Measurement 66 (2015) 54–61

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Lateral heat conduction based eddy current thermography for detection of parallel cracks and rail tread oblique cracks

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ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form 6 December 2014
Accepted 28 January 2015
Available online 7 February 2015

Keywords:
Eddy current thermography
Lateral heat conduction
Rail oblique crack
Parallel crack

ABSTRACT

Rail tread oblique crack, initiated by rolling contact fatigue (RCF) damage, is one of the most significant phenomena and has serious influence on rail industry. Electromagnetic non-destructive testing (EM NDT) methods are usually used in rail regular inspection. However, the conventional EM NDT methods based on eddy current field distribution are difficult to detect the cracks parallel to the inductive coil (parallel cracks) and natural oblique cracks. This paper studied lateral heat conduction (LHC) induced by eddy current for detection of these defects. The proposed method was verified through both numerical and experimental studies as well as the investigation of characteristic of LHC. Due to significant temperature gradient in the direction of lateral heat conduction, the spatial derivative and gradient were proposed to improve the defect detectability on the thermograms. Finally, the test of natural oblique cracks on a rail was conducted to validate the proposed methods.

1. Introduction

Rail tracks are subjected to intense stresses, deformation and wear. With the tendency of the railway transportation into heavy haul and high speed, the problem of surface damage due to wheel-rail rolling contact fatigue (RCF) becomes more and more serious [1]. In 2000, the Hatfield derailment accident was an outstanding example of the possible consequences of RCF, which resulted 39 injuries and huge economic fallout in United Kingdom [2]. RCF is a group of rail damages due to overstressing of the rail material, which occurs on the rail surface in form of shelling, squats and gauge corner cracks or within the subsurface in form of deep seated shells. The rail tread oblique crack, which belongs to RCF initiated damage, is one of the most significant phenomena which will cause failure. After initiation, oblique cracks prolong to the centre of the rail tread with a 45° angle along rail side and facing the direction of traffic, as shown in Fig. 1(a). At the same time, the cracks extend to inside of rail with an acute angle (15–40°) along rail tread, as shown in Fig. 1(b). As the deep increasing, the acute angle has a gradually increase. Up to 8–10 mm in depth, they would turn into the transverse crack and lead to a fracture of rail, as shown in Fig. 1(c).

Research on the application of NDT methods for the detection of defects in rails began as early as 1877 [3]. The regular inspection of the rail infrastructure was initiated in the late 1920s in the USA when Dr. Elmer Sperry developed the Sperry Car to detect fissures in the rail. By now, more than ten NDT techniques can be used

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http://dx.doi.org/10.1016/j.measurement.2015.01.024

to detect the rail defects. For example, ultrasonic technique has been proven to be a very successful technique to detect defects. In general, ultrasonic techniques perform relatively well in detecting deep surface-breaking and internal defects, particularly in the rail head and web. Unfortunately, RCF defects that are smaller than 4 mm deep are usually not detectable by high-speed systems. Ultrasonic technique can also miss some defects in the rail foot, especially corrosion, as this part of the rail can only be scanned partially. That is to say, the existing ultrasonic system is inadequate to detect RCF because of these dead zones (such as surface area) [4]. In addition, electromagnetic non-destructive testing (EM NDT) methods are usually used in rail regular inspection. Pulsed eddy current (PEC) probes perform far better than Magnetic flux leakage (MFL) to detect the rail defect but with lift-off variation problem [5]. Alternating Current Field Measurement (ACFM) have a good potential for RCF with maximum operating lift-off, but it is not sensitive for sub-surface defect, and it is also difficult to identify multi-cracks [6]. Electromagnetic acoustic transducers (EMATs) can generate the surface wave to detect RCF in rail at a small standoff distance, which is a non-contact technique with high speed potentiality yet with lift-off limitation [7]. However, with the feature of multiple defects including surface and subsurface oblique cracks [8], the characterisation of RCF, such as size, shape and orientation are important for the rail maintenance and quality control [9].

Infrared thermography is a non-destructive evaluation (NDE) method with an increasing span of applications. In the active scheme, an external thermal stimulation is brought to material under test (MUT) and the thermal response is recorded by an infrared camera to provide information about the internal structure of MUT (such as thermal properties, presence of defects etc.). Eddy current thermography (ECT) is an emerging active thermography NDT methods especially for conductive material, which combines the advantages of eddy current testing and IR thermography, such as non-contact, fast and high resolution [10,11]. Due to electro conductivity, thermal conductivity, and high permeability of rail, ECT is very suitable for its damage detections. In 2011, it was applied to image multiple RCF cracks on rail for the first time [12]. Many researchers have proposed various ECT methods, such as thermal-inductive [13], electromagnetic-thermal [14], tone burst eddy current thermography (TBET) [15], eddy current pulsed thermography (ECPT) [10,16–20], induction thermography [21], eddy current lock-in thermography (ECLT) [22], eddy current pulsed phase thermography [11] (or inductive pulsed phase thermography [23]) and eddy current step heating thermography [24]. Among these works, the methods for defect detection can be classified into two groups. One is based on the longitudinal heat conduction from surface to subsurface. For example, the subsurface defect in steel was quantitatively evaluated based on the heat conduction using induction thermography [25,26]. Eddy current pulsed phase thermography (ECPPT) technique and related features in the frequency domain were proposed for subsurface defect evaluation [11,27]. The other is based on the analysis of eddy current field perturbation by surface or subsurface defects which are in the extent of skin depth. In this case, the defect which is orientated at 90° to the eddy currents can result in a diversion of eddy currents around the defect. This causes an increase in eddy current density at the tips of the defect and colder spots at the centre of the defect [28,29]. However, the defects, which are parallel to the inductive coil, produce a very low thermal contrast. It is caused by the fact that the defect geometry does not affect (prevent) eddy currents which are induced parallel to the coil. In most cases, the thermal contrast is covered by noise due to surface topography and ultimately by the thermal noise [30]. Therefore, the inductive coil has to be arranged perpendicular to the defect, which leads to the complex operations. This phenomenon is the same in EM NDT including eddy current testing [31,32]. In fact, the orientation of realistic RCF cracks is unknown. So the suitable approaches need to be developed to improve the detectability of RCF cracks.

In this work, the lateral heat conduction induced by eddy current is proposed to detect both parallel and RCF oblique cracks. The rest of the paper is organised as follows. Firstly, the defect characterisation methods based on lateral heat conduction are analysed in Section 2. Then, numerical studies including parallel and oblique cracks are introduced in Section 3. Experimental studies for artificial defects and real RCF cracks are carried out in Section 4. Finally, conclusions and future work are outlined in Section 5.

2. Methodology

Fig. 2 shows the principle of lateral heat conduction induced by eddy current to detect both parallel and

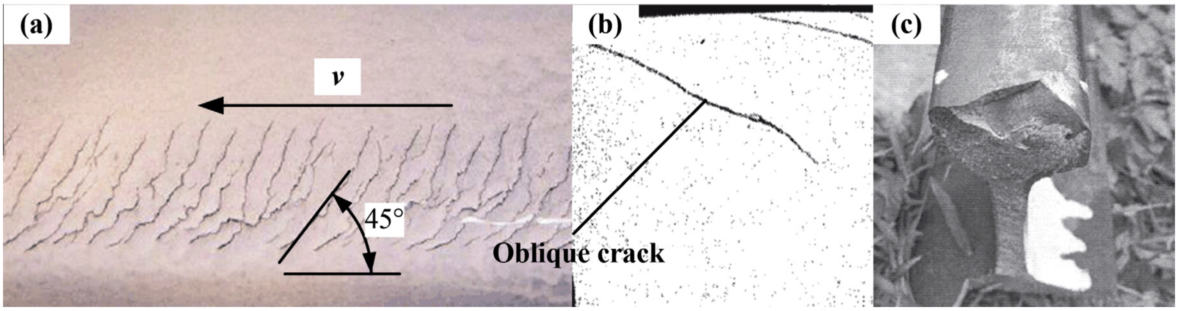

Fig. 1. (a) Top view of multi RCF cracks, (b) section view of a RCF crack, and (c) ruptured RCF crack.