A method for crack identification in base material under spray coatings by vibrothermography

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Abstract
In order to detecting fatigue cracks in base material which covered by spray coatings. The heat generation pattern between coating crack and substrate crack were compared when excitated by low frequency ultrasonic vibrancy, the turbulence to the coating crack thermal wave caused by heat generation of a substrate crack was observed, and the contrast in the time frequency features of the coating crack thermal wave and mixed thermal waves was analysed. Phase declination (PD) is abstracted as a recognition feature of the mixed thermal wave and polynomial fitting (PF) and wavelet decomposition (WD) are employed in the image reconstruction of the thermal wave. On this basis, a method to identify fatigue cracks in the base material under the spray coating is proposed.

Keywords: Crack inspection, Spray coating, Vibrothermography, Image processing, Phase declination

1. Introduction
In most aspects of industry, spray coatings have played a crucial role in preserving components by enhancing a plethora of properties including anticorrosion, wear-resistance, thermal insulation, anti-fouling and many more. Quality evaluation of spray coatings on the base metal is still a difficult problem in engineering practice partly due to the complex internal structure and heterogeneous interface. Visual inspection and some non-destructive testing (NDT) methods are currently employed to find coating cracks, interface debonding, or assess coating thickness [1, 2] but for fatigue cracks in the base material, which is covered by the sprayed coating, it is still difficult to discriminate for lack of an efficient NDT tool at present.

One of the more state of the art NDT methods is active infrared thermography. This method has been used to reveal surface and subsurface defects by thermally exciting the test material, usually by irradiating with an infrared source, keeping the material in a non-equilibrium state and measuring the transient temperature field with a thermal infrared imager [3,4]. For defects that exist both on the surface and penetrate to the subsurface, such as fatigue cracks in composite materials or metals, low frequency (range of 20~40 KHz) ultrasonic vibrations has been shown to be one of the most effective methods to thermally excite the material under test and thus garner information on the inhomogeneities in the material [5]. This method is known vibrothermography. A widely accepted mechanism for the thermal excitation involves the frictional rubbing of contacting regions on a crack [6, 7]. Vibrothermography is an important method as reflected by the increasing number of investigations in the literature. This includes the work by Han et al. [8] who have used vibrothermography to locate cracks in both the coating and/or the underlying surface. They built a finite element model of fatigue cracks in the metal surface and calculated the expected energy dissipation in a crack during sonic infrared imaging. They conclude by confirming previous experimental results that observe an enhancement of heat generation in the presence of acoustic chaos and thereby increasing the probability of crack detection. Ptaszek et al. [9] quantifies the difference between coating cracks and disbonding defects, proposes an artificial coating crack testing method based on experimental work using vibrothermography. This method has also been used to solely characterise subsurface cracks. An investigation by Bendada et al. [10] used infrared vision to reveal subsurface cracks in Kevlar composite materials. They concluded that this technique provides more straightforward detection capabilities than other NDT methods for inner closed defect types. Manohar and...
Lanza [11] suggest that the phase of thermal wave is closely relate to the crack depth and hot property of material, so the phase characteristic is related to crack depth or coating thickness. It is clear that there has been much advancement in the detection of inhomogeneities (e.g. cracks) in the surface and subsurface regions of a material. However, there still lacks detailed information in the instance where cracks exist in the same position in both the coating and underlying material – a situation that commonly occurs in real components. It is to the authors’ knowledge that there is yet to be an experiment focusing on the existence of fatigue cracks in the base material underneath existing coating cracks. Here we aim to directly address this issue. In this paper, the coating crack thermal wave is compared with the mixed thermal wave both in time and frequency domains. The mixed thermal wave is composed of a coating crack component and substrate crack component and the PD is extracted as a wave feature to distinguish the mixed thermal wave from the coating crack thermal wave. Thus the PD of the thermal wave suggests the existence of a crack in the base material. Furthermore, PF and WD are used in the image processing for the visualization of the mixed thermal wave i.e. the substrate crack.

2. Theory analysis and simulator investigation

2.1 Heat generation of coating crack and substrate crack

Previous work in the literature suggests that in many situations, cracks in the substrate are accompanied by coating cracks, when substrate cracks propagate to the interface the fragile coating can be stretched by a huge stress concentration and split open [12-14]. When excited by ultrasonic vibrations, fatigue cracks in the base material generate heat at the closed contacting position of two crack surfaces. Experimental observations [15, 16] and theoretical simulations [17] suggest that the locus of heating is usually inward from the crack tips, in other words, heat is generated in the crack closure region of the metal specimen. Comparatively, cracks in a spray coating will generate heat in a more size along the crack owing to much more rugged crack surfaces than a base material crack. Fig.1 displays the visible and thermal images of the substrate face (Fig.1 (a)) and coating face (Fig.1 (b)) of the same specimen captured by IR cameras during vibration process. The crack on substrate surface seemed a produce dot-like heating source in the thermal image whereas the coating crack shows as a line-like heating source. So, when the heat of the substrate crack conducts to the coating surface, and superimposes upon the coating crack heat, a mixed thermal wave will be formed. This shown schematically in Fig.2, where components 1 and 2 represent the heating source of the coating crack and substrate crack, respectively. The mixed thermal wave is formed in the region where components 1 and 2 overlap. Consequently, in order to distinguish the substrate crack from a coating crack by the thermal wave on a coating surface, a mixed thermal wave can be employed as the distinguishing feature of the substrate crack. However, there still lays the problem of how to discriminate the mixed thermal wave.

![Fig.1 Visible and thermal images on two surfaces of the specimen.](image-url)
2.2 Feature extraction of mixed thermal wave

A numerical model containing cracks in both the coating and base material is built, where two line-like heat sources are located in the coating and substrate independently, as shown in Fig.2 (a). A top view of the coating surface (Fig.2 (b)), shows component 1 as a line-like heating source and component 2 is a dot-like heating source, consistent with the experimental results. On the coating surface, thermal waves at point A, B and C are collected as shown in Fig.3. It is obvious that the mixed thermal wave formed at point A is not only hotter than those at B and C but also has a faster increase in temperature as well. However, this is not enough information to distinguish wave A from waves B and C by the curves in time domain.

Discrete Fourier Transform (DFT) is the most elementary and significant transformational equation in signal processing. Through DFT the frequency-domain parameters, such as amplitude and phase versus frequency, of the thermal wave can be obtained. The equation of DFT is shown in Equation (1):

$$F(f) = \frac{1}{N} \sum_{n=0}^{N-1} T(n)e^{-j2\pi nf/N} = R(f) + iI(f)$$  \hspace{1cm} (1)

Where N is the number of sampling, R (f) and I (f) are the real and imaginary components of F (f), respectively. Furthermore, the phase spectra can be calculated from Equation (2):

$$\phi(f) = \arctan \left( \frac{I(f)}{R(f)} \right)$$  \hspace{1cm} (2)

The phase spectra of the thermal wave at points A, B and C is gained by DFT, as shown in Fig.3. The phase spectrum at point A is obviously lower than the curve of point B, contrary with in Fig.2. This means that a declination has emerged for phase spectrum A. At the same time, declination does not emerge for phase spectra B and C. Trace to source, the only difference is that thermal wave at point B and C are caused by the same coating crack heat source, component 1, but the mixed thermal wave at point A is composed of both component 1 and component 2. Consequently, as characteristic parameters, the PD suggests the mixed thermal wave is on the coating crack surface and further yet, it means the crack defect in the base material is under the spray coating. It is clear to see how problems in detecting the base material crack, present under the spray coating, can cause difficulties in searching for the mixed thermal wave along the coating crack.
3. Experimental results and image processing

In order to validate the results found for the simulator investigation, experimental work was carried out on a C1045 steel (45 carbon steel) sheet tensile sample with a fatigue crack, then 420S45 (3Cr13) coating is prepared on one face of the tensile sample by flame spraying. The coating covers the substrate crack however a new crack will form in the coating material at the same position as the substrate crack due to stress concentration. The sample is ultrasonically vibrated (frequency = 25 KHz) for 1s. A IR camera (NEC Avio R300D) is used to record the range of surface temperature with a resolution of 0.03 °C. The infrared acquisition frequency is 60 Hz. Raw thermal images of the substrate and coating surfaces can be seen in Fig.1.

3.1 Experimental results

In order to analysis the phase feature in the different positions of the coating crack, we used 7 equi-distributed points along the crack as shown in Fig.5 (a). Thermal wave curves and the corresponding phase spectra of every point are exhibited in Fig.5 (b) and (c), respectively. The wave curves in time domain are analogous in both gradient and maximum temperature, however, the phase spectra distributed in a disordered fashion, mainly because of the low-resolution ratio in frequency. According to equation (1), it’s the small sampling number of raw thermal wave curve, which causes low-resolution ratio in frequency in the phase spectra, so the sampling rate needs to be increased through data processing.

![Fig.5 Heating process of different points in the coating crack.](image-url)
3.2 Experimental results

Polynomial fitting is a method for data smoothing, in this work, PF is employed to fit the thermal wave curves on the coating surface. The $n$ degree polynomial fitting can be expressed as following equation:

$$T(t) = c_1t^n + c_2t^{n-1} + \cdots + c_n + c_{n+1}$$

(3)

The 4th degree polynomial fitting results of the thermal wave in points 1-7 are exhibited in Fig.6 (a). It can be seen that the thermal waves at points 1 and 2 have a greater gradient than the other five points in time domain. Fig.6 (b) displays the phase spectra computed by DFT. It is evident that phase declination emerges from the phase spectra of points 1 and 2. This is a characteristic feature of a mixed thermal wave and so we can conclude that a substrate crack is present, which generates heat during vibration excitation. Fig.6(c) is a phase image reconstructed from the phase spectra, where the coating crack is clearly visible in the image even though a large number of noise points are present. However, the mixed thermal wave cannot be distinguished from the image with the reason being the phase spectra of points 1 and 2 skew downward relative to the other points and arrive at the region filled by the phase spectra of un-defect points. It is clear that using this method to generate a reconstructed phase image of the mixed thermal wave at points 1 and 2 is unfeasible thus other methods must be employed.

(a) Fitted thermal wave of 7 points  
(b) Phase spectra of 7 points  
(c) Reconstructed phase image  

Fig.6 Polynomial fitting of thermal wave and image reconstructing.

One such method is wavelet decomposition (WD) also known as wavelet transform. It is one of the most common used transforms in numerical analysis and a key advantage it has over Fourier transforms is temporal resolution – it captures both frequency and location information in time. Unidimensional Wavelet decomposition can be expressed as the following equation:

$$WD_{K-1} = \sum_{K=0}^{K-1} x[2n-k]g[k] + \sum_{K=0}^{K-1} x[2n-k]h[k]$$

(4)

In equation (4), coefficient $k$ is the decomposition level, $g[k]$ is the approximation coefficient in level $k$, which reflect the low frequency component and $h[k]$ is the detail coefficient that reflect the high frequency component of signal.

Equation (4) is used to fit the thermal wave curves of the 7 points in the coating crack. When decomposition comes to level 2, the phase spectra appear to show a significant upward shift.
(ascending) so it can keep away from the phase spectra of the normal region, as shown in by
the black arrows in Fig.7 (a). The thermal image reconstructed (Fig.7 (b)) clearly shows
significantly less noise points than in Fig.6(c). Furthermore, image of the mixed thermal wave
can be reconstructed separately from the coating crack thermal wave, which means using this
method allows the visual identification of the substrate crack under the coating.

![Fig.7 Phase spectra of wavelet decomposition and phase image reconstructing.](image)

(a) Phase spectra of second floor details coefficient  (b) Reconstructed phase image

Fig.8 exhibits magnified images of the crack region with different processing. Obviously, the
position and shape of the mixed thermal wave in reconstructed phase image (f) is very similar
to the raw thermal image of the coating surface (d). This corroborates that the mixed thermal
wave in the coating crack is qualified to represent the substrate cracks in the base material.
Through PF and WD of the raw thermal wave in the coating crack, the mixed thermal wave can
be exposed distinctly in the reconstructed phase image.

![Fig.8 Comparison of different images.](image)

(a) Optical image of coating surface; (b) Optical image of substrate surface; (c) Raw thermal
image of coating surface; (d) Raw thermal image of coating surface; (e) Reconstructed image
of coating crack by PF; (f) Reconstructed image of mixed thermal wave (substrate crack) by
WD.

4. Conclusions

1) The temperature of the cracks, in both the spray coating and base material, rises quickly
under the excitation of low frequency ultrasonic vibrations. An IR camera collects the thermal
waves on the coating surface during the excitation process. At some position of the coating
crack, the coating crack and substrate crack components overlap to form a mixed thermal wave. Here, the temperature rises quickest and is also the hottest when compared to other points on
the coating surface.

2) Frequency domain analysis suggests that the coating material postpones the phase of the
thermal wave component generated by the substrate crack, as does the mixed thermal wave. PD
is extracted as a distinguishing feature of the mixed thermal wave – this feature represents the
fatigue crack in the base material under the spray coating.
3) PF and WD can be employed to thermal image processing. After using PF and WD for the thermal wave in every pixel of the raw thermal image sequence, the phase of the thermal wave reconstituted by the 2nd level detail coefficient appearing as a significant upward (ascending) shift. In the reconstructed thermal image, the mixed thermal wave can be shown independently from the coating crack thermal wave meaning that this method can be used to identify cracks in the base material under spray coatings.

It should be noted that this study has confirmed only the special tensile crack in the base material for convenience of comparison and preparation.

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References


17. Lesthaeghe T J. Evaluation of some parameters influencing vibrothermographic crack heating, Iowa State University. United States Iowa. 2015, 35-46