Numerical Analysis of Influencing Factors and Capability for Line Laser Scanning Thermography Nondestructive Testing Technology in Chemicals Corrosion Defect Detection

Zhengwei Yang\textsuperscript{a,b\ast}, Xingyu Xie\textsuperscript{a}, Yin Li\textsuperscript{a} and Gan Tian\textsuperscript{a}

\textsuperscript{a}Xi’an Research Inst. of Hi-Tech, Hongqing Town, Xi’an 710025, PR China
\textsuperscript{b}School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an 710049, PR China

Abstract. A new Infrared Thermal Wave Nondestructive Testing (IR TWNDT) technology—line laser scanning thermography nondestructive testing (LLST NDT) technology is applied to detect the defect that caused by chemicals corrosion. The heat conduction process is derived and simulated by the numerical method. Parameters of LLST NDT as the maximum surface temperature difference ($\Delta T_{\text{max}}$), the best detection time ($t_{\text{best}}$), and the temperature difference holding time ($\tau_{\Delta T \geq 0.1}$) are discussed as the targets. Based on these parameters, factors influencing the detection results of materials, defect characters (size and depth), and thermal excitation source parameters (line laser scanning speed and power) are analyzed. Simulation results show that LLST NDT is a rapid and effective technique to detect the inside defect of the specimen. The relationship exists between $\Delta T_{\text{max}}$ with the parameter $s$ are described. This work lays a theoretical foundation for further application of the technology and paves the way for optimal design of LLST NDT system.

1. Introduction

Corrosion defect is a common event in the storage of chemicals, especially in petroleum chemical engineering and aerospace areas. Corrosion decreases wall thickness and strength, and serious corrosion will lead to leakage, which is dangerous for not only bringing economic loss, but also environmental pollution and personnel incidents. Thus, it’s very necessary to detect the corrosion defect to make sure the safety of chemicals. Infrared Thermal Wave Nondestructive Testing Technology (IR TWNDT), as a great way for defect detection, has been widely used, due to its large test area, rapid test speed, non-contact, easy to operate, etc\textsuperscript{0}. In active IR TWNDT, the surface area of target is heated by the thermal excitation source; as a result, the thermal wave is produced and conducted into the specimen. When the thermal wave is conducted to the defect interface, part of the thermal wave is reflected to reheat the surface, which could cause the surface temperature of the defect area is higher than that of the normal area as shown in Fig.10. In this case, by applying an infrared camera to monitor the surface temperature fields, the information of defect inside the specimen can be obtained.

![Figure 1. Basic principle of active IR TWNDT.](image-url)
At present, the thermal excitation source mainly includes high-energy flash lamp, ultrasonic, eddy current, etc. Previous scholars stated that the detection results is closely affected by the adopted thermal excitation source and each excitation source has its specific advantages, e.g. the high-energy flash lamp excitation source is suitable for detecting the large area defects with large thermal impedance0. The ultrasonic excitation source is suitable for detecting the kissing defects such as cracks0, while the eddy current excitation source is suitable for detecting the deep surface defects0. However, any one of the excitation source cannot be applied to all kinds of defects. Thus, it is vital to explore new excitation ways to meet different testing needs, which is always one of the research hotspots in IR TWNDT.

In this work we present a new Thermal Wave Nondestructive Testing Technology——Line Laser Scanning Thermography Nondestructive Testing Technology (LLST NDT), which uses line laser to scan the surface of specimen to implement the thermal excitation as shown in Fig. 2.

![Figure 2. Line laser scanning thermography nondestructive testing technology system diagram.](image)

When it works, a beam of high power laser is shaped by lens into a line uniform and controlled by galvanometer to irradiate the target surface, forming a heat wave to propagate in the target. Once the surface temperature of specimen changes caused by the defects, it can be caught by infrared camera and the defects can be detected by analyzing the infrared image sequence. Its unique excitation way makes this method with the advantages of high controllability and excellent detection accuracy, and the most appropriate detection parameters can be set according to the characteristics of materials and defects, which also can be viewed as an effective supplement to cover the limitations of main thermal excitation sources, including the heating inhomogeneous and tail-light in the high-energy flash lamp excitation, the coupling problem between ultrasonic-gun and specimen in the ultrasonic excitation, and eddy current excitation only suitable for detecting ferromagnetic materials0-.

Form the above analysis, it can be known that the LLST NDT is a promising thermal wave nondestructive testing technology. But the influence factors in the LLST NDT are barely involved, which limits its applications. Thus, in this work, we derive the heat conduction theory and use numerical simulation method to calculate the heat transfer process in LLST NDT. On this basis, parameters that can influence the detection results are analyzed, and the quantitative relationship between defect detection parameters is established. This work is of importance as it paves the way for optimal design of LLST NDT system, which is the future study.

2. Modeling and Computation

2.1. Simulation Model
Flat bottomed holes are often used to stand for the real defects in simulation 0. Following this way, the model used in this paper is shown in Fig.3, where $\Delta h$ the depth of defect and $D$ is is the diameter.
In this research, we assume that the ambient temperature $T_a = 22 \degree C$ and the convective heat transfer coefficient of environment $h_c = 20 W/m^2 \cdot \degree C$ remains unchanged, there is no internal heat source, and the convection and radiation at the side is ignored. Selected grid cell is SOLID87 3D 10-node tetrahedral thermal solid element, the curvature meshing method is used in this work, and the grid at the defect is much denser to ensure that the calculation results with high accuracy.

2.2. Parameters of the Detection Capability
Generally, the detection capability of IR TWndt is characterized by such three parameters as $\Delta T_{max}$, the maximum surface temperature difference, $t_{best}$, the best detection time and $\tau$, the temperature difference holding time. IR TWndt is actually based on the surface temperature difference between defect area and normal area to achieve the detection, the bigger the temperature difference, the easier the defect is to be detected, so $\Delta T_{max}$ is the most important parameter and it’s very necessary to determine the relationship between $\Delta T_{max}$ and each influence factors. $t_{best}$ is the time when the surface temperature difference reaches the maximum and the detection effect is best. The defects can be effectively evaluated by analyzing relationships of the two parameters with the detection results. Besides, due to the limitation of image acquisition frequency of the thermal camera (currently, the acquisition frequency is a few Hz to tens of Hz), so the temperature difference holding time should be longer than the time of the camera sensitivity to ensure that the camera has recorded the temperature difference information. In this work, the thermal sensitivity of the camera is set to 0.1 $\degree C$, so $\tau_{max}$ is the parameter that we care about.

2.3. Surface Temperature Field Distribution
As shown in Fig.4.(a), a specimen with the dimension of $0.25 \times 0.15 \times 0.005$ m is established in ANSYS 18.0, and it includes all simulation models. The first row corresponds to the model 1, while the second row corresponds to the model 2. The calculated parameters of the models are shown in Table 1. In the following analysis, all simulations are calculated based on the model 1, except the simulation to calculate the depth of defect which is done in the model 2. All the data are collected from the outside surface center over the 20mm diameter defect. In addition, the heat conduction is two-dimensional heat conduction, so the temperature of the defect center will rise before scanned by the laser. Therefore, the data extraction shall start at the first three seconds before the laser scanning reaches the center of the defect, so as to show the whole process of heat conduction.

| Parameter | Model 1 | Model 2 |
|-----------|---------|---------|
| $\Delta h$ (mm) | 4 | 4 | 4 | 2 | 3 | 4 | 4.5 |
| D(mm) | 30 | 20 | 15 | 10 | 20 | 20 | 20 | 20 |
Simulation results of surface temperature field distribution for structural steel are shown in Fig. 5 (also shown in video file: simulation result. avi). It can be seen that at t=5.6s, the line laser has not yet reached the defect, and the defects cannot be seen on the surface of the specimen. At t=12.5s, the line laser scanned at the center of defect with D=30mm and $\Delta h=2mm$, the defect can be observed through hot spots on the surface, but due to $\Delta h=2mm$ is too deep, the temperature difference between the defect and the normal area disappears very quickly. At t=18.4s, the defect with D=30mm can be observed clearly but the defect with $\Delta h=2mm$ cannot be observed already. At t=25s, the line laser scanned at the center of defect with D=20mm and $\Delta h=3mm$, because of the decrease of depth, the defect with $\Delta h=3mm$ can be observed much more clearly than $\Delta h=2mm$, but still cannot be completely observed as the defect with the same diameter but a lower depth in the second row at t=28s. As the depth becomes more and more deep, the defect in the first row become more and more obvious, but the defect in the second row becomes more and more unclear due to the decrease of diameter. Finally, at t=53.7s, only the defect with $\Delta h=4.5mm$ can be observed on the surface. And at t=57.2s, there is nothing on the surface of the specimen. Through the simulation, we can draw a simple conclusion that the bigger the diameter and the deeper the defect is, the easier it will be detected. And the defect can only be detected for a short time. Therefore, study the parameters influence on defect detection is of great significance to improve the detection ability of LLST NDT.

3. Discussion and Conclusion
In this work, the heat conduction theory is analyzed and the calculation model is established. On this basis, the effects of parameters on detection results are comprehensively investigated. The conclusions are listed as follows:

From the simulated detection results, the $\Delta T_{\text{max}}$ is generally greater than 0.1 °C, which can fully meet the demands of sensitivity of infrared camera, and proves LLST NDT is an effective detection technique to detect the inside defect of the specimen. Additionally, the discussion on the different line laser scanning speed shows that LLST NDT is also an efficient detection technique, usually only takes a few seconds.
4. Acknowledgments

This work was supported by National Natural Science Foundation of China (Grant nos. 51575516 and 51605481), Xi’an science and technology project (Grant no. 2017089CG/RC052 (HJKC001)).

5. Reference

[1] Zhou Y, Cai J. Infrared thermal wave nondestructive testing technology and its application. International conference on computer engineering, information science & application technology 2016.

[2] Heriansyah R, Abu-Bakar S A R. Defect detection in thermal image for nondestructive evaluation of petrochemical equipments. NDT & E International 2009; 42(8):729-40.

[3] Palumbo D, Tamborrino R, Galiotti U, et al. Ultrasonic analysis and lock-in thermography for debonding evaluation of composite adhesive joints. NDT&E International 2016; 78:1-9.

[4] Iino M, Carr D J. Pulse thermography applied on a complex structure sample: comparison and analysis of numerical and experimental results. Proc Conferencia Panamericana De End. ELSEVIER 2007; 69–72.

[5] Maldague X P V. Introduction to NDT by active infrared thermography. Materials evaluation 2002; 60(9):1060-73.

[6] Sakagami T, Kubo S. Applications of pulse heating thermography and lock-in thermography to quantitative nondestructive evaluations. Infrared Physics & Technology 2002; 43(3–5):211-218.

[7] Chen D, Zhang C, Feng L, et al. Ultrasonic infrared thermal wave technology and its applications in nondestructive evaluation. Laser & Infrared, 2008; 457(1):1011-30. (in Chinese)

[8] Yan H P, Yang Z W, Tian G, et al. Analysis of influencing factors of geometry size in crack inspection using eddy current thermography. Chinese Journal of Scientific Instrument 2016; 37(7):1610-17 (in Chinese).

[9] Abidin I Z, Tian G Y, Wilson J, et al. Quantitative evaluation of angular defects by pulsed eddy current thermography. NDT & E International 2010; 43(7):537-46.

[10] Cheng L, Tian G Y. Surface crack detection for carbon fiber reinforced plastic (CFRP) materials using pulsed eddy current thermography. IEEE Sensors Journal 2011; 11(12):3261-68.

[11] Jin G F, Wei Z, Yang Z W, et al. Application of Ultrasonic Infrared Thermal Wave Technique in Detection and Recognition of Interface Kissing Damage. Journal of Sichuan University 2013; 45(2):167-75 (in Chinese).

[12] Zhang H J. Non-quasi-steady analysis of heat conduction from a moving heat source (III). Journal of Engineering Thermophysics 1991; 112(3):777-79.

[13] Louaaayou M, Naït-Saïd N, Louai F Z. 2D finite element method study of the stimulation induction heating in synchronic thermography NDT. NDT & E International 2008; 41(8):577-81.

[14] Wang D, Tian Z, Shen L, et al. Numerical simulation of temperature field of laser remelting MCrAlY coating prepared by plasma spraying on titanium alloy. Applied Laser 2007; 27(6):444-49.

[15] Gui J B. Studies of high-power laser heat effect simulation and laser beam description. Master thesis: Kunming University of Science and Technology 2004. (in Chinese)

[16] Guofeng J, Wei Z, Jun S, et al. Numerical analysis of influencing factors and capability for thermal wave NDT in liquid propellant tank corrosion damage detection. Measurement Science Review 2013; 13(4):214-22.

[17] Dodd C V, Pate J R, Deeds W E. Eddy-current inversion of flaw data from flat-bottomed holes. NDT & E International 1989; 30(3):305-12.

[18] Liu J M. Simple technique for measurements of pulsed Gaussian-beam spot sizes. Optics Letters 1982; 7(5):196.

[19] Jönsson M, Rendahl B, Annergren I. The use of infrared thermography in the corrosion science area. Materials & Corrosion 2015; 61(11):961-65.

[20] Yang Z W, Zhang W, Tian G, et al. Numerical simulation of influencing factors for thermal wave NDT in composite materials. Journal of System Simulation 2009; 21(13):3918-21.

[21] Dai, G.H.. Heat Transfer, 2nd ed. Beijing: Higher Education Press 1999.