion coating deterioration using near-infrared spectral characteristics. *NDT E Int.* **2022**, *132*, 102708. [CrossRef]
2. Sakata, T.; Kishigami, S.; Ogawa, Y.; Arima, N.; Nishitani, M.; Shiozawa, D.; Sakagami, T. Quantitative assessment of heavy-duty anticorrosion coating thickness via near-infrared measurements. *NDT E Int.* **2023**, *138*, 102893. [CrossRef]