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PREDICTING THE DIRECTION OF CRACK PROPAGATION ALONG THE CIRCUMFERENCE OF A MODEL RAILWAY CARRIAGE UNDER VARIOUS OPERATING CONDITIONS

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Abstract: *This contribution deals with reliability of railway wheels as influenced by the occurrence of impaired limiting material strength. Results are presented of material investigation, experimental and computational modelling of crack propagation. The presented computational prediction of the direction of propagation of primary cracks differing in their length and position under various operation conditions is entirely original.*

Keywords: ***Railway wheel, fatigue failure, experimental and computational modeling, fracture mechanics, prediction of crack propagation direction.***

1. Introduction

Reliability of railway wheels is an essential factor affecting railway traffic reliability. Railway wheels reliability depends on attainment of their limit states, primarily the limit states of wheel material failure, more specifically the occurrence of topologically different cracks. The problem remains topical as the requirements imposed on the strength of materials continue to grow as the train speeds continue to rise. The essentials of limit states initiation, fatigue failure and their modifications have been investigated along several directions using various types of modelling: (1) Examination of the occurrence of limit states and their analysis for railway wheels in operation (the resulting knowledge underlying knowledge modelling). (2) Experimental modelling on special testers that simulate operating conditions, using different wheel materials and different heat treatments. (3) Computational, computer-assisted simulation of crack initiation and prediction of crack propagation, always using continuum mechanics and fracture mechanics. (4) Material investigation as a part of material and technology engineering (investigation of the effect of structure on fracture resistance of the material concerned).

2. Methods

The contribution presents the approaches employed and the results of experimental and computational modelling of impaired strength of railway wheel materials.

2.1. Experimental material investigation and modelling using a tester

The strength of railway wheels is adversely affected by fatigue processes that take place in the material concerned. The affected locations appear in parts of the material subject to recurring plastic deformation. Both conditions apply to railway wheels (the wheel rotates, locations subject to plastic deformation exist) and, accordingly, fatigue-related cracks will definitely occur. It is always just a matter of time when surface cracks appear. The time until crack initiation depends on the properties and behaviour of the material concerned and on the character of the operating conditions.

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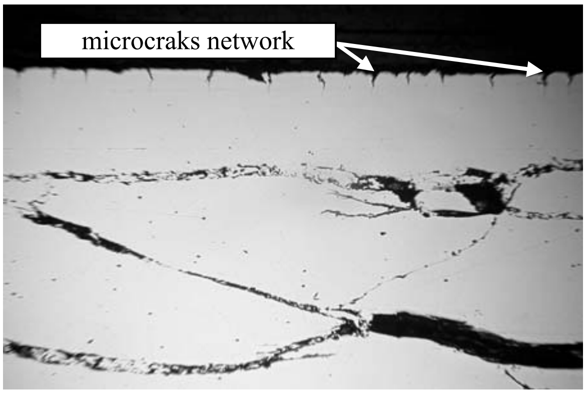

Fig. 1: Network of microcracks perpendicular to the contact surface.

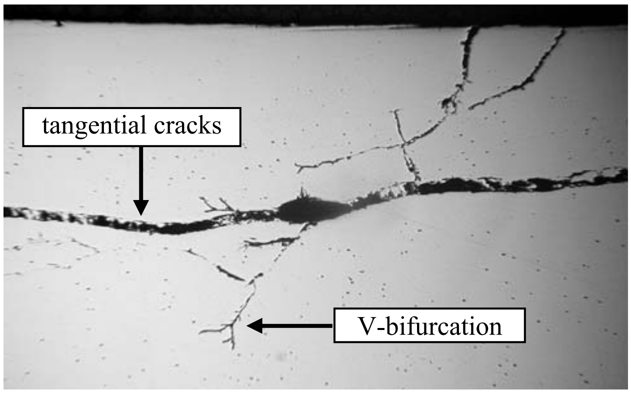

Fig. 2: Network of tangential cracks beneath a hardened surface layer.

Fig. 3: Part of railway wheel perimeter crumbled away.

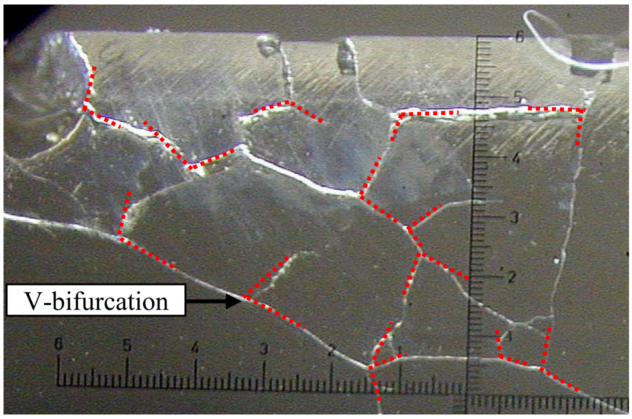

Fig. 4: "V-bifurcation" of cracks beneath a railway wheel contact surface.

The following facts are presented here: Standard materials of railway wheels exhibit a ferritic-pearlitic structure with carbon content up to 0.56 %. Higher values of strength (in particular the fatigue-strength limit) are achieved by suppressing the content of structurally free ferrite and refining the structure (by reducing the interlamellar perlite spacing) through appropriate heat treatment of the surface layers.

With increasing carbon content "sensitivity" of the material to the adverse effect of temperature also increases. Once the limit adhesion is exceeded at the point of contact railway wheel/rail, temperature rises above the phase transition temperature, resulting in formation of high-carbon twinned martensite that constitutes one of several typical initiating effects that lead to crumbling away of the contact surface (Fig. 3). A trend exists towards a phase transition at a given rate of cooling so that conditions underlying anisothermal decomposition of austenite are satisfied. Surface cracks are then initiated as network of microcracks perpendicular to the contact surface (Fig. 1). Outside the hardened layer cracks bend along typical transition zones after partial austenitisation. This structural effect on orientation of the cracks is thus restricted by the range of the phase transitions up to a depth of 2 to 3 mm. The above reason underlying crack initiation results from a certain "non-standard operating operation" - brake action.

Contact-fatigue material damage represents another mechanism underlying crack formation in railway wheels. Inside a layer up to 0.2 mm thick a mechanism of cumulative plasticity depletion has been revealed, resulting in initiation of surface cracks. Within the range of the deformation field subsequent damage is then oriented along the direction of plastic flow of the steel.

The two mechanisms of damage initiation are important inside a certain domain close to the wheel tread. Cracks however propagate also outside that domain and branch in the shape of a very open letter V. The present authors suggest the name V-bifurcation for this type of crack splitting (Fig. 2 and Fig. 4). This phenomenon has not been systematically analysed yet. Most instances of experimental and computational modelling focus on crack initiation, where a surface without any cracks represents the starting model of the wheel tread.

To study the phenomenon of V-bifurcation one has to use a different geometrical model; one must start with a tread containing primary cracks and investigate, using the methods of fracture mechanics, how the cracks - depending on their geometrical parameters (shape, length, angle) - behave when subject to various operating conditions (start, braking, steady drive). Computational (computer-assisted) modelling is the preferred approach.

2.2. Computational modelling - behaviour of cracks under various operating conditions

Problem to be solved: "A primary, straight crack - of length L and at angle α with regard to the perimeter tangent - exists at the wheel perimeter. The direction of its propagation is to be predicted under various operating conditions (start, braking, steady drive) and for various positions of cracks".

Input data for the algorithm: Wheel: R = 460 mm, G = 10^4 kg, material: E = 2.1×10^5 MPa, μ = 0.3. Partial calculation models of the wheel have been developed: model "rotary desk of constant thickness" - Fig. 5; model of relations (contact wheel perimeter - rail); model of load (rotation and load imposed on the axle; model of the material (homogeneous, isotropic); model of deformation (small deformation); model of stress (plain strain). Crack length: between 2 mm and 70 mm; crack angle: 10^o to 90^o. Discretization of the crack surroundings is apparent from Fig. 6. Operating conditions investigated are shown in Fig. 7.

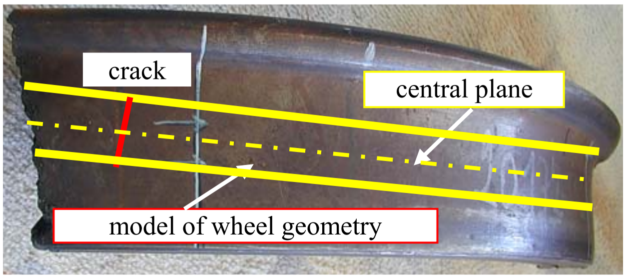

Fig. 5: Railway wheel tread and model geometry.

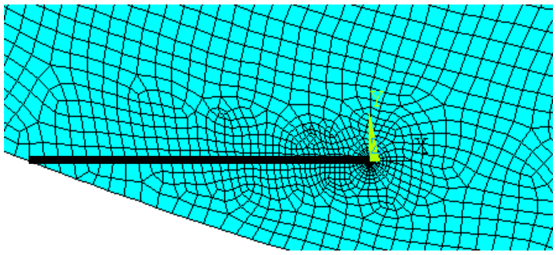

Fig. 6: Discretization od railway wheel crack surroundings.

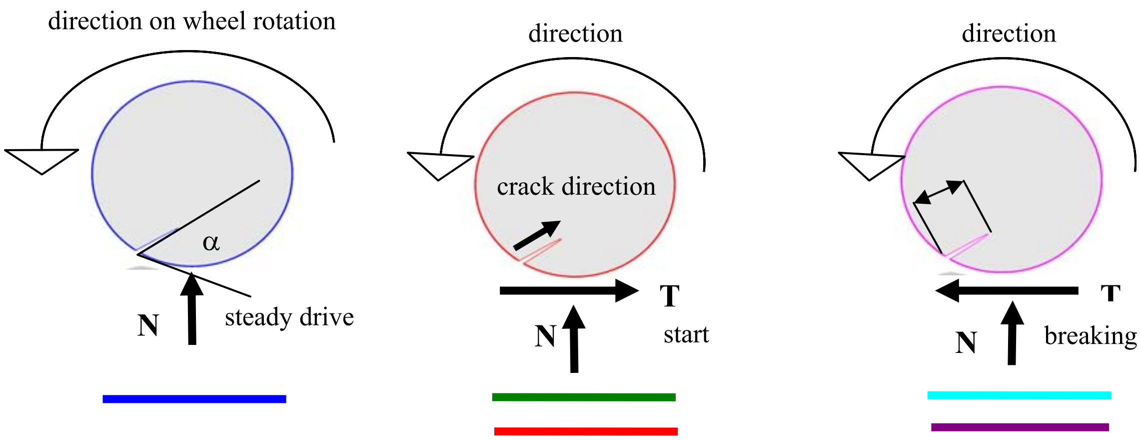

Fig. 7: Operating conditions of wheel – crack propagation.

Output from the algorithm: Stress, first mode K_I, second mode K_{II}, effective stress coefficient K_{ef}, predicted direction of crack propagation from its root - angle Ω - is calculated from the maximum tangential stress using the formula

$$\Omega = \arccos \frac{3K_{II}^2 + K_I \sqrt{K_I^2 + 8K_{II}^2}}{K_I^2 + 9K_{II}^2}. \tag{1}$$

The sign of angle Ω is determined from the ratio K_I/K_{II}; since $K_I > 0$ the sign of angle Ω is given by the sign of K_{II}: if $K_{II} < 0$ Ω < 0 as well, in other words, the predicted direction of crack propagation is towards the wheel perimeter. If $K_{II} > 0$ the predicted direction is towards the wheel centre.

The sign of angle Ω is determined from the ratio K_I/K_{II}; since $K_I > 0$ the sign of angle Ω is given by the sign of K_{II}: if $K_{II} < 0$ $\Omega < 0$ as well, in other words, the predicted direction of crack propagation is towards the wheel perimeter. If $K_{II} > 0$ the predicted direction of crack towards the wheel centre.

The results of computational modelling are plotted in Fig. 8 as dependencies of K_I, K_{II}, K_{ef} *and* Ω on the place of stress (the place of the crack tip with regard to the place of contact wheel/rail) for the various operating conditions investigated. The results of computational modelling lead to the following conclusions: ❶ The first mode stress coefficient K_I *is* significantly smaller than the second mode stress coefficient K_{II}. ❷ The sign of the second mode stress coefficient K_{II} differs for start and braking; accordingly, depending on the sign the crack slews towards the wheel perimeter or towards the wheel centre: during one rotation a V-bifurcation thus originates with an angle of around 135°. ❸ For cracks of small length (1.5 to 3 mm) and small angles of the primary crack (between 10° and 20°) the crack propagates predominantly towards the perimeter. ❹ For longer cracks (starting at around 50 mm) and higher angles of the primary crack the crack propagates predominantly towards the wheel centre, regardless of the operating conditions.

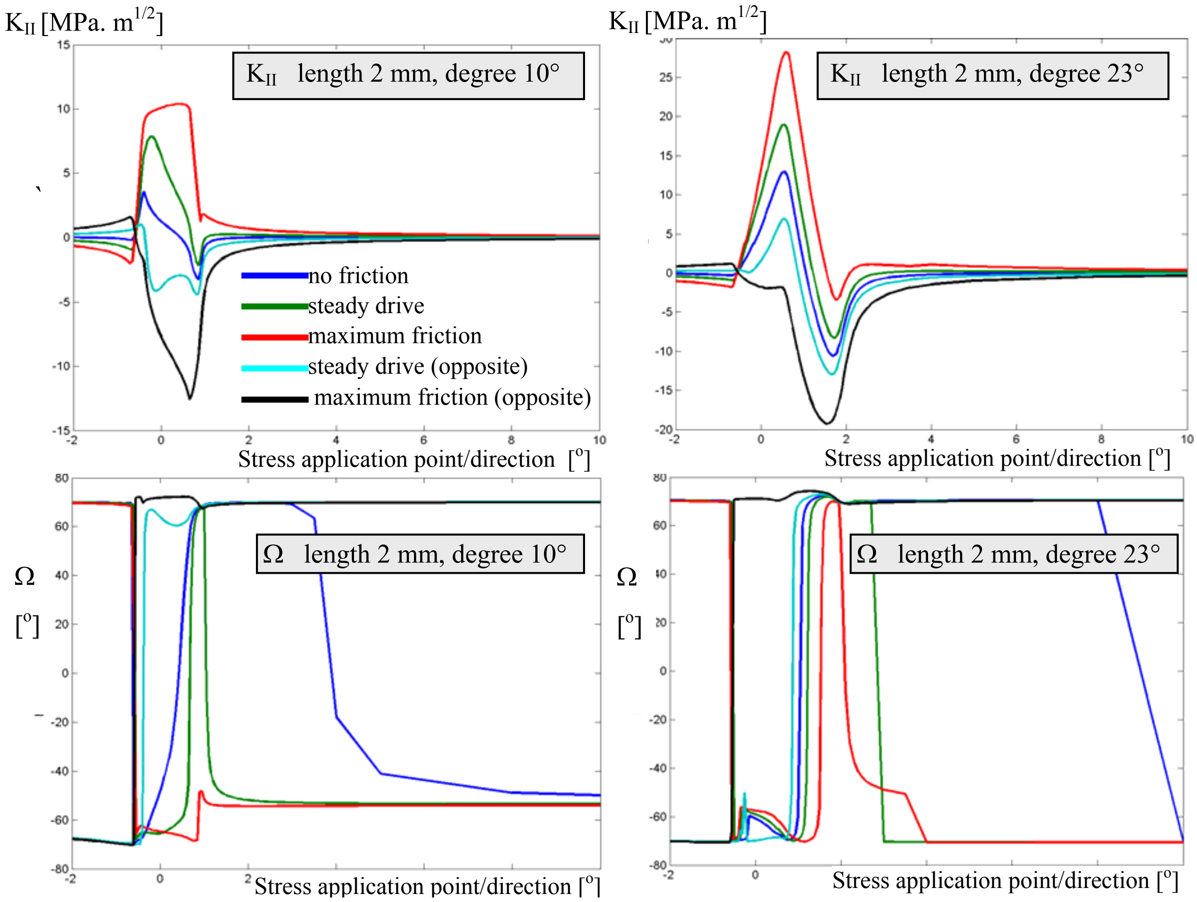

Fig. 8: Results of computational modelling - behaviour of cracks in railway wheel. From top to bottom: stress coefficient K_{II}, predicted angle of crack propagation Ω.

3. Conclusions

The results of computational modelling agree with the facts observed for actual railway wheels - computational modelling thus provides plausible results.

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