

Nondestructive Defect Evaluation of Polyethylene Pipes

ZHIBIN ZHU^{1,2}, SHUNCONG ZHONG^{3,4*}, XU QIU⁴, YUEXIN HUANG⁴, XIAOXIANG YANG⁴

¹ School of Chemical Engineering, Fuzhou University, Fuzhou 350108, P. C. CHINA

² Xiamen Special Equipment Inspection Institute, Xiamen 361000, P. R. CHINA

³ Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde,
Glasgow G4 0LZ, UNITED KINGDOM

⁴ Laboratory of Optics, Terahertz and Non-destructive Testing & Evaluation, School of Mechanical
Engineering and Automation, Fuzhou University, 350108, P. R. CHINA

*zhongshuncong@hotmail.com www.fzu.edu.cn

Abstract: - We report an approach for nondestructive testing and evaluation of polyethylene pipes by using active infrared thermography technique, in which an electrical heating bar and a high-sensitivity high-speed infrared camera was respectively used as the novel thermal excitation source and the detector. Mathematical morphology is employed for defect feature extraction from thermographic images and realized the automatic evaluation of PE pipe defects. Various defects with different dimensions in PE pipes were investigated and they would affect the thermal distributions from which the relationship between thermographic images and defect sizes and locations was established. A finite element model was built to mimic the transient heat transfer in PE pipes. The finite element simulation results are well agreed with the one obtained from experiments and it demonstrated that finite element method can be an effective method to analyze infrared imaging. To further verify the capability of developed active infrared thermography in defect detection of PE pipes, defects in heat fusion joints of PE pipes were fabricated and measured. The experimental results showed that active infrared thermography based on an electrical heating bar, with defect extraction by mathematical morphology, could provide a novel tool for nondestructive evaluation and health monitoring of PE pipes.

Key-Words: - Active Infrared thermography; Mathematical morphology; Polyethylene pipes.

1 Introduction

Polyethylene (PE) pipe is piping constructed of a flexible plastic created with the use of petroleum byproducts. It provides a good balance of strength, stiffness, toughness and durability meeting the demands of the gas pipe industry [1]. The flexibility of the pipe is one of the main advantages of PE piping, as this makes it possible to install piping into spaces and configurations that would never be possible with metal pipes. Defects in joints of PE pipes will ultimately lead to the failure of the PE pipes. Basically, there are two methods to join PE pipes: heat fusion and electro fusion. The common problems in manufacture of these PE joints are contamination, lack of fusion, lack of penetration and insufficient heat applied to the weld which results in weak bond [2]. Phased array technique is widely used to detect and monitor the flaws in PE pipes. Caravaca et al. [2] developed ultrasonic phased array method for the inspection of the electrofusion joints. The method can detect conventional defects and can determine whether the weld has been correctly heated by analyzing the position of the heat affected zone. Zheng et al. [3]

developed ultrasonic equipment and investigated safety assessment of electrofusion joints of PE pipes. They divided the defects in electrofusion joints into four categories (lack of fusion, voids, wire dislocation and cold according to geometrical characteristic and ultrasonic response. Arjun et al. [4] described ultrasonic testing using 128-channel linear array with a Dynaray system to acquire data from a range of joints created using electrofusion welding. Frederick et al. [5] discussed ultrasonic phased array for inspecting butt-fusion joints in high-density PE pipes. Phased array has successfully demonstrated the ability of detecting and characterizing the defects using low frequency ultrasound.

There are some other detection methods used for PE pipes [6-10]. Capacitive sensor [6] and passive acoustic detection method [7] were used for defect detection in polyethylene gas distribution pipes. Stakenborghs et al. [8] presented a detection method of PE pipes based on the creation of an image using electromagnetic energy in the microwave frequency range. Terahertz wave [9] was used by Jördens et al. for detection of plastic weld joints using. Terahertz time-domain spectroscopy clearly reveals

contamination like metal or sand within the weld joint of two high-density polyethylene sheets. Furthermore, areas can be identified where the welding process has failed and the parts to be joined are separated by a small air gap. Pulse infrared and lock-in infrared thermography are two approaches in non-destructive evaluation [10] of PE pipes. In the present work, we employed an electrical heating bar as the novel thermal excitation source in active infrared thermography for non-destructive testing and evaluation (NDT&E) of PE pipes. Mathematical morphology approach was used for defect feature extraction from thermographic images. A finite element model was built to mimic the transient heat transfer in PE pipes, in which constant heat flux boundary condition was applied to the inner surface of the PE pipes. Various defects with different diameters and depths were simulated in PE pipes and they would affect the thermal distributions from which the relationship between thermographic images and defect sizes and locations would be established.

2 PE pipe defect detection by active thermal imaging

2.1 Temperature-difference Based Thermal Imaging

Thermal imaging is generally based on temperature differences of detected objects. Being able to detect the small temperature is important in most thermal imaging applications. For the application of PE pipe defect detection, high-sensitivity infrared camera is needed to “see” the extremely small temperature differences around the defect locations. In the present work, we employed an electrical heating bar as a novel thermal excitation source in active thermography. Fig.1 shows the model for a PE defective pipe (a hollow cylinder length of L) with some defects heated by an electrical heating bar, in which r_1 and r_2 are respectively the inner and outer radius of the PE pipe, T_{1U} and T_{2U} are the temperature of inner and outer surface of the intact PE pipe. A temperature gradient ($\frac{dt}{dx}$) within a homogeneous substance results in a heat transfer rate (\dot{Q}) within the medium which can be calculated by Fourier's law as

$$\dot{Q} = -kA \frac{dt}{dx} = -k2\pi rL \frac{dt}{dr} \quad (1)$$

Where k is thermal conductivity ($W/m \cdot K$). In Fig.1, the temperature gradient is in the direction normal to the surface area $A=2\pi rL$.

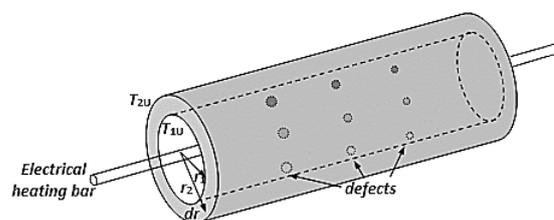


Fig.1 A PE defective pipe with different dimensions under heating by an electrical heating bar: r_1 is inner radius of the PE pipe; r_2 is outer radius of the PE pipe; T_{1U} and T_{2U} are respectively the temperature of inner and outer surface of a intact PE pipe.

Therefore,

$$\int_{T_{1i}}^{T_{2U}} dt = \int_{r_1}^{r_2} \frac{-\dot{Q}}{2\pi kL} \frac{dr}{r} \quad (2)$$

$$T_{2U} = T_{1U} + \frac{\dot{Q}}{2\pi kL} \ln \frac{r_2}{r_1} \quad (3)$$

For the PE pipe with internal defects,

$$T_{2D} = T_{1D} + \frac{\dot{Q}}{2\pi kL} \ln \frac{r_{2D}}{r_{1D}} \quad (4)$$

where r_{1D} and r_{2D} are respectively the inner and outer radius of the defect PE pipe. So the temperature difference (ΔT) around the defect location is

$$\Delta T = T_{2D} - T_{2U} \quad (5)$$

For a case of internal surface defects ($r_1 > r_{1D}$, $r_2 = r_{2D}$ and $T_{1U} = T_{1D}$), the temperature difference $\Delta T > 0$, which means that the temperature at the defect location is greater than the temperature around it. High-sensitivity infrared cameras can sense the temperature difference and defect detection can be made.

2.2 Feature Extraction based on Mathematical Morphology

Due to the weak temperature difference around the defect location, it is challengeable to locate and size the small defects, In the meanwhile, non-uniform heat field of the thermal excitation source and also the environmental noise will affect the quality of thermal images of PE pipes. Therefore, some image processing methods need to be employed to facilitate to get a better defect detection. In the present work, the thresholding technique was used to do the binarization to enhance the clarity of defect-deduced heat area. The further steps of image

processing continue with the mathematical morphology. The mathematical morphology [11] used are the opening and closing operation which are also known as dilation and erosion process. The detailed information about the technique can be found in the reference 11. Mathematical morphology provides an approach to image processing based on shape concept stemmed from set theory [11], not on traditional mathematical modeling and analysis. In the theory, images are treated as sets, and morphological transformations which derived from Minkowski addition and subtraction are defined to extract features in images [12]. The following is the basic mathematical morphological operators of grey-scale images.

Let $f(x, y)$ denote a grey-scale image and g denote the structuring element. Dilation and erosion of the grey-scale image by a grey-scale structuring element $B(s, t)$ is

$$(f \oplus g)(x, y) = \min_{i, j} \{f(x-i, y-j) + g(-i, -j)\} \quad (6)$$

$$(f \ominus g)(x, y) = \min_{i, j} \{f(x-i, y-j) - g(-i, -j)\} \quad (7)$$

Opening and closing are defined as

$$(f \circ g)(x, y) = [(f \ominus g) \oplus g](x, y) \quad (8)$$

$$(f \bullet g)(x, y) = [(f \oplus g) \ominus g](x, y) \quad (9)$$

In mathematical morphological theory, dilation is a transformation of expanding which increases the grey-scale value of the image whilst erosion is a transformation of shrinking which decreases the grey-scale value of the image. Both of dilation and erosion are sensitive to image edges whose grey-scale value changes obviously [13]. Generally, opening is erosion followed by dilation and it can smooth the contour of an image and breaks narrow gaps. However, closing is dilation followed by erosion and it tends to fuse narrow breaks, eliminates small holes, and fills gaps in the contours. Therefore, morphological operation is used to detect image edge and also for image denoising. It has great potential application in defect detection of PE pipes based on thermal images since the temperature differences caused by defects result in grey-scale value changes around the defect location.

3 Finite element simulations and experiments of thermal imaging

Fig.2 demonstrated the experimental configuration of the active infrared thermography employed in the present work. An electrical heating bar, the thermal excitation source, was inserted into the centre of defective PE pipes. Due to the defect effects, the external surface temperature of the PE pipes will be different at the defect locations. An infrared camera (PI450, Optris, Germany) provides real-time thermographic images in high speed of 80Hz and its optical resolution of 382×288 pixels. The infrared camera runs in the range of 7.5 to $13\mu\text{m}$ and has a very high sensitivity of 40 mK, which is suitable for the detection of temperature differences in NDT&E of PE pipes, especially for small defect detection. Time-serial thermographic images can be recorded showing the process of transient heat transfer in defective PE pipes.

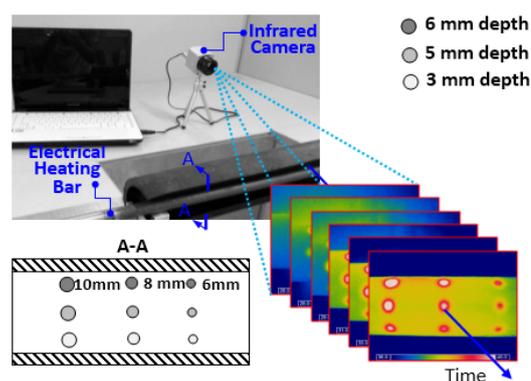


Fig.2 Active infrared Thermography based on an electrical heating bar for defect detection of PE pipes

In order to validate the experimental results of this active thermal imaging, a finite element (FE) model was built to mimic the transient heat transfer in defective PE pipes and. In the model, constant heat flux boundary condition was applied to the inner surface of the PE pipes. In the meanwhile, to establish the relationship between thermal images and PE defects, various defects with different dimensions (depths and diameter) were modelled and their effects on thermal distributions were investigated. For the FE model, the defective PE pipe, whose diameter, thickness and length are 100mm , 10 mm and 200mm respectively, was modelled using three dimensional twenty node solid element which is denoted in the ABAQUS FE package as DC3D20. Its material properties are: density $\rho = 952$ kg/m^3 , thermal conductivity

$k = 0.53 \text{ W/m} \cdot \text{K}$, and specific heat $C_p = 2300 \text{ J/kg} \cdot \text{K}$. The Polyethylene pipe has nine defects in the, as shown in the A-A cross-section view of Fig.2, in which there are 3 defect depths (6, 5 and 3mm) and 3 defect diameters (10, 8 and 6 mm).

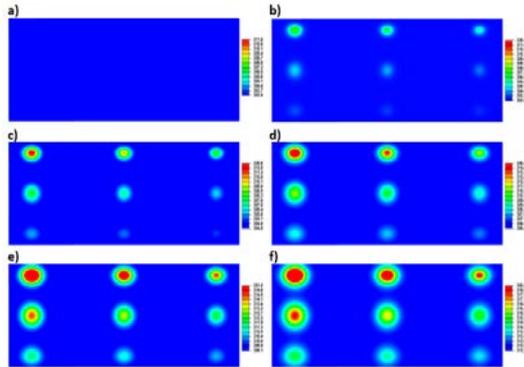


Fig.3 FE simulated time-serial thermographic images of the defected PE pipe at the time of a) 0 second; b) 24 seconds, c) 48 seconds, d) 72 seconds, e) 96 seconds, and f) 120 seconds.

Fig.3 show the FE simulated time-serial thermographic images of the defective PE pipe at the time of 0, 24, 48, 72, 96 and 120 seconds. From Fig.3 (a) to (f), we could find the temperature difference around the defect location gradually become obvious. It can be seen from the figures that if the defect diameters are same, the deeper defect the higher temperature of outer surface at the location of defects; also, if the defect depths are same, the larger defect the higher temperature of outer surface at the location of defects. Eqs. (3) and (4) could be used for the explanations of these phenomena.

For the PE pipe with thickness of 10 mm, due to slow heat transfer, it about needs 60 seconds to get a good thermographic image for defect detection of PE pipes. However, the quality of the thermographic image will increase with the time increasing; for example, the thermographic image at 120 seconds is enough for identification of PE defects. In the experiment, we recorded the thermographic images up to 120 seconds.

Fig.4 demonstrated the experimental time-serial thermographic images obtained by Optris infrared camera from a PE pipe sample with the same defects with the simulated model. From Fig.4 (a) to (f), we could also find the temperature difference around the defect location gradually become obvious. If the defect diameters are same, deeper defect the higher temperature of outer surface at the location of defects; also, if the defect depths are same, larger defect the higher temperature of outer

surface at the location of defects. Therefore, the trends for temperature difference of FE simulation result is well agreed with the one obtained by infrared camera.

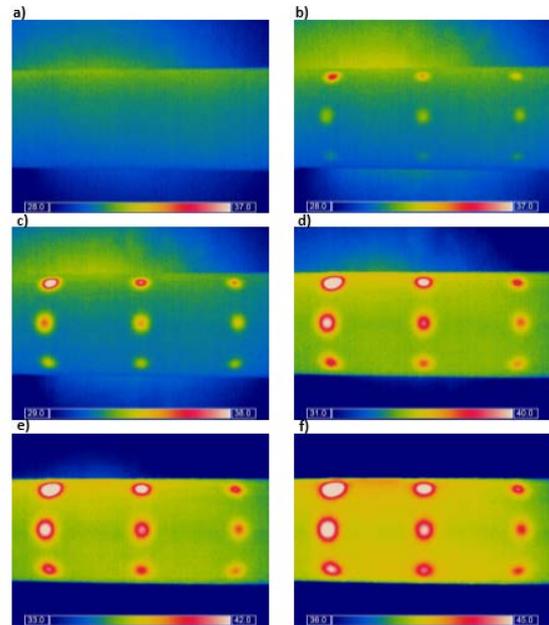


Fig.4 Experimental time-serial thermographic images of the defected PE pipe at the time of a) 0 second; b) 24 seconds, c) 48 seconds, d) 72 seconds, e) 96 seconds, and f) 120 seconds.

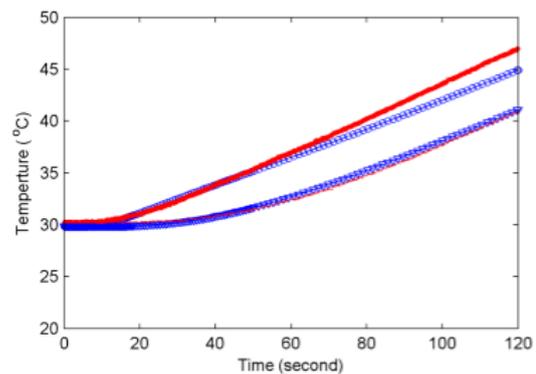


Fig.5 Comparisons of time-serial temperature at the central-left defect position and around the defect obtained by FE simulation and experiment: circle indicates FE result for the central defect position; triangle indicates time-serial temperature around the defect by FE; solid line indicates experimental result for the centraldefect position; dashed line shows time-serial temperature around the defect by Finite Element analysis.

To compare quantitatively the temperature at locations with and without defects, time-serial temperatures at the central-left defect position and around the defect obtained by FE simulation and experiment were compared, as shown in Fig.5.

It demonstrated good agreement of FE simulation and experiments of active thermal Imaging. Here, the finite element model has been validated by the active thermal imaging experiment; in the meanwhile, the experiment could be well predicted by the FE model. From Fig.5, we could find the temperature difference at the time of 120 seconds is the largest which is the best time for defect detection of PE pipes in the time-serial images recorded.

4 Automatic Defect Feature Extraction of PE Pipes by Mathematical Morphology

For automatic evaluation of PE pipe defects, mathematical morphology approach was employed for feature extraction of PE pipes. Mathematical morphology has superiority in image edge detection. To pre-process of the thermographic images, the thresholding technique was first used to do the binarization to enhance the clarity of defect-deduced temperature difference at the defect locations. Further image processing continues with the mathematical morphology. In the analysis, dilation and erosion are very sensitive to image edges. Opening can smooth the contour of an image and breaks narrow gaps whilst closing tends to fuse narrow breaks, eliminates small holes, and fills gaps in the contours. Take the thermographic image at Fig.4 (f) as an example, the dilation and erosion, opening and closing morphology operations were applied to the thermographic image. Fig.6 (a) shows the defect extraction results by mathematical morphology and it demonstrated that the defect feature can be effectively extracted by mathematical morphology. In Fig. 6 (b), the boundaries of the defect features were drawn by closed circles for the calculation of the area of the feature.

To establish the relationship between defect feature of thermal images and PE defects, the area of the defect features were calculated. Fig.6 (c) shows the relationship between the area of the defect features and defect depths, defect diameters. Similar to the discussion previously, we can draw a conclusion from Fig.6 (c) that the larger defect the higher temperature of outer surface at the location of defects; also the deeper defect the higher

temperature of outer surface at the location of defects. These nonlinear relationships can facilitate in building a defect database for nondestructive testing and evaluation of PE pipes if more defects with different dimensions were investigated by the active infrared thermography.

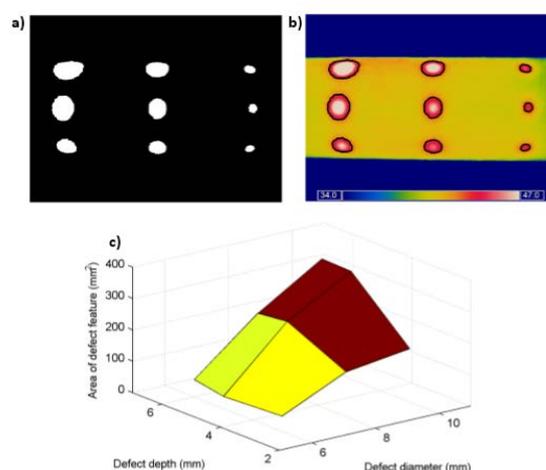


Fig.6 a) Defect features extracted from thermographic images by mathematical morphology; b) Thermographic image with some closed circles showing the location and sizes of the defect features; c) The relationship between the area of the defect features and defect depths, defect diameters.

Defects in heat fusion joints of PE pipes were also investigated in the present work to further verify the capability of this active infrared thermography in defect detection of PE pipes. Polyurethane composite material was embedded in the heat fusion joints to mimic the defects in PE pipes, as shown in Fig.7 (a) and (c). Two PE pipes were fabricated: 1) #1 PE pipe with 2 defect whose width are ~ 3 mm and ~ 7 mm; 2) #2 PE pipe with 2 smaller defect whose width are ~ 2 mm. It is noted that there is a crack defect whose width is ~ 1 mm in #2 PE pipe, as the arrow shown. The corresponding thermographic images of these two PE pipes are shown in Fig.7 (b) and (d). The defect information of four defects in two PE pipes are included in the thermal images, as shown in the dashed circles.

In the meanwhile, the small crack defect feature (indicated by an arrow) in #2 PE pipe also was shown in Fig.7 (d). However, due to the non-uniform heat field, there are some background noises in the figure, especially for Fig.7 (d).

Using mathematical morphology approach, the four defects (indicated by circles) and the small crack (indicated by an arrow) were identified, as

shown in Fig.7 (c) and (e). The boundaries of defect features were drawn by closed curves. Mathematical morphology has effective capability in defect feature even contaminated by background or environment noise and therefore, it also has the ability in image denoising. So the active infrared thermography based on an electrical heating bar as thermal excitation and mathematical morphology as feature extraction approach, could be recommend in detecting and monitoring flaws in the PE pipes.

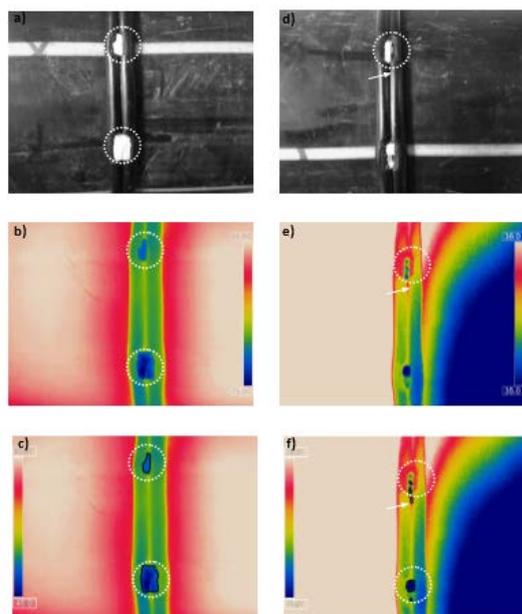


Fig.7 (a) #1 PE pipe with 2 defect whose width is ~ 3 mm and ~ 7 mm; (b) and (c) are the corresponding thermographic image obtained by a high-sensitivity infrared camera and the defect feature extraction of the PE pipe by mathematical morphology. The dashed circles indicate the locations of defects. (c) #2 PE pipe with 2 defect whose width are ~ 2 mm: the arrow indicates a small crack whose width is ~ 1 mm; (d) and (e) are the corresponding thermographic image obtained by the infrared camera and the defect feature extraction of the PE pipe by mathematical morphology.

5 Conclusions

In summary, we report an approach for nondestructive testing and evaluation of polyethylene pipes by using active infrared thermography technique, in which an electrical heating bar was used as the novel thermal excitation source and a high-sensitivity infrared camera was used as the detector. Mathematical morphology is employed for defect feature extraction and realized

the automatic evaluation of PE pipe defects. Mathematical morphology has effective capability in defect feature even contaminated by background or environment noise. A finite element model was also built to mimic the transient heat transfer in PE pipes. The finite element simulation results are well agreed with the one obtained from the infrared imaging experiments and it demonstrated that finite element numerical method can be an effective method to analyze infrared imaging. To further verify the capability of the developed active infrared thermography in defect detection of PE pipes, defects in heat fusion joints of PE pipes were fabricated and detected. The experimental results showed that active infrared thermography based on an electrical heating bar, with defect extraction by Mathematical morphology, could provide a novel tool for nondestructive evaluation and health monitoring of PE pipes.

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