International Journal of Multimedia and Ubiquitous Engineering
Vol.11, No.3 (2016), pp.249-256
http://dx.doi.org/10.14257/ijmue.2016.11.3.24

Computer Simulation of Metal Surface Micro-Crack Inspection Using Pulsed Laser Thermography

Tang Qingju[a], Bu Chiwu[b], Liu Yuanlin[a], Yu Fengyun[a] and Zhao Yawei[c]

[a] School of Mechanical Engineering, Heilongjiang University of Science and Technology, Harbin, 150022, P. R. China
[b] College of Light Industry, Harbin University of Commerce, Harbin, 150028, P. R. China
[c] College of Engineering and Information Technology, University of Chinese Academy of Sciences, Beijing, 100049, P. R. China
E-mail: tangqingju@126.com

Abstract

Surface micro cracks are easy to produce in the preparation and service process of metal material, which impacts on the safe operation of metal components. Pulsed laser spot excitation and infrared thermal imaging technology are combined to detect metal surface micro-cracks. The working principle of laser infrared thermal imaging detection technology was described. The three dimensional heat conduction model of pulsed laser excitation flux transfer in metal plate was established, and calculated using finite element method (FEM). The results showed that, thermal flow in the image is a "D" shape. There are temperature differences between the sound regions and defective regions, and the defects experiences the process of obscure, gradually clear, and gradually obscure. Pulsed infrared thermography sequence was processed by polynomial fitting method, and the coefficient images effectively improve the contrast between defective and non-defective areas, which is beneficial to the determination and of recognition micro cracks.

***Keywords**: Micro-crack; Thermography; Pulsed laser; FEM; Polynomial fitting*

1. Introduction

Surface micro cracks are easy to produce in the metal preparation process, due to the processing technique, heat treatment environment, *etc.* And in the installation and service process of metal parts, surface micro cracks are also easy to produce, due to a variety of factors such as temperature, chemical corrosion, load. Microcracks tend to expand and merge, forming a macroscopic crack, may eventually lead to the fracture of metal parts. Therefore, in order to ensure the safety and reliability of metal components, whether in the manufacturing or service period, it is necessary to monitor the metal status [1-5].

With the development of modern science and industrial technology, nondestructive detection technology has become the necessary method to guarantee the quality of products and the safe operation of equipment. At present, metal surface micro-cracks are usually detected by acoustic emission testing, ultrasonic testing, radiographic testing, magnetic particle testing, penetrate testing, and eddy current testing methods. The traditional detection technology has achieved good results in the detection of metal components which has low intensity, and improved product quality, reduced production cost and improved the social benefit of products [6-11].

The infrared thermal wave nondestructive detection technique (IR TNDT) is a new nondestructive testing method. Compared with the conventional detection technology, IR TNDT has many advantages, such as a large detection area, high detection speed, non-contact, easy to use, safety, intuitive and simple operation, so it get more and more

ISSN: 1975-0080 IJMUE

extensive research and application [12-17]. The laser has good monochromatic, strong directivity, centralized energy and good coherence characteristics, and is easy to obtain uniform temperature field. Therefore, pulsed laser spot excitation and infrared thermal imaging technology are combined, forming a new nondestructive detection technology, which is named as laser infrared thermal imaging detection technology to detect metal surface micro-cracks.

2. The Working Principle of Laser Infrared Thermal Imaging Detection Technology

The working principle of laser infrared thermal imaging detection technology is shown in Figure 1. The tested specimen was excited by pulsed laser, and the surface temperature changes with the thermal conduction of the flux. Infrared thermography of the specimen surface can be captured by professional infrared cameras. If the specimens contain internal defects, the surface temperature distribution will be affected, and show abnormally, thus we can detect the internal defects, including their location, shape and size.

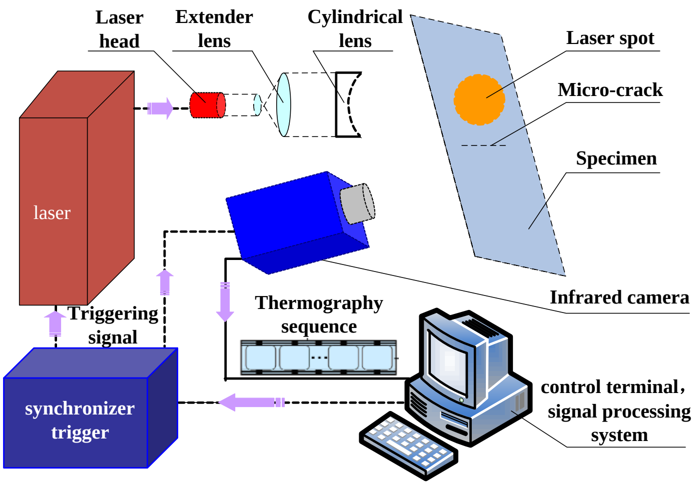

Figure 1. The Working Principle of Laser Infrared Thermal Imaging Detection Technology

3 Presentation of the Heat Transfer Model

In this section, the heat transfer model for crack defects of stainless steel detection is established. The geometric mesh model of the test specimens are shown in Figure 2.

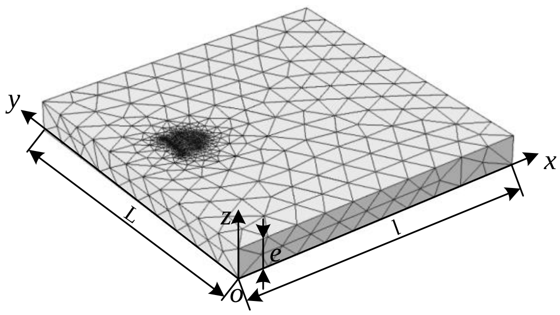

Figure 2. Geometric Mesh Model of the Studied Samples

Given (x, y, z) the Cartesian coordinates and (l, L, e) the length, width and thickness of the studied sample, as shown in Figure 2, and under the assumption that transverse and longitudinal conductivities are uniform in the sample, the following system (balance equation, boundary and initial conditions) is obtained [10].

$$\lambda_x \cdot \frac{\partial^2 T}{\partial x^2} + \lambda_y \cdot \frac{\partial^2 T}{\partial y^2} + \lambda_z \cdot \frac{\partial^2 T}{\partial z^2} = \rho c \cdot \frac{\partial T}{\partial t} \quad (1)$$

The front face net heat pulse flux and the rear face heat flux are established with regard to the convection heat transfer.

$$-\lambda_z \frac{\partial T(x,y,z,t)}{\partial z}\Big|_{z=e} = Q + h_{\mathrm{f}}\left[T_{am} - T(x,y,0,t)\right] \quad (2.a)$$

$$-\lambda_z \frac{\partial T(x,y,z,t)}{\partial z}\Big|_{z=0} = h_{\mathrm{r}}\left[T_{am} - T(x,y,0,t)\right] \quad (2.b)$$

Other boundaries are assumed to be insulated.

$$-\lambda_x \frac{\partial T(x,y,z,t)}{\partial x}\Big|_{x=0} = -\lambda_x \frac{\partial T(x,y,z,t)}{\partial x}\Big|_{x=l} = 0 \quad (2.c)$$

$$-\lambda_y \frac{\partial T(x,y,z,t)}{\partial y}\Big|_{y=0} = -\lambda_y \frac{\partial T(x,y,z,t)}{\partial y}\Big|_{y=\mathrm{L}} = 0 \quad (2.d)$$

The initial condition expresses the temperature distribution in the whole domain at the time t=0.

$$T(x,y,z,t)\big|_{t=0} = T(x,y,z,0) = T_{am} \quad (3)$$

Where λ_x, λ_y, λ_z are the thermal conductivities in the x, y, and z directions, Q is the heat distribution of the laser beam, δ is the Dirac function, h is the convective heat transfer coefficient, and T_{am} is the ambient temperature.

The thermal physical properties parameters of stainless steel specimens and air gap which simulate the crack defects are shown in Table 1.

Table 1. Thermal Physical Properties Parameters

Parameter / Component	Density ρ [kg/m^3]	Specific heat c [J/(kg℃)]	Thermal Conductivity λ[W/(m℃)]	Thermal diffusivity $\alpha\times10^6$ [m^2/s]
Stainless steel	7900	485	13.5	3.5234
Air	1.205	1000	0.025	20.747

4. FEM Simulation

4.1 Temperature Distribution Caused by Laser Spot Source

The heat transfer FEM simulations have been done for stainless steel specimen size of 30mm×30mm×3mm with crack size of length 3mm, depth 1mm and width 0.1mm, laser spot to the crack distance of 15mm, laser spot radius of 15mm, and laser beam power of 20 W.

Figure 3 shows the normalized temperature distribution of specimen surface at some moments after the laser pulse excitation. It can be seen that thermal flow in the image as a "D" shape, which is because of the heat blockage by the crack. It is found that there are temperature differences between the sound regions and defective regions, and the heat flux transverse diffusion occurs gradually with the proceeding of heat conduction, so the defects experiences the process of obscure, gradually clear, and gradually obscure.

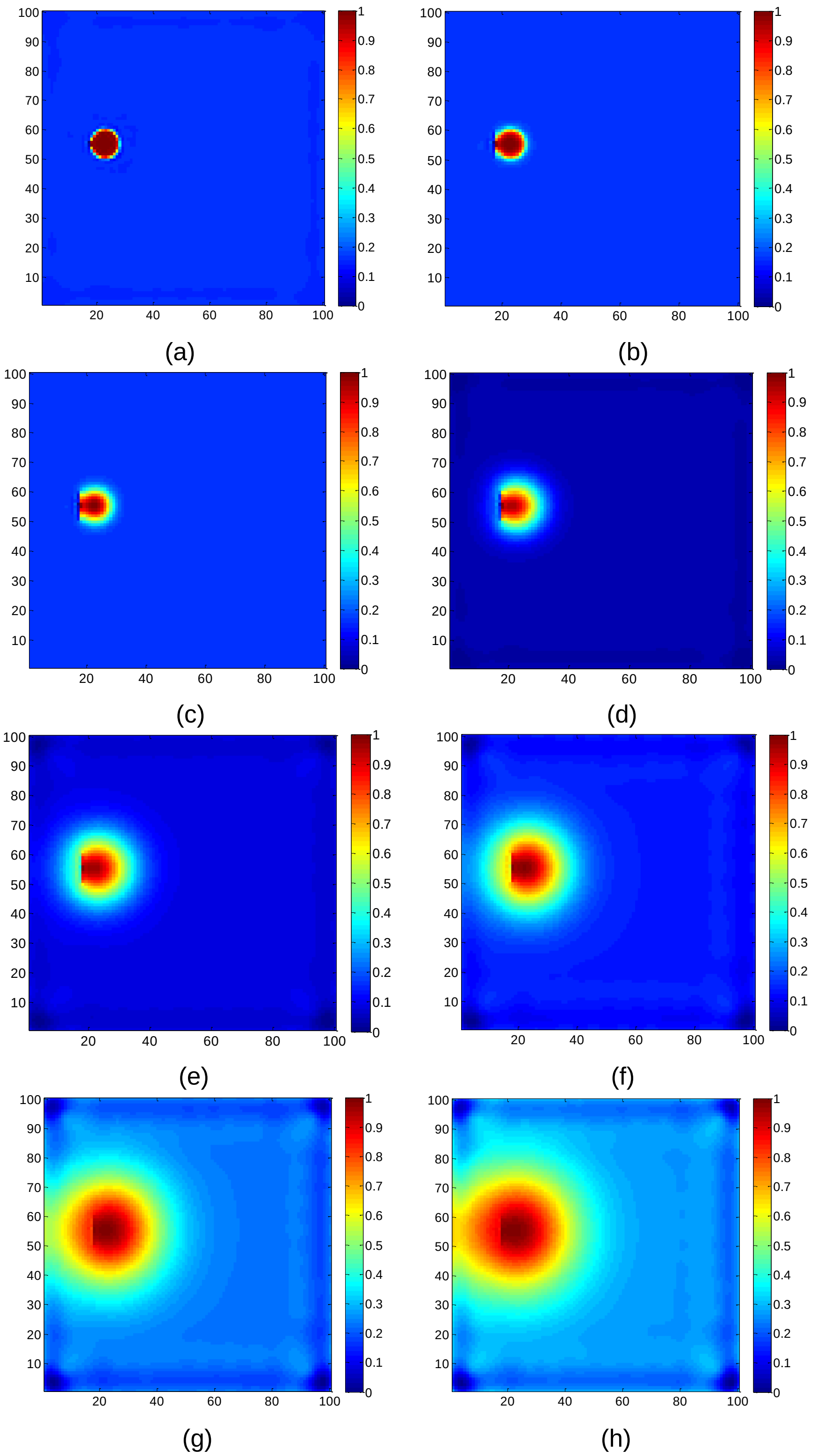

Figure 3. The Normalized Temperature Distribution of Specimen Surface: (a) t=0.005s, (b) t=0.05s, (c) t=0.1s, (d) t=0.5s, (e) t=1.0s, (f) t=1.5s, (g) t=2.5s, and (h) t=3.0s

4.2 The Effect of Laser Beam Power

Figure 4 shows the temperature rise at the laser spot center caused by laser beam power of 10 W, 20 W, 30 W, 40 W, 50 W and 60 W. From Figure 4, it can be seen that, the temperature rise more with the rise of laser beam power. It means that the cracks can be more easily detected when using big laser beam power. However, over heat may lead to the ablation of the specimen surface. Usually, when small laser beam power is used, in order to improve the signal to noise of defects, some processing algorithms can be used to the pulsed thermography sequence.

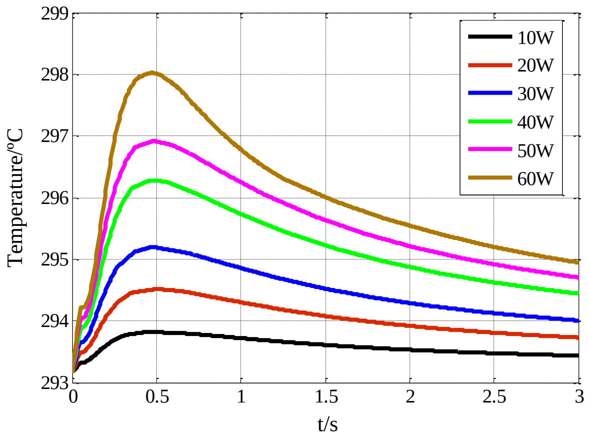

Figure 4. The Temperature Rise at the Laser Spot Center Caused by Different Laser Beam Power

5. The Processing of Thermography Sequence

Set the analysis time 3s, sampling frequency 200Hz, then a thermography sequence was got which included 600 pieces of infrared images. From Figure 3, it can be seen that the uneven heating of pulsed laser has a certain influence on the discrimination of metal surface micro-crack.

The pulsed laser infrared thermography sequence was processed using polynomial fitting time differential method. Use the polynomial model shown in equation (4), according to the least square criterion, polynomial coefficients of every pixels were obtained, and formed intensity images.

$$T = c_1 t^n + c_2 t^{n-1} + \cdots + c_n t + c_{n+1} \quad (4)$$

Polynomial fitting is a smooth operation, polynomial coefficients can be used to recover the original image sequence without high frequency noise. The 580 pieces of infrared images at the cooling stage were processed using 5 order polynomial fitting method. The polynomial fitting coefficient images were shown in Figure 5 (a) ~ (f). From Figure 5, it can be seen that compared with the original infrared images, the polynomial coefficient images effectively improves the contrast of defective and non-defective areas, which is beneficial to the determination and recognition of micro-cracks.

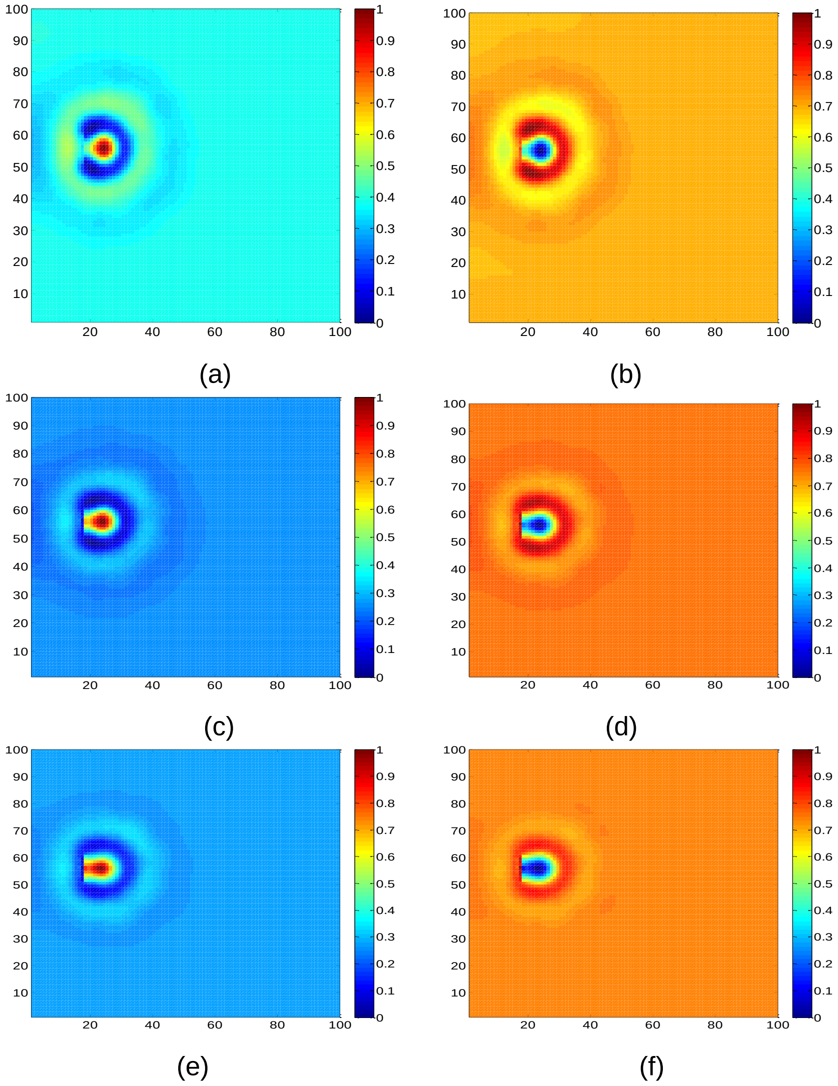

Figure 5. The Polynomial Fitting Coefficient Images: (a) Constant, (b) First-Order, (c) Second-Order, (d) Third-Order, (e) Fourth-Order and (f) Fifth-Order

6. Conclusion

Pulsed laser spot excitation and infrared thermal imaging technology are combined, forming a new nondestructive detection technology, which is named as laser infrared thermal imaging detection technology to detect metal surface micro-cracks. The working principle of laser infrared thermal imaging detection technology was described. The three dimensional heat conduction model of pulsed laser excitation flux transfer in metal plate was established, and calculated using FEM. The results showed that, thermal flow in the image is a "D" shape, and there are temperature differences between the sound regions and defective regions, and the defects experiences the process of obscure, gradually clear, and gradually obscure. Pulsed infrared thermography sequence was processed by polynomial fitting method, and results show that the coefficient images effectively improve the contrast between defective and non-defective areas, which is beneficial to the determination and of recognition micro cracks.

Acknowledgment

This project is supported by Young Talent Fund Project of Heilongjiang University of Science and Technology (Grant No. Q20130104), Youth Innovation Talent Training Program of Heilongjiang Province Regular Institutions of Higher Education "Study on CFRP laminate defects detection using infrared thermal wave nondestructive testing technology under modulated laser exitation", and Harbin Special Funds for Scientific and Technological Innovation Talents (Grant No. 2015RAQXJ069).

Reference

[1] Y. K. An, J. H. Kim and H. J. Yim, "Lamb Wave Line Sensing for Crack Detection in a Welded Stiffener", Journal Sensors, vol. 14, **(2014)**, pp. 12871-12884.
[2] A. Israr, "Model for Vibration of Crack Plates for use with Damage Detection Methodologies", Journal of Space Technology, vol. 1, **(2011)**, pp. 17-25.
[3] M. Navarrete, M. V. Muniz and L. Ponce, "Photo acoustic detection of micro-cracks induced in BK7 glass by focused laser pulses", Journal of Optics & Lasers in Engineering, vol. 40, **(2003)**, pp. 5-11.
[4] P. Lura, J. Weiss and O. M. Jensen, "Detection and Analysis of Micro-cracks In High-Performance Cementitious Materials", Advances in Construction Materials, **(2006)**, pp. 607-614.
[5] Y. Fujinawa, Y. Noda and K. Takahashi, "Field Detection of Micro-cracks to Define the Nucleation Stage of Earthquake Occurrence", International Journal of Geophysics, **(2013)**.
[6] J. Kerouedan, P. Quéffélec and P. Talbot, "Detection of Micro-Cracks on Metal Surfaces Using Near-Field Microwave Resonators", Journal Review of Progress in Quantitative Nondestructive Evaluation: proceedings of the 35th Annual Review of Progress in Quantitative Nondestructive Evaluation, vol. 1096, **(2009)**, pp. 386-393.
[7] J. Kerouedan, P. Quéffélec and P. Talbot, "Detection of micro-cracks on metal surfaces using near-field microwave dual-behavior resonator filters", Journal Measurement Science & Technology, vol. 19, **(2008)**, pp. 252-253.
[8] X. Guo, D. Zhang and J. Zhang, "Detection of fatigue-induced micro-cracks in a pipe by using time-reversed nonlinear guided waves: A three-dimensional model study", Ultrasonics, vol. 52, **(2012)**, pp. 912-919.
[9] H. Park, M. Choi and J. Park, "A study on detection of micro-cracks in the dissimilar metal weld through ultrasound infrared thermography", Journal Infrared Physics & Technology, vol. 62, **(2012)**, pp. 124-131.
[10] S. Charunetratsamee, B. Poopat and C. Jirarungsatean, "Feasibility Study of Acoustic Emission Monitoring of Hot Cracking in GTAW Weld", Journal Key Engineering Materials, vol. 545, **(2013)**, pp. 236-240.
[11] S. Johnsen, Z. Liu and J. A. Peters, "Thallium Chalcohalides for X-ray and gamma-ray Detection", Journal of the American Chemical Society, vol. 133, **(2011)**, pp. 10030-10033.
[12] J. Y. Liu, L. Q. Liu and Y. Wang, "Experimental study on active infrared thermography as a NDI tool for carbon–carbon composites", Journal Composites Part B: Engineering, vol. 45, **(2013)**, pp. 138-147.
[13] R. V. Hernandez, A. Melnikov, A. Mandelis, K. Sivagurunathan, M. E. R. Garcia and J. Garcia, "Non-destructive measurements of large case depths in hardened steels using the thermal-wave radar", Journal NDT&E International, vol. 45, **(2012)**, pp. 16-21.
[14] P. A. Howell, W. P. Winfree and K. E. Cramer, "Infrared On-orbit Inspection of Shuttle Orbiter Reinforced Carbon-Carbon Using Solar Heating", Proceeding of SPIE, London, England, **(2005)**.
[15] B. B. Lahiri, S. Bagavathiappan and T. Jayakumar, "Medical applications of infrared thermography: A review", Journal Infrared Physics & Technology, vol. 55, **(2012)**, pp. 221-235.
[16] C. Hildebrandt, "An Overview of Recent Application of Medical Infrared Thermography in Sports Medicine in Austria", Journal Sensors, vol. 10, **(2010)**, pp. 4700-4715.
[17] A. D. Filho and A. C. Packer, "Accuracy of infrared thermography of the masticatory muscles for the diagnosis of myogenous temporomandibular disorder", Journal of Manipulative & Physiological Therapeutics, vol. 36, **(2013)**, pp. 245-252.

Author

Tang Qingju, She received the B.S. and M.S. degrees from Harbin University of commerce, Harbin, China, in 2003 and 2006, respectively, and the Ph.D. degree from Harbin Institute of Science and Technology, Harbin, China, in 2014.

She is currently a Research Engineer in School of Mechanical Engineering of Heilongjiang University of Science and Technology. Her research interests lie in the area of infrared nondestructive testing and advanced manufacture.