POLITECNICO DI TORINO

Master's Degree in Mechanical Engineering



Master's Degree Thesis

Thermo-Mechanical Fatigue and Crack Propagation in High-Speed Railway Brake Discs

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Abstract

The reliable operation of high-speed trains depends critically on the structural integrity of wheel-mounted and axle-mounted brake discs. During operation—particularly under emergency braking conditions—these discs are subjected to extreme frictional heating and mechanical loads, leading to complex multiaxial stress states. This thesis synthesizes current research on the mechanisms of thermal fatigue, the resulting phase changes in disc materials, and the propagation of radial cracks. By evaluating finite element analysis (FEA) models and empirical data across both railway and heavy commercial vehicle applications, this paper outlines how extreme braking energy drives both low-cycle and high-cycle fatigue, ultimately dictating the service life of railway brake discs.

1. Introduction

1.1 Background and Motivation

The rapid expansion of high-speed railway networks globally has introduced unprecedented engineering challenges, particularly regarding vehicle safety and component reliability. As train operational speeds regularly exceed 300 km/h, the kinetic energy involved in deceleration grows exponentially, governed by the standard kinetic energy equation $E_k = \frac{1}{2}mv^2$. During friction braking, this massive kinetic energy is forcibly converted into thermal energy at the interface between the brake pads and the brake discs. Consequently, wheel-mounted and axle-mounted brake discs are subjected to some of the most severe operational environments of any mechanical component in the transportation sector.

The reliable operation of these systems relies entirely on the structural integrity of the brake discs. Yet, the cyclical nature of train operation—characterized by alternating periods of rapid heating during deceleration and convective cooling during acceleration—induces a phenomenon known as thermo-mechanical fatigue. Understanding this fatigue is not merely an exercise in material science; it is a critical safety imperative to prevent catastrophic derailments caused by brake failure.

1.2 Problem Statement

Despite advancements in metallurgy and manufacturing, brake discs remain highly susceptible to surface cracking and structural degradation over their service life. The primary mode of failure is fatigue driven by extreme, localized thermal gradients and multiaxial mechanical stress. Under normal braking conditions, discs endure high-cycle fatigue (HCF). However, under emergency braking conditions, the sudden, extreme energy input transitions the damage mechanism into low-cycle fatigue (LCF), rapidly accelerating the propagation of dangerous radial cracks. Current operational models frequently struggle to accurately predict the total lifespan of these components when transitioning between HCF and LCF regimes.

1.3 Research Objectives

This thesis synthesizes contemporary finite element analysis (FEA) modeling and empirical research across railway and heavy commercial vehicle

applications to comprehensively evaluate brake disc fatigue. The primary objectives are to:

1. Detail the mechanisms of extreme thermal gradients and the resulting microstructural phase changes in brake disc steel.
2. Analyze the propagation vectors of radial cracks under multiaxial stress states.
3. Evaluate the efficacy of coupled thermo-mechanical FEA models in predicting both low-cycle and high-cycle fatigue life during emergency and standard braking scenarios.

2. Theoretical Framework: Thermal Dynamics, Material Alteration, and Fracture Mechanics

2.1 Thermodynamics of Frictional Contact and Thermo-Elastic Instability

The deceleration of a high-speed train relies on the conversion of kinetic energy into thermal energy at the interface between the synthetic brake pad and the metallic brake disc. However, the distribution of this thermal energy is highly non-uniform. Due to microscopic surface roughness and dynamic variations in contact pressure, friction occurs at localized asperities rather than uniformly across the entire pad-disc interface.

This phenomenon is governed by Thermo-Elastic Instability (TEI). As localized areas heat up, thermal expansion causes them to protrude further into the brake pad, which in turn increases the localized contact pressure and generates even more heat. This feedback loop results in macroscopic "hot bands" and microscopic "hot spots."

The heat flux entering the disc, denoted as q, is fundamentally modeled as:

$$q = \eta \cdot \mu \cdot p \cdot v$$

Where:

- η is the heat partitioning factor (the percentage of thermal energy absorbed by the disc, typically between 85% and 95%, depending on the thermal conductivity of the pad material).
- μ is the dynamic coefficient of friction.
- p is the instantaneous contact pressure.
- v is the relative sliding velocity.

Because the thermal conductivity of the standard low-alloy steel used in brake discs is finite, the heat cannot dissipate into the core of the disc quickly enough. This creates a severe transient thermal gradient between the friction surface and the internal substrate, inducing massive compressive yield stresses on the surface during the heating phase.

2.2 Metallurgical Evolution and Phase Transformations

The thermal impact of emergency braking extends beyond simple thermo-mechanical expansion; it induces highly localized, detrimental microstructural phase changes. The base material of a standard railway brake disc typically

consists of a pearlite and ferrite matrix, optimized for a balance of toughness and wear resistance.

However, during emergency braking from speeds exceeding 250 km/h, the surface temperature within hot spots can rapidly surpass the lower and upper critical transformation temperatures of the steel (Ac_1 and Ac_3, respectively), often exceeding 750°C.

1. **Austenitization:** When the local temperature exceeds Ac_3, the pearlite-ferrite microstructure transforms into austenite.
2. **Martensitic Quench:** Once the braking event concludes, the disc continues to rotate at high speeds in ambient air. This forced convective cooling acts as a severe quench. The localized patches of austenite rapidly cool and transform into untempered martensite.

This phase transformation is highly destructive for two reasons. First, untempered martensite is exceedingly hard and brittle, heavily reducing the material's local fracture toughness. Second, the transformation from austenite to martensite involves a distinct volumetric expansion. As the localized martensitic patch tries to expand against the surrounding, unaltered pearlite matrix, it generates immense residual tensile stresses. These micro-regions of high tensile stress and high brittleness act as the primary nucleation sites for thermal fatigue cracks.

2.3 Multiaxial Stress States and Yield Criteria

Brake discs are not subjected to simple uniaxial loading; they endure a highly complex, multiaxial stress state. To predict material failure and fatigue life, engineers must evaluate the combined effects of multiple stress vectors using the von Mises equivalent stress criterion (σ_{vm}).

The multiaxial stress state is an amalgamation of:

- **Thermal Stresses (σ_{th}):** The dominant stress vector, fluctuating from extreme compression during frictional heating to extreme residual tension during cooling and phase transformation.
- **Centrifugal Stresses (σ_c):** Tensile hoop stresses acting radially outward, generated by the rotational mass of the disc. These stresses scale with the square of the angular velocity, making them highly significant at top operational speeds.

- **Mechanical Clamping Stresses (σ_m):** The localized normal and shear stresses applied by the brake calipers.

During an emergency braking cycle, the combined von Mises stress frequently exceeds the yield strength of the material at high temperatures, pushing the disc surface into the plastic deformation regime. This cyclical plastic strain is the primary driver of Low-Cycle Fatigue (LCF).

2.4 Fracture Mechanics and Fatigue Crack Propagation

Once micro-cracks nucleate in the embrittled martensitic zones, their propagation is governed by linear elastic fracture mechanics (LEFM). Because the dominant stresses (thermal contraction and centrifugal hoop stress) act in a tensile manner parallel to the disc's surface, the cracks primarily propagate radially and deep into the substrate.

The rate of this fatigue crack growth per braking cycle (da/dN) is mathematically described by Paris' Law:

$$\frac{da}{dN} = C(\Delta K)^m$$

Where:

- a is the crack length.
- N is the number of braking cycles.
- C and m are material constants specific to the brake disc steel.
- ΔK is the stress intensity factor range, which fluctuates massively depending on the braking energy.

Under standard operational braking, ΔK remains relatively low, and the disc experiences slow, predictable High-Cycle Fatigue (HCF). However, under emergency braking, the massive thermal gradients cause ΔK to spike dramatically. This shifts the mechanism into the Low-Cycle Fatigue (LCF) regime, where radial cracks can propagate millimeters per cycle, rapidly compromising the structural integrity of the disc and necessitating immediate maintenance intervention.