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A REVIEW ON EDDY CURRENT THERMOGRAPHY TECHNIQUE FOR NON-DESTRUCTIVE TESTING APPLICATION

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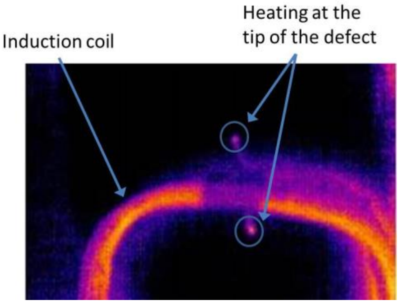
Graphical abstract



Abstract

Eddy current thermography is one of the non-destructive testing techniques that provide advantages over other active thermography techniques in defect detection and analysis. The method of defect detection in eddy current thermography has become reliable due to its mode of interactions i.e. eddy current heating and heat diffusion, acquired via an infrared camera. Such ability has given the technique the advantages for non-destructive testing applications. The experimental parameters and settings which contribute towards optimum heating and defect detection capability have always been the focus of research associated with the technique. In addition, the knowledge and understanding of the characteristics heat distribution surrounding a defect is an important factor for successful inspection results. Thus, the quantitative characterisation of defect by this technique is possible compared to the conventional non-destructive which only acquired qualitative result. In this paper, a review of the eddy current thermography technique is presented which covers the physical principles of the technique, associated systems and its applications. Works on the application of the technique have been presented and discussed which demonstrates the ability of eddy current thermography for non-destructive testing of conductive materials.

Keywords: Non-destructive testing, eddy current thermography, eddy current, thermography, defect detection

Abstrak

Termografi arus pusar adalah salah satu teknik dalam ujian tanpa musnah yang mempunyai banyak kelebihan berbanding teknik termografi aktif yang lain bagi mengesan dan menganalisa sesuatu kecacatan. Teknik pengesanan kecacatan menggunakan termografi arus pusar telah menjadi satu teknik yang boleh diharapkan berdasarkan mod interaksinya i.e. pemanasan oleh arus pusar dan resapan haba, yang diperolehi melalui penggunaan kamera inframerah. Keupayaan ini memberi kelebihan kepada teknik tersebut dalam aplikasi ujian tanpa musnah. Parameter dan aturan dalam eksperimens yang menyumbang kepada pemanasan yang optimum dan keupayaan pengesanan sesuatu kecacatan sentiasa menjadi tumpuan kepada penyelidikan yang berkaitan dengan teknik tersebut. Tambahan pula, pengetahuan dan pemahaman tentang ciri-ciri pengagihan haba di sekitar kecacatan adalah menjadi satu faktor penting untuk kejayaan mendapatkan keputusan pemeriksaan yang tepat. Dengan itu, pengklasifikasian kecacatan secara kuantitatif melalui teknik ini adalah mustahil berbanding dengan ujian tanpa musnah yang konvensional, yang hanya boleh memperolehi keputusan secara kualitatif. Dalam kertas kerja ini, ulasan mengenai termografi arus pusar telah dibentangkan termasuk prinsip fizikal tentang teknik, system yang berkaitan dan aplikasinya. Kajian tentang aplikasi teknik tersebut telah dibentangkan dan dibincangkan untuk menunjukkan keupayaan termografi arus pusar dalam ujian tanpa musnah bagi pengujian terhadap bahan konduktif.

Kata kunci: Ujian tanpa musnah, termografi arus pusar, arus pusar, termografi, pengesanan kecacatan

1.0 INTRODUCTION

Thermography in non-destructive testing (NDT) can be divided into two categories, the passive and active approaches. The passive approach tests materials and structures which are naturally at different (often higher) temperatures than the ambient background, while in the case of active thermography, an external heating stimulus is used to induce relevant thermal contrast. The active approach to thermography has numerous applications in NDT. Moreover, since the characteristics of the required external stimulus are known, i.e. heating time applied to the sample, quantitative characterisation becomes possible. Two categories of heating techniques are applicable to NDT defect detection; those that deposit heat on the material surface and then rely on the heat to propagate through the material to detect subsurface defects, and those that excite the material itself and have some direct interaction with subsurface defects.

Traditional thermographic inspection utilises direct deposition of heat on the material surface using heat lamps [1, 2]. Despite the popularity of the technique, the utilisation of this type of heating for thermography does have a number of potential disadvantages; the reflected heat from the material under inspection can interfere with the measured signal, causing SNR problems, and it can be difficult to deposit a sufficient amount of heat on the material surface in the short time needed for pulsed thermography.

Heating of the material under inspection can also be accomplished via the application of sonic or ultrasonic energy using a device such as an ultrasonic welding horn; this is known as vibrothermography, thermosonics or sonic infrared (IR) [3]. The applied excitation vibrates the material under inspection and leads the crack faces to rub against each other, the mechanical energy is converted to heat and the generated heat is detected at the material surface. Disadvantages include the need for contact between the test piece and the ultrasonic welding horn and the unreliability of this contact, which leads to the vibration spectrum produced being highly variable from contact to contact [3].

An alternative to heat lamp or sonic excitation for the testing of conductive materials is found in eddy current thermography. The technique, also known as induction thermography [4], tone burst eddy current thermography [5], pulsed eddy current thermography [6], thermo-inductive [7], and eddytherm [8], uses an induction coil to induce eddy currents to heat the sample being tested [7-10]. Defect detection is based on the changes of the induced eddy current flows revealed by the thermal distribution captured by an infrared IR camera. Thus, eddy current thermography has many potential advantages over heat lamp and sonic excitation techniques; there is no interference from applied heating or excitation equipment (the change in temperature of the coil itself is very small), there is little chance of damage to the material under inspection, as heating is limited to a few °C and for near-surface defects, direct interaction with eddy currents can improve detectability [11].

In this paper, the underlying phenomena of eddy current technique is prevailed due to the signature temperature characteristics. Furthermore, the associated system for the technique and related heating parameters for application is discussed, provided with the illustration of system setup. Finally, a brief overview about the approaches and applications of the technique as a viable NDT technique for industrial inspection has been discussed following the conclusion of the review towards eddy current thermography for non-destructive application.

2.0 METHODOLOGY

2.1 Physical Principles of Eddy Current Thermography Technique

The inspection sensitivity in eddy current thermography has a close relationship with the eddy current penetration of depth. The current density decreases with depth and the point at which it decreases to 1/e which is about 37% of the current density at the surface is called the standard of penetration (δ) and can be calculated by Eq. 1 [12]. The word 'standard' denotes plane wave electromagnetic field excitation within the sample; a condition which are rarely achieved in practice.

$$\delta = \frac{1}{\sqrt{f\pi\mu\sigma}} \qquad (1)$$

where f is the frequency of the electromagnetic wave in Hz, μ is magnetic permeability and σ is electrical conductivity.

When inductive heating is used, heat energy, E, is produced through ohmic heating according to Joule's Law [13]:

$$E = I^2 Rt \tag{2}$$

where I is current, R is resistance and t is the time of exposure to the magnetic field.

Thus the ohmic heating is proportional to the square of the current density and increases proportionally with time. When considered in conjunction with skin depth formula, this shows that the effective direct heating depth in a material is even lower than the calculated δ might suggest.

In eddy current thermography, both direct heating (from the induced eddy currents) and diffused heating contributes to defect detection. Defects such as cracks, voids or delamination which are within the range of the eddy current distribution disturb the current flow and thus change the temperature distribution. Defects which do not directly interact with the induced eddy currents may interact with the heat generated at the surface as it propagates through the material [14]. Therefore, the effect of thermal diffusion must also be taken into account in eddy current thermography. Eq. 3 shows the relationship between thermal diffusion length, μ, with thermal diffusivity, α, in terms of time, t [7]. For steel this equates to a thermal diffusion length of around 2mm in 0.1s, greater than the δ under most test conditions. So for magnetic materials (low δ), both joule heating and thermal diffusion must be taken into account.

$$\mu = 2\sqrt{\alpha t} \tag{3}$$

The resultant surface heat distribution from direct eddy current heating and diffused heat for defect detection can be easily obtained with an IR camera but for quantitative defect characterisation, techniques for the determination of heating mechanisms around a particular defect are required. Vrana *et al*. [4], described the effects of slots and notches in a finite body on the current density distribution via numerical and analytical models. Two fundamental defect models i.e. slot and notch, shown to cause a characteristic heat distribution were introduced in their work but experimental implications and discussion of the contributing factors were limited.

Wilson *et al* [14] extended the work done by Vrana to look at a defect, which combines the characteristics of the two fundamental defects (slot and notch), in a mild steel sample using both simulation and experimental approach. In the investigation, the distance between the induction coil and the end of the defect is varied and the results are related back to the fundamental defect types in order to explain the heat distribution. This fundamental understanding of eddy current distribution and heating propagation through thermal visualisation and mapping aid in the understanding and the development of feature extraction and pattern recognition via the eddy current thermography technique.

Through the research works done for the eddy current thermography technique, it has been acknowledged that the technique provide a signature temperature characteristic i.e. heating or hotspot at the tip (Figure 1) of the detected defect, which provide an approach for defect detection and characterization [4, 6-7, 9, 14-16]. This phenomena which depends highly on the positioning of the excitation coil, is a unique observation compared to other active thermography techniques that uses heat lamp [18-20] or sonic excitation [21-24].

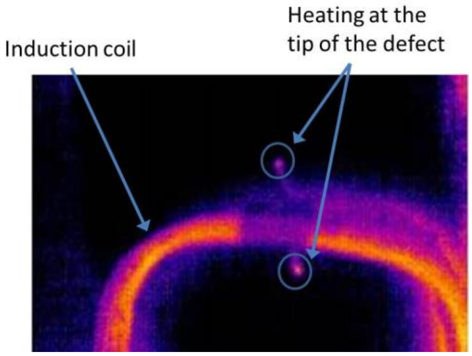


Figure 1 The signature heating characteristic of eddy current thermography

2.2 Heating System

In the case of active thermography, an external heating stimulus is used to induce relevant thermal contrast as shown in Figure 2. As mentioned in Section 1, the external heating stimulus for eddy current thermography comes from the induction coil that operates at relatively high excitation frequency (typically 50-500 kHz). For pulsed thermography [7, 14, 25] this is simply switched on for a short period (between 20ms–2s), in contrast to lock-in techniques [26], where the amplitude of the high frequency is modulated by a low frequency lock-in signal.

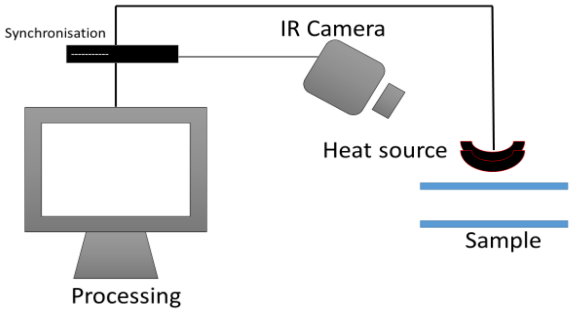


Figure 2 Schematic diagram of active thermography

Existing systems designed for induction welding [27] are commonly used for eddy current thermography applications. Figure 3 shows a typical eddy current thermography system setup [6].

The system consists of an induction heating control box which supplies power to the work head. The work head contains a transformer coupled resonant circuit, including two capacitors and the excitation coil itself. The excitation frequency is dictated by the values of the capacitors, the inductance of the coil and the load of the circuit, i.e. the material, volume and proximity of the sample under inspection. A PC which is linked to the IR camera stores the thermal images captured by the camera for subsequent analysis.

With the commercial induction heater, the excitation frequency is determined according to the impedance of the resonant circuit, thus it is determined by the coil and sample combination. Since much of the published research in eddy current thermography employs commercial heating systems [6-10, 28-29]; the frequencies used have been rather arbitrary. In practice, the inductance of the coil has been found to be roughly proportional to the length of the copper tube used to construct the coil; a shorter coil operates at a higher frequency and a longer coil operates at a lower frequency. If the coil inductance is not within a certain range, the circuit will not resonate and the induction heater will not work. The coils design also depends upon optimum defect detection capability, which is based on the type and geometry of the tested sample. In many cases, new coils need to be designed and fabricated to fulfil the test and inspection needs.

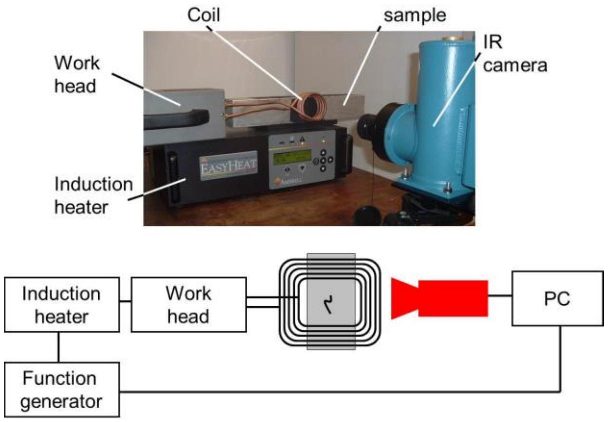
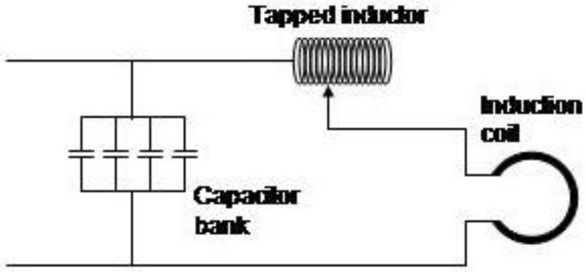
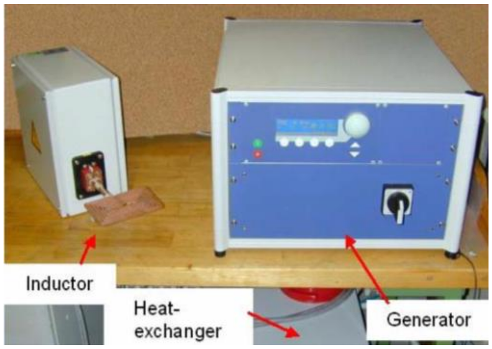


Figure 3 Typical eddy current thermography setup for NDT application [6]

Some control over the excitation frequency can be obtained by introducing several variable components into the oscillator circuit. This approach has been taken in the design of the eddy current thermography system, shown in Figure 4, at the Institute of Polymer Testing and Polymer Science, Department of Non-Destructive Testing (IKP-ZFP) in Germany [30]. The excitation frequency is still determined by the induction coil, the sample and the other components in the circuit, but the changeable capacitors and the tapped inductor allows control of the excitation frequency, within the absolute limits of 30kHz – 300kHz of the induction heater. Tuneable frequency range for a given sample and coil configuration is not explicitly given, but results are shown for 46kHz and 100kHz excitation using the same sample and coil combination [30].



(a) Variable frequency oscillator circuit



(b) Component of the system

Figure 4 Eddy current thermography system used at IKP-ZFP [30]

Work done for eddy current thermography had shown that the frequency of the applied field will have a large impact on the distribution of the induced eddy currents. Most papers which report actual experimental results for induction thermography quoted excitation frequencies between 50kHz and 500kHz [4-8, 10, 14, 15, 28, 31, 32]. Simulation results are reported for frequencies as low as 50Hz [33], but these low frequencies may not be practical for real world applications. It is clear that in order to optimise induction heating for thermography applications, work must be done to ascertain the optimum excitation frequency for different material and defect combinations.

3.0 RESULTS AND DISCUSSION

The characteristics of inductive heating for thermography mean that very different results are expected in different conductive materials. For instance, ferromagnetic materials with relatively high permeability values will limit the penetration of eddy currents to the surface [12]. Consequently, only defects very close to the surface of the material will have a direct interaction with the induced currents, and onlydeeper defects will interact with diffused heat. Non-ferromagnetic materials on the other hand will have relatively higher penetration of eddy currents, thus increase the probability of direct interaction with deeper defects by the induced currents. Different approaches have been taken by research groups working with eddy current thermography when dealing with different combinations of samples and defects. Techniques for data acquisition, analysis and the related excitation with different types of samples has shown the capability of eddy current thermography as a viable NDT technique for industrial inspection.

Eddy current thermography has been used to detect defects in both metals [9] and CFRP structures [34] using phase image analysis. The lock-in thermography approach by Busse *et al*. have been implemented on a CFRP aircraft landing flap with stringer rupture under the 3mm thick outer skin. The approach has given a more clearly defined defect image using induction heating compared to sonic excitation.

Zenzinger *et* al. [8, 15] have performed eddy current thermography inspection of turbine blades made from Ni alloys and Ti using commercial induction heating system. 100kHz-550 kHz, 50-100ms duration excitations is used in the tests with the generated image stack analysed to produce phase images. The work concentrates on surface breaking cracks where the induced eddy currents are perpendicular to the defects under inspection.

The influence of both crack depth and orientation on the change in thermal contrast over defects in ferromagnetic steel sample have been studied by Walle and Netzelmann [28]. They had found that the crack signal (thermal contrast) has a reasonably linear relationship with crack depth up to around 0.8mm. After this limit, it can be observed that the change in crack signal with depth decreases. There are two factors which influence this behaviour; the increase in diffusion of the heat signal with depth, common to all thermographic inspection techniques and the decrease in the direct interaction between the induced eddy currents and the defect as defect depth increases.

Tian *et al*. [6, 14, 16] have conducted the study on the system development and evaluation of eddy current thermography. Based on the developed system, tests were conducted on a mild steel, turbine blades and POD samples for the quantitative evaluation of cracks. From the analysis of the acquired thermal responses i.e. single and transient images, features for defect characterisation have been presented to show the potential of eddy current thermography for defect detection and evaluation in in-service sample.

4.0 CONCLUSION

The review on eddy current thermography technique has been presented in this paper along with its application. Highlights on the underlying principles of the technique and its associated systems has been discussed in achieving optimum inspection results. Based on its capability and the advantages it present, the technique provide an alternative option in NDT application for defect detection in conductive materials.

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