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Thermal crack growth-based fatigue life prediction due to braking for a high-speed railway brake disc

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A B S T R A C T

Railway brake discs are the safety–critical components usually designed for up to ten years of operation. To guarantee the safety, fracture mechanics method was applied to perform the thermal fatigue crack growth simulation. Before that, thermo-physical mechanical and fracture parameters for brake discs made of an alloy forged steel were experimentally determined under different temperatures. By using novel extended finite element method (XFEM) and crack tip region meshing refinement based on virtual-node polygonal finite element method (VPM), a semi-elliptical surface crack was then inserted into a predicted macroscopic hot spot to carry out the thermal fatigue cracking analysis under consecutive emergency braking. Computational results were employed to evaluate the fatigue life and safety domain of in-service. Predicted peak temperature and calculated crack geometry were well in agreement with the experimental. Thermal fatigue crack propagation was acquired for evaluating the safety degree of the brake disc due to emergency braking mode. Finally, some remarks were provided for the design and regular maintenance of high-speed railway brake discs.

1. Introduction

The disc brake is one of the most fundamental safety–critical components in high-speed railway trains. The good quality of braking performance enhances the riding quality of passengers especially when the emergency braking happens [1,2]. During the complex braking process, a huge amount of heat energy is generated and rapidly dissipates into the disc volume and environment mainly through conduction, convection and radiation heat transfer. With the increased running speed and reduced mass of next generation high-speed vehicles, transient friction heat and mechanical loadings induce significant temperature variation and resultant thermal deformation under the sliding surface. Such coupled thermo-mechanical behaviors would give rise to so-called macroscopic hot spots and consequent thermal fatigue cracks in several months mainly along the radial direction, which seriously degrades the material and fatigue life of a brake disc [3–5].

The occurrence of hot spots virtually determine the low cycle fatigue crack initiation and propagation. Generally, once thermal fatigue cracks initiate due to cyclic transformation of kinetic energy into braking heat, one or more of critical cracks stably propagates along the radial direction [6–8]. It has been also well recognized that such crack front develops to be semi-elliptic regardless of its initial shape. On the other hand, the crack growth, favored on the surface, is very limited in thickness of the disc and significantly extends in the radial direction [6,9]. Such stable cracking stage usually represents a significant part of the fatigue life of a brake disc by up to 90% of the total lifetime. It is therefore of great importance to precisely reproduce the hot spot during routine and emergency braking [10,11]. A postulated crack is usually inserted into the material region of interest with the highest thermal gradient or temperature. Finally, the remaining life of brake discs can be predicted numerically and a suitable maintenance plan can be designated [12,13].

However, for the strong discontinuous problems such as dynamic cracks or evolved flaws of complex railway brake disc systems with reversed thermal and mechanical loadings, it is computationally expensive and technologically difficult for the standard finite element method (FEM) to provide accurate stress intensity factor (SIF) solutions [14,15]. To tackle above drawbacks, the extended finite element method (XFEM) has been recently proposed by the partition of unity approach and successfully applied to dynamic fracture mechanics and Stefan problems only by enriching the displacement function of standard FEM [16]. Compared with classical FEM, the novel XFEM can efficiently extract the SIFs of evolved crack front without the burden of building a conforming mesh [17].

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Unfortunately, even though the fatigue cracking can be simulated effectively, it is still not easy for individual XFEM to achieve a balance between the accuracy and efficiency especially for large-scale complex structures [18]. A peculiar case here is the brake disc that contains highly nonlinear heat transfer due to braking. To overcome this problem, a good adaptive strategy of elemental mesh around the crack tip is thus developed and has been successfully implemented by employing a virtual-node polygonal element method (VPE) and an octree algorithm [19]. Such approach has been realized into the transient high temperature gradient field due to laser welding [20].

In this study, the advanced XFEM and VPE approaches are used to conduct the thermal fatigue crack growth analysis and life evaluation. Before that, fracture mechanics parameters ($R = 0.1$) of both the threshold stress intensity factor ΔK_{th} and the fatigue crack growth rate curve (da/dN) of the alloy forged steel are firstly investigated under different temperature conditions. Subsequently, transient temperature gradient and thermal stress of brake discs are reproduced by the commercial software ABAQUS® during various braking and cooling phases. Based on non-destructive testing (NDT) results, a macroscopic fatigue crack with a length equal to 2 mm at given positions inside the brake disc is selected as an initial crack size $2c_0$. The thermal fatigue crack propagation simulation is then carried out in the framework of linear elastic fracture mechanics. In order to perform such complex thermal fatigue crack growth analysis, an in-house software termed as PreCrack® has been developed based on the Fortran platform. Finally, a suitable safety domain is suggested from the fatigue life data as a reference to the designer.

2. Experiment and modeling

2.1. The material

The alloy steel for high-speed railway brake discs is manufactured by a forging process, whose basic chemical compositions are very close to the 38CrMoV5 steel [12,21]. After a well-designed austenitization, quenching, tempering and air cooling treatment, the peak yield strength of the steel can be reached to 1000 MPa at room temperature. The density and Poisson's ratio of the alloy forged steel are about 7850 kg/m^3 and 0.28, respectively. Monotonic tensile tests at different temperatures from room temperature to 700 °C were firstly conducted to evaluate the mechanical properties of the material. The detailed thermo-mechanical properties of the brake disc are presented in Table 1.

2.2. Fatigue cracking parameters

It is well-known that thermo-physical properties of the material change sharply around the hot spots, which inevitably causes the stress concentration and thermal cracks after several thousand miles. At elevated temperatures, these cracks then continue to propagate rapidly along the radial direction of the brake disc [22], as illustrated in Fig. 1.

Therefore, it is extremely necessary for the fatigue life prediction and damage tolerance evaluation to precisely obtain thermal fatigue cracking parameters of the high-temperature stages. Standard three-point bending single-edge notched (SEB) samples according to ASTM D5045 were elaborately designed to perform the thermal elastic fracture mechanics tests under varied temperatures, as illustrated in Fig. 1.

Table 2 gives the threshold stress intensity factor and fatigue crack growth rate parameters of C and m according to the Paris law at different temperatures. It should be noted that during the fatigue life simulation, ΔK_{th} (MPa m$^{1/2}$) is the calculation criteria whether a crack grows or not at the corresponding temperature. Besides, the failure criterion can be fracture when the maximum K factor in a loading cycle reaches or exceeds the fracture toughness K_{IC} (MPa m$^{1/2}$) of the brake disc, $K_{max} \geqslant K_{IC}$.

Note that for design purposes a conservative upper bound da/dN–ΔK curve should be employed. Nevertheless, it is still a challenging and expensive task to obtain K_{IC} and ΔK_{th} at high temperatures. In order to ensure the operation safety and reliability of brake discs, a half of K_{IC} (25 °C) was selected as the failure criteria during the calculation. Besides, in the absence of fracture parameters at high temperatures, the material performance can also be roughly extrapolated by the material performance of low temperature.

2.3. Elemental mesh model

Three-dimensional (3D) geometrical models of assembled brake disc and pad were built using the commercial software Pro/E and then imported into the HyperWorks® for a solid elemental mesh. Fig. 2 presents the schematic meshed model, boundary conditions and loadings, where Γ_0, Γ_1, Γ_2 and Γ_3 represent the boundaries of prescribed temperature, heat generation, convection and radiation. In particular, due to geometrical symmetry and the consideration of computational cost, only a quarter meshed brake disc was employed for thermal and fatigue cracking analyses. Then the quarter model has totally 27025 nodes and 22260 elements using the solid 8-node brick element (C3D8).

Theoretical and experimental results have shown that the crack initiation and propagation usually start from the hot spots near the bolt holes in the middle region of brake discs. Furthermore, the initial crack shape is modeled as a semi-elliptical flaw and the crack profile stays semi-elliptical in most cases. Other vital data for the thermal fatigue cracking analysis of the brake disc are listed in Table 3. Note that contact pressure p and the contact area A_1 can be integrated by using the data in the table.

2.4. Fatigue cracking calculation

To carry out the damage tolerance evaluation of railway brake discs, a fatigue crack larger than 1 mm in length is necessarily assumed near the hot spots. In this work, an initial crack length $2c_0 = 2$ mm is adopted due to the limitations of NDT. Then a thermal fatigue crack propagation analysis is based on the long crack da/dN–ΔK curve. Fig. 3 presents a standard calculation scheme of a fatigue crack growth analysis of a brake disc [23].

The primary result of a damage tolerance analysis is the crack depth versus total braking times or loading cycles. As discussed above, based on present knowledge, a crack easily tends to generate after several emergency braking processes. It is therefore presumed that the total in-service or residual life of a braking disc is mainly controlled by Regions II of the da/dN–ΔK diagram where Region III plays a minor role.

3. The formulation

3.1. Heat transfer

The unsteady heat conduction of the braking disc described by the Cartesian coordinate system with domain Ω bounded by Γ satisfies the following equations:

$$\rho c \frac{\partial T(\mathbf{x},t)}{\partial t} = \mathrm{div}[k \cdot \mathrm{grad}\ T(\mathbf{x},t)] + Q \quad \text{for } \mathbf{x} \text{ in } \Omega,\ t > 0 \tag{1}$$

$$T(\mathbf{x},t) = T_0 \quad \text{for } \mathbf{x} \text{ on } \Gamma_0,\ t > 0 \tag{2}$$