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Reconstruction of the rolling contact fatigue cracks in rails using X-ray computed tomography

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ABSTRACT

Rolling contact fatigue (RCF) defects are associated with complex crack networks at the subsurface. A computed tomographic (CT) scanning technique has been developed to reconstruct the 3D geometry of the RCF cracks in the railhead. Sample rails having squats of different severities were taken from the Dutch railway network. Four specimens of different sizes were prepared and investigated with the CT scanner. The detailed procedures of the CT experiment and post-processing work were described. A sequence of high-quality X-ray images was collected during each scan. These 2D images were combined to construct the 3D visualization of the specimen. Various image processing tools were applied to extract and rebuild the internal crack geometries, thus allowing the crack networks to be differentiated from the bulk steel. For validation, the CT results were compared with metallographic observations of the rail surface for all the defects and the vertical section when needed. Discussions were made regarding the proper size of the rail samples and severity of the squats. According to the results, CT allows for a 3D visualization of RCF defects, providing high-quality data on the geometry of the internal cracks. By choosing the appropriate settings and specimen size, CT could accurately reconstruct the squat cracks at different growth stages. This research shows the potential of the CT technique as an intermediate detection and characterization tool among the methods for detecting macro cracks and those for characterizing micro/nano cracks. Finally, a practical specimen design and a detailed scanning procedure are proposed, based on the CT experiments performed in this research.

1. Introduction

Rolling contact fatigue (RCF) is an important form of damage in wheels and rails that is typically associated with surface and subsurface cracks. RCF cracks often develop with complex patterns in subsurface materials and can potentially cause broken wheels or rails. To study the nature of RCF defects and their behaviours, it is of great value to characterize the crack geometries, networks and patterns. This characterization will become more interesting if it can provide proper understanding of various types of RCF defects, such as head checks and squat defects. Squats in Europe are currently the dominant form of rail RCF that incurs the most maintenance costs and imposes the most threat to operational safety.

The detection, characterization and monitoring of RCF cracks in rails have been important topics in the literature. Serial cutting (or multi-sectioning) can help reconstruct the geometry of subsurface cracks. This method involves the following steps: *(i)* specimen sectioning and subsequent recording with optical microscopy in sequential slices; in this stage, indentations with known dimensions, i.e., known hardness, are marked as a depth reference; and *(ii)* alignment of 2D cracks in separate sections and rebuilding a three-dimensional volume with available software packages. For example, this method has been applied to RCF cracks in Ref. [1] to build up the 3D data on crack shapes and characteristics. However, this method has the following limitations: 1) It is significantly destructive without the possibility of retrieving the original sample. 2) Metallographic examination of rail samples is time-consuming and laborious. 3) Furthermore, parallel slices can be made along only one single axis, typically normal to the primary crack alignments. 4) The

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number of possible cross-sections is limited, which causes data loss on the fracture. The word 'fracture' is used interchangeably with 'crack' in this paper, as it is often used by computed tomography (CT) experts. 5) The thickness of the cutting blades causes loss of material, which leads to discontinuity in crack patterns.

1.1. *Computed tomography vs. ultrasonic and eddy current measurement*

Due to the above-mentioned limitations of serial cutting, the non-destructive inspection tools are more promising for the early detection and characterization of RCF defects. These tools have been widely used for quality control in many industrial fields, e.g., during the manufacturing process of rails or for the damage inspection of rails in service. A comprehensive review of non-destructive systems for evaluating rail defects was published in Ref. [2]. Traditionally, ultrasonic and eddy current testing are the most common inspection techniques for the non-destructive detection of rail defects. Both methods have been widely used to detect the presence of fatigue cracks or internal rail defects [3].

Despite the widespread application of ultrasonic and eddy current testing, these testing techniques have limitations in detecting rail defects, particularly at the early stage. Shadowing effects and the shielding of overlapped cracks in ultrasonic examination hinder the detection of shallow head checks and squat cracks [3]. Ultrasonic inspection has difficulty with detecting cracks with a depth of less than 4 mm by rough estimation. Eddy current can detect small, shallow surface cracks. However, overestimation of small cracks and inaccuracies in crack sizes have been limitations that threaten the reliability of eddy current measurements [4,5]. The typical crack depth that can be detected by eddy current is 0.3–5 mm. Furthermore, when there is group of cracks in a defect cluster, shallower cracks may mask deeper defects. Therefore, the defect depth might be underestimated [6].

The detection of small, shallow cracks near the surface is important because RCF cracks are typically small and shall when first forming. It is also essential to determine the geometry of cracks at different life stages to understand the initiation and development process of RCF defects. The above-mentioned techniques provide some insight into the presence of RCF cracks despite their aforementioned limitations. However, detailed information on the geometries of the RCF cracks cannot be obtained. The crack pattern on the surface can be characterized by microscopic observations or even by the naked eye, depending on the scales. However, shallow subsurface cracks are difficult to evaluate, as available non-destructive methods fail to access their 3D geometries.

CT is a potentially more powerful non-destructive technique for characterizing internal fractures than ultrasonic and eddy current methods. Using X-ray images taken from different angles, the CT technique can reproduce the cracks in three dimensions while avoiding the inaccuracies in the detection of shallow cracks and shielding of overlapped cracks. In this paper, we use the CT technique to measure and reconstruct the RCF crack network in steel. The CT scan settings, measurement process and subsequent data post-processing are discussed in detail. Cross-sectional (tomographic) images are collected from the CT scans for each reconstruction. These X-ray images are processed and compiled to form the 3D volumetric data, including internal fractures, with the available commercial software. Various image processing tools are then used to detect surface and subsurface cracks in the bulk steel. Finally, the 3D geometry of the internal crack networks is reconstructed. In this paper, four rail specimens with different RCF severities were examined to show the potential of the CT technique for detecting and reproducing RCF cracks. Metallographic experiments were conducted to validate the reconstructions.

1.2. *CT vs. SEM, TEM and EBSD*

Fig. 1 shows the crack development and potential methods to detect and characterize the cracks with the categorized dimensions. As shown in this figure, it is challenging, if not impossible, for the non-destructive method to detect and reconstruct RCF cracks at the meso and micro scales. An alternative advanced automatic damage reconstruction is 3D EBSD [7], which can also be performed by SEM and TEM [8]. The disadvantages of SEM, TEM, and EBSD are their 1) destructiveness, 2) limited specimen dimensions, 3) tedious data collecting process, and 4) lack of information on the locations and orientations of the subsurface cracks to prepare the initial sample.

In this research, we could generate high-resolution images of the cracks at the macro, meso and micro scales. Although all the studied RCF defects were visible at the macro scale, the detectability of the X-ray images was adequate to detect crack tips and branches up to the micro level. Thus, CT is shown to be able to bridge the gap between the methods for macro cracks and the methods for micro and nano cracks, as shown in Fig. 1. When this gap is filled, one will be able to trace down the complete crack development process to allow for the study of the complete evolution process of the RCF cracks. When the complete crack geometry is reconstructed with a CT scan, a sample and cracks can be viewed and studied in any arbitrary 3D orientation, e.g., axial, transverse or normal planes. The crack dimensions and orientations can be measured accurately in a virtual workspace, which includes the sample geometry with internal fractures. With this information, a proper understanding of the initiation and growth mechanism of such defects can be obtained. When the locations and orientations of the RCF cracks are known using the CT scan, small samples can be prepared to encompass the internal crack network. Such samples can be further analysed using advanced crystallographic characterization techniques, such as EBSD, SEM or TEM.

1.3. *Relevant history of CT technology*

In addition to medical applications, CT is used in other fields, such as non-destructive material testing and archaeological studies [9]. Industrial CT generates a 3D representation of the objects and internal structures. CT has occasionally been used to inspect internal damage in materials; see, e.g., the applications to aluminium alloys [10], polymer composites [11], soil aggregates [12,13] and concrete [14,15]. CT has also been used to detect RCF cracks in high-strength steel with artificial defects [16,17]. Some fundamental works on the CT technology and its applications can be found in Refs. [18–20].

Nicholson et al. [21] used X-ray tomography to determine the size and morphology of the RCF cracks in cylindrical samples machined from a rail. RCF cracks at different levels, a light and a moderate one, were reconstructed, and their shapes and sizes were measured. Another research, devoted specifically to the RCF of rail materials [22], proposed different methods to describe the squat crack networks geometrically. The methods were a mixture of destructive and non-destructive, i.e., X-ray radiography, metallography, X-ray tomography, and topography. A

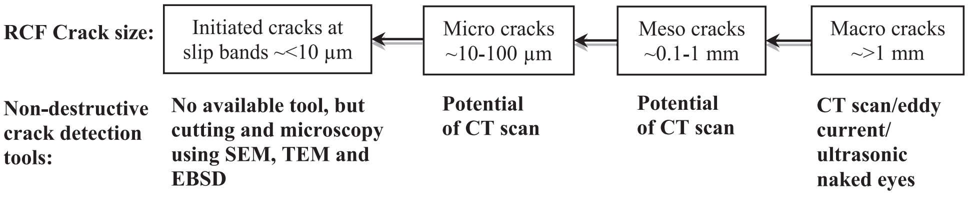

Fig. 1. RCF crack development: sizes of the cracks on the different scales and the appropriate non-destructive detection tests.