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Infrared thermography based defect detection in ferromagnetic specimens using a low frequency alternating magnetic field

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HIGHLIGHTS

- A new IRT technique is developed for defect detection in ferromagnetic materials.
- Low frequency magnetic field induced heating is used.
- The MFL increases with defect depth, whereas, temperature contrast decreases.
- The temperature contrast decays exponentially with defect depth.
- Temperature decay rate increases with decreasing defect depth.

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ABSTRACT

A new active infrared thermography based technique is proposed for defect detection in ferromagnetic specimens using a low frequency alternating magnetic field induced heating. The test specimens (four mild steel specimens with artificial rectangular slots of 8.0, 5.0, 3.3 and 3.0 mm depths) are magnetized using a low frequency alternating magnetic field and by using an infrared camera, the surface temperature is remotely monitored in real time. An alternating magnetic field induces an eddy current in the specimen which increases the specimen temperature due to the Joule's heating. The experimental results show a thermal contrast in the defective region that decays exponentially with the defect depth. The observed thermal contrast is attributed to the reduction in induction heating due to the leakage of magnetic flux caused by magnetic permeability gradient in the defective region. The proposed technique is suitable for rapid non-contact wide area inspection of ferromagnetic materials and offers several advantages over the conventional active thermography techniques like fast direct heating, no frequency optimization, no dependence on the surface absorption coefficient and penetration depth.

1. Introduction

In today's world, almost all components spanning over heavy industry to day-to-day life contain different types of steel. Steel can be broadly classified into two categories, viz. alloy steel and non-alloy steel. Mild steel is a low carbon (approximately up to 0.3%) non-alloy steel, which is extensively used in various industries like construction, transportation, metal, electrical, oil and gas pipelines and storage tanks [1–3]. Plain carbon steel is also used for roof slab in prototype fast breeder reactor (PFBR) and is a potential candidate for safety vessels of future breeder reactors [4]. Most commonly used industrial components made of mild steel include construction beams, backstays, chimneys, sliding and rod type gates etc. The fabricated components must be routinely inspected to ensure structural integrity and safe operation. Defects in metallic component may render a part of the structure unable to meet design standards and may cause premature failure of the component in-service or while manufacturing. Hence, Non-destructive evaluation (NDE) is essential to avoid sudden catastrophic failures and huge economic losses.

Numerous NDE techniques like X-ray radiography [5,6], ultrasonic [7,8], eddy current testing (ECT) [9,10], infrared thermography [11–14], magnetic flux leakage (MFL) [15,16], nanofluids based sensors [17–19] etc. have been used for inspection of various ferromagnetic steel components. In MFL technique, initially the test specimen is magnetized and using a magnetic flux sensor

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Nomenclature

Symbol	Quantity (Unit)		
q	rate of energy emission (W)	Y_0	depth of the rectangular slot (M)
A	area of emitting surface (m^2)	f	AC frequency (Hz)
T	absolute temperature (K)	ω	angular AC frequency (Hz)
σ	Stefan Boltzmann's constant ($Wm^{-2}\,K^{-4}$)	μ	magnetic permeability of the material (Hm^{-1} or NA^{-2})
ε	emissivity (dimensionless)	μ_0	magnetic permeability of free space (Hm^{-1} or NA^{-2})
H_x	tangential component of the leakage magnetic field (A/m)	μ_r	relative magnetic permeability of the material
H_y	normal component of the leakage magnetic field (A/m)	H_{MFL}	total magnetic leakage field (A/m)
H_g	magnetic field inside the slot (A/m)	H_{int}	internal magnetic field (A/m)
H_a	applied magnetic field (A/m)	$H(0)$	surface (at $z = 0$) magnetic field at time $t = 0$ s (A/m)
H_a^{AC}	AC magnetizing field (A/m)	E	electrical field (Vm^{-1})
H_a^{DC}	DC magnetizing field (A/m)	σ_E	electrical conductivity of the material (Sm^{-1})
l_g	width of the rectangular slot (M)	j	eddy current density inside the material (Am^{-2})
		Q	heat loss (W)
		δ	skin depth of the material (m)

the diverted or leaked magnetic flux, due to the presence of the defects, is detected using a suitable sensor (generally a Hall sensor). MFL technique is heavily used in industries for inspection of oil and gas pipelines, track ropes, sub-surface notches, storage tank floors, cracks, non-metallic inclusions, corrosions, abrasive wear etc. in ferromagnetic components [15,20–25].

Infrared thermography (IRT) is a non-contact temperature measurement methodology, where the infrared radiation (wavelength lies between 0.75 and 1000 μm) emitted from the surface of the object under inspection is recorded using an infrared camera and the temperature of the object is calculated from the intensity of the emitted radiation using Stefan–Boltzmann's law, which is described below.

$$\frac{q}{A} = \varepsilon\sigma T^4 \tag{1}$$

Here, q is the rate of energy emission (W), A is the area of the emitting surface (m^2), T is the absolute temperature (K), σ is the Stefan–Boltzmann's constant ($\sigma = 5.676 \times 10^{-8}\,Wm^{-2}K^{-4}$) and ε is the emissivity of the surface. For a perfect black-body, emissivity is unity and for real surfaces $\varepsilon < 1$. Infrared thermography can be broadly classified into two categories, viz. passive and active thermography [26]. In passive thermography, no external heating is required, whereas, in active thermography an external heat stimulus is used. Depending on the heat stimulus, active thermography can be further subdivide into various categories like pulsed, lock-in, pulsed phase, step heating, vibrothermography, eddy current thermography etc. [27]. Detailed discussions on various IRT based experimental procedures, data analysis techniques and numerous applications can be found elsewhere [26,28].

In conventional active thermography optical excitations are widely used as external heat stimuli. Wallbrink et al. used lock-in thermography for quantitative estimation of defect depths in mild steel specimens [29]. Fourier transform, four-point correlation and digital lock-in correlation algorithm have been used for analyzing subsurface defects in carbon steel specimens [30]. Maldague et al. used pulsed phase thermography for defect (flat bottom holes) detection in mild steel specimens [11]. Laser spot thermography is routinely used for crack detection in mild steel specimens [12,31]. Eddy current thermography (EC-IRT) is a comparatively new and emerging inspection methodology, where conductive specimens are heated inductively [32]. In comparison to the conventional optical stimulation, inductive heating is beneficial as heat is generated directly within the specimen and is not limited by the surface absorption coefficient [33]. In EC-IRT, an excitation coil is used which induces eddy current inside the test specimen. The temperature of the specimen increases due to Joule's heating during the flow of the induced eddy current and the presence of discontinuities affect the flow of this eddy current which in turn changes the surface temperature distribution [34]. EC-IRT has been extensively used for crack detection, estimation of defect depths and inspection of slots, notches and angular defects in steel specimens [33–39]. Recently pulsed phase EC-IRT has been developed for defect detection in steel specimens and it is reported that non-uniform heating can be avoided using this technique which improves the defect detectability [32]. In spite of all its advantages, EC-IRT suffers from serious drawbacks like frequency optimization, geometry and orientation of the test specimen and the defect, height of test specimen with respect to the induction coil etc. [40–42].

In this paper we propose a new IRT based methodology for defect detection in ferromagnetic materials by applying low frequency AC magnetic induction directly to the specimens. This new technique, which is versatile, fast and non-contact in nature, offers several advantages over conventional active thermography techniques like fast direct heating, no dependence on surface absorption coefficient, penetration depth or frequency optimization. Although the influence of external magnetic field on defect contrast during induction thermography in magnetic steel has been studied earlier [43], to the best of our knowledge, there are no experimental studies on defect detection in ferromagnetic materials using low frequency magnetic induction aided thermography. The proposed thermography technique facilitates rapid imaging based inspection of large areas of flat surfaces in a non-contact manner. Rectangular slots of various depths were artificially fabricated in mild steel specimens and the specimens were subjected to a low frequency AC magnetic field. The temperature of the specimens increased due to generation of eddy current and the defects could be easily identified from the thermal images acquired using an infrared camera. The temperature difference between the defect and defect-free regions is found to be higher for shallower defects. Moreover, the peak temperature difference between the defect and defect-free region exponentially decreased with increasing defect depths. For understanding the observed surface temperature profiles we consider the mechanism of magnetic flux leakage and low frequency magnetic field induced heating. The limitations of the proposed low frequency AC magnetization induced heating methodology are also discussed.

2. Materials and experimental methods

2.1. Materials

In the present study four mild steel specimens with artificially made rectangular slots of various depths were used. The dimensional details of the specimens are shown in Table 1. A typical