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Volume or inside heating thermography using electromagnetic excitation for advanced composite materials

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A B S T R A C T

Conventional active thermography heats the surface of materials by using conductive thermal sources like hot water, convective thermal sources like air jet, or irradiative thermal sources like a flash lamp. Quantification and characterization methods are mainly built on heat conduction from surface to inner. Currently, electromagnetic induction, microwave and terahertz wave are increasingly used for heating advanced materials such as composites, polymers and biomaterials. Their heating principles and quantification methods vary widely from that of conventional surface heating thermography. This work presented volume heating thermography (VHT) and inside heating thermography (IHT) for advanced composite materials through these electromagnetic excitations. Physical principle of VHT/IHT for defect quantification has been investigated, and several specific VHT/IHT methods have been built in style of (square) pulse and step analysis in time domain and phase analysis in frequency domain, such as volume lock-in thermography. 1D solution, simulation involving 3D finite element model and experiments studies demonstrate that polytetrafluoroethylene insert, impact, and delamination in carbon fibre reinforced polymer can be qualitatively detected and characterised using proposed methods, especially in phasegram after eliminating non-uniform heating effect and periodic structures. VHT and IHT through electromagnetic induction, microwave and terahertz wave have a potential application on inspection and characterization of composites, polymers and biomaterials.

1. Introduction

Thermography including passive and active thermography has become an important tool for material characterization, health monitoring and non-destructive testing (NDT) of metals, polymers, composites and biomaterials [1–8]_ENREF_1. With conventional active thermography, surface of material under test is usually heated by using 1) conductive thermal sources such as hot water, 2) convective thermal sources such as hot air jet, or 3) irradiative thermal sources such as flash lamps. Defect quantification and property characterization methods are built based on heat conduction from the surface to inner and heat reflection from defect's interface to material's surface. These methods can be categorised as surface heating thermography (SHT). Currently, electromagnetic excitations including high-frequency eddy current, microwave and terahertz wave are increasingly used for heating advanced materials [9–13]. For example, microwave has been used to heat glass fibre reinforced polymer and biomaterials. And, high-frequency induced eddy current has been employed to heat carbon fibre reinforced polymer (CFRP) [14–16]. In these cases, heating physical principles vary widely from SHT. Therefore, quantification and characterization methods are also greatly different from SHT. This work proposes volume heating thermography (VHT) and inside heating thermography (IHT) through these electromagnetic excitations for inspecting and characterising advanced composite

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Abbreviations: CFRP, Carbon fibre reinforced polymer; FEM, Finite element method; IHT, Inside heating thermography; NDT, Nondestructive testing; PPT, Pulsed phase thermography; PT, Pulsed thermography; SHT, Surface heating thermography; ST, Step thermography; VHPPT, Volume heating pulse phase thermography; VHPT, Volume heating pulse thermography; VHST, Volume heating step thermography; VHT, Volume heating thermography; VHLT, Volume heating lock-in thermography.

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materials. More specifically, IHT can be considered as a kind of VHT where only inside defects or interesting objects are heated while the host material is not. For instance, eddy current thermography is a type of VHT for CFRP detection due to small conductivity and large skin depth of induction heating. Microwave thermography is a type of IHT for water inspection in composite structures. Also, photothermal radiometry is a kind of VHT when it is applied to (semi) transparent materials and structures [17–19].

VHT/IHT's physical principles have been investigated in this work for defect quantification. Three quantification and characterization methods have been built, which are: 1) volume heating step thermography (VHST) or inside heating step thermography based on temporal temperature analysis caused by step excitation in time domain; 2) volume heating pulse thermography (VHPT) or inside heating pulse thermography based on temporal temperature analysis caused by (square) pulse excitation in time domain; 3) volume heating pulse phase thermography (VHPPT) or inside heating pulse phase thermography based on phase analysis in frequency domain. VHPPT is compared with volume heating lock-in thermography in terms of theoretical analysis to show the advantage of multi-frequency phase.

2. Physical principles

2.1. Surface heating thermography

The common types of SHT fall into two groups: 1) time domain analysis including step thermography (ST) [20], and pulse thermography (PT) [21]; 2) frequency domain phase analysis including lock-in thermography [21], pulse phase thermography (PPT) [22] and frequency modulated thermography [23,24]. According to relative position of excitation and IR camera, there are two configurations for SHT: 1) reflection mode, where excitation and camera are situated at the same side; 2) transmission mode, where excitation and camera are located at the opposite side. Usually, reflection mode configuration is more practical. Furthermore, defect depth can be quantified under reflection mode whilst not under transmission mode [3]. Specifically, ST heats material continuously with a long pulse and temperature's rising process will be analysed. With ST, the real temperature-time$^{1/2}$ curve for defect-free area under reflection mode (where IR camera and thermal source are located on the same side) is linear, as shown in equation (1), where Q is heat applied on the surface, α is thermal diffusivity, k is thermal conductivity [25]. This curve can be used for defect quantification and characterization [25]. PT normally warms MUT with a short duration pulse and temperature's decreasing process is analysed. With PT, the temperature decrease ΔT with time t can be expressed by a power function in equation (2), where e is thermal effusivity [26,27]. After logarithm transform, temperature-time curve decreases linearly with the slope of $-1/2$ and it can be used for defect quantification and characterization [28]. Sometimes, PT is called square pulse thermography (SPT) when square pulse is used. In this case, SPT can be considered as a step thermography followed by a pulse thermography, because both heating and cooling phases are analysed. Lock-in thermography uses periodic thermal excitation in order to derive information at specific depth from reflected thermal wave at specific frequency. As a link between PT and LT, PPT uses the pulse as excitation like PT and conducts phase analysis like LT at multi frequencies. These conclusions are derived from heat conduction from the surface to inside and heat reflection from defect's interface to material's surface, and it can be used to measure the depth of inner defects or interesting objects under reflection mode. However, they are invalid under the transmission mode where IR camera and thermal source are located at the opposite sides of MUT.

$$T = \frac{2Q}{k}\left(\frac{\alpha t}{\pi}\right)^{1/2} = \frac{2Q}{k}\left(\frac{\alpha}{\pi}\right)^{1/2} t^{1/2} \tag{1}$$

$$\Delta T = \frac{Q}{e\sqrt{\pi t}} = \frac{Q}{e\sqrt{\pi}}t^{-1/2} \Rightarrow \ln(T) = \ln\left(\frac{Q}{e\sqrt{\pi}}\right) - \frac{1}{2}\ln(t) \tag{2}$$

2.2. Volume heating thermography and inside heating thermography

According to heating function and signal process, VHT can also be classified into step thermography, pulse thermography, lock-in thermography, pulse phase thermography and frequency modulated thermography. And, all kinds of VHT mentioned above can be deployed as reflection mode and transmission mode like SHT [3]. However, VHT's physical principles are totally different from SHT in heating style. The heating styles for SHT and VHT can be found in Fig. 2 in Ref. [3]. With volumetric heating utilizing induced eddy current, microwave or terahertz wave, all the infinitesimal elements constituting the volume of material under test are heated individually, ideally at substantially the same rate. And then, heat conduction inside material under test and temperature responses on the surface of material under test are also different from that of SHT. This work takes eddy current thermography for CFRP as example. With eddy current thermography, high-frequency alternating current is driven to inductive coil along CFRP. Then, the current passing through the coil will induce eddy currents in CFRP. From the macroscopic view, the eddy currents are governed by skin depth due to the skin effect [29], which can be calculated by $\delta = (\pi\mu\sigma f)^{-1/2}$, where, f is frequency of excitation signal, σ is electrical conductivity (S/m) and μ is magnetic permeability (H/m) of material under test. It is concluded that skin depths for CFRP with small conductivity (1000 S/m) and no magnetic are significantly great (about 50 mm under 100 kHz excitation). This depth usually exceeds the thickness of CFRP component. Thus, heating style of eddy current thermography for CFRP is volumetric heating [14]. The sum of the generated resistive heat $q(t)$ per unit volume is proportional to the square of the magnitude of the electric current density or the electric field intensity vector E, namely

$$q(t) = \frac{1}{\sigma}|J_s|^2 t = \frac{1}{\sigma}|\sigma E|^2 t \tag{3}$$

where J_s denotes eddy current density and t is heating time (s). The heat will diffuse as the time delays till it reaches balance in CFRP. In general, by taking account of heat diffusion and Joule heating, the heat conduction govern equation is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{1}{\rho c}q(t) \tag{4}$$

where, T is temperature (K), k is thermal conductivity of MUT (W/m × K), ρ is density (kg/m^3), and c is heat capacity (J/kg × K). At the same time of induction heating, the electromagnetic radiation in infrared waveband (1.5–5 μm in this work) from CFRP is monitored by an IR camera. And then, the temperature on the surface of CFRP is computed according to the Planck's law. IR camera captures all pixels of infrared radiation with a sampling frequency as a series of digital images.

2.3. Volume heating step thermography

The physical principle of VHST for defect quantification is