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Study of the damage induced by thermomechanical load in ER7 tread braked railway wheels

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Abstract

This work aims to better understand the complex damage phenomena taking place at the wheel/brake block interface due to the thermomechanical load. An experimental procedure, articulated in three series of tests carried out with a bi-disc machine, was designed in order to experimentally simulate in controlled laboratory conditions the thermomechanical history of the real wheel during stop braking. The first series of tests was performed on ER7 wheel steel discs paired with cast iron shoe material discs, setting the sliding speed and the contact load in such a way to generate the heat flux needed to reproduce the typical tread temperature of a real wheel in stop braking. The second series was carried out by repeating the tests in the conditions of the first series and subsequently subjecting the tested wheel specimens to rolling/sliding contact with discs of 350HT rail steel. The third series was carried out by repeating the two phases of the second series and subsequently adding water to the contact interface of the wheel-rail specimens. Measurements of friction coefficient, surface temperature and weight changes were carried out during the tests. At the end, cross-sections of the specimens were observed with an optical microscope. The hardness along the depth was measured. It was observed that during the braking phase parts of the wheel specimen surface are coated by a discontinuous layer of cast iron that is transferred from the brake block specimens. During the braking phase and the subsequent phase of dry contact with the rail specimen, the transferred material is removed, promoting the nucleation of surface cracks; in addition, surface cracks are generated also by ratcheting due to high friction. During the subsequent wet contact phase, these cracks propagate in the wheel disc due to the pressurization of the fluid entrapped inside the cracks. The propagation of surface cracks in wet contact was assessed by a fracture mechanics approach, including the Finite Element simulation of a surface crack with entrapped fluid. The stress intensity factor range during a load pass was calculated and compared with the propagation threshold of the ER7 steel, determining this way the critical depth of surface cracks. This study is a step towards a damage tolerant approach for the designing and maintaining tread-braked wheels.

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1. Introduction

Tread braking is achieved by means of brake blocks applying pressure and friction directly to the wheel tread, thereby dissipating mechanical energy. This practice, usual in freight trains and in metro and suburban trains, has recently come to interest also for high-speed trains, although it is limited to emergency purpose due to the recommendations of the technical standards (such as the EN 15734-1). Therefore, tread braking systems have to be added to electrodynamic brakes and come into operation only when the speed is below 120 km/h, provided that the braking energy input is appropriately limited. On the other hand, block braking systems have also some significant advantages: they contribute to keep the wheel tread clean, by removing dust, leaves, ice or other contaminants which are known to be damaging factors (Faccoli et al. (2018), Mazzù et al. (2018)). Secondly, eliminating the braking discs is also an advantage, as they are rotating dead masses increasing the axle weight and the risk of undesired vibrations at high speed.

The thermomechanical problem associated with tread braking has been studied in depth by several authors. In particular, Peng et al. (2013) introduced a FE thermomechanical model to study the effect of thermal loads on crack propagation. They studied two types of braking: “stop braking”, e.g. the arrest of a train from an initial velocity, and “drag braking”, e.g. a continuous braking to keep the train speed constant along a slope. They found that drag braking is much more severe for the wheel tread, as far higher temperatures are reached: about 680° C in drag braking, compared with about 200 °C in stop braking. Teimourimanesh et al. (2016) applied a temperature-dependent elastic-plastic material model, coupled with a fatigue model, to the case of a metro train, considering both stop braking and drag braking: they found also that in the case of repeated stop braking the fatigue life is controlled by mechanical loads rather than by thermal loads. Caprioli et al. (2013) studied the propagation of cracks due to thermal loading induced by tread braking in heavy haul applications. They found that fully functional brake systems on heavy haul trains are not likely to induce thermal crack propagation in stop braking, unless in the case of severe drag braking due to malfunctioning brakes.

Overall, these studies identify the drag braking on heavy haul trains as the most severe application for tread-braked wheels, as in stop braking, especially in passenger trains, the temperature reached on the wheel tread is not so high to induce phase transition into the material.

However, in high speed applications the damage related to stop braking cannot be neglected. High speed trains are characterized by a lower axle load than freight trains and by rarer stop braking operations with respect to metro trains but, on the other hand, are subjected to a higher number of cycles. Even though microstructure changes or significant thermal cracks are not expected, small surface cracks generated during tread braking can be preferential sites for Rolling Contact Fatigue (RCF) initiation, especially under the action of fluid contaminants, which promote crack propagation by means of the pressurization of the fluid entrapped inside the cracks, as shown, for instance, by Makino et al. (2012).

In a recent study, Faccoli et al. (2019a) studied the effect of shoe braking by cast iron blocks on various wheel steels by means of bi-disc contact tests, with brake and wheel cylindrical specimens put in rolling and sliding contact. The authors found that the damage mechanisms occurring at the surface of the wheel specimens were wear, ratcheting and surface crack nucleation. In addition, they documented a mechanism of material transfer from the brake specimens to the wheel ones, generating a “third body” layer on the surface of the latter. When it is detached, it also involves the steel substrate, probably promoting the nucleation of surface cracks.

In this paper, a typical steel used for tread braked wheels in Europe (ER7 steel grade complying with EN 13262) was studied in working conditions aimed at reproducing the damage due to tread braking and subsequent dry and wet contact with rails. Cylindrical specimens extracted from wheels were first put in dry contact with cast iron brake block
specimens, then in dry contact with rail steel specimens, finally in wet contact again with rail specimens. The damage in the tested wheel steel was evaluated in terms of wear, crack nucleation and propagation.

2. Materials and methods

The tests were carried out on a bi-disc bench whose schematic is shown in Figure 1 (for details see Donzella et al (2011)). The discs were mounted on two shafts driven by independent engines, one of which can be displaced orthogonally to the shaft axis by means of a hydraulic piston, which also applies the contact load.

The wheel discs were made of ER7 steel, which is one of the two steels permitted by the UIC 812.3 Standard for tread braked wheels for freight cars or passenger transportation in Europe. They were machined out of wheel rims, as close as possible to the running surface, with their axis perpendicular to the wheel tread. The wheel steels were tested in coupling with a brake block cast iron and subsequently with the rail steel R350HT EN 13674-1. The rail discs were made of 350 HT steel and were machined out of a rail head, with their axis orthogonal to the long axis of the rail. The chemical composition and mechanical properties of wheel and rail steels are shown in Table 1. The tensile properties were obtained using standard specimens extracted from the components, according to EN 6892-1 Standard. The Brinell hardness was measured on the radial section of the wheel rims in accordance with EN ISO 6506-1 Standard. The Brinell hardness was measured on the radial section of the wheel rims in accordance with EN ISO 6506-1 Standard, in the same position as that of the disc extraction. The brake discs were extracted from cast iron brake blocks having a Brinell hardness of 230 HB and the chemical composition shown in Table 2.

Table 1. Main chemical elements and mechanical properties of the wheel and rail steels.

| Chemical composition (wt%) | Ultimate tensile strength [MPa] | Yield strength [MPa] | Elongation [%] | Hardness HB |
|----------------------------|---------------------------------|---------------------|----------------|------------|
| C  Mn  Si  S  P             |                                 |                     |                |            |
| ER7 0.49 0.75 0.34 0.002 0.008 | 910                            | 584                | 15             | 280        |
| 350 HT 0.63 1.095 0.296 0.018 0.01 | ≥1175                           | -                  | ≥9             | 355        |

Table 2. Chemical composition of the brake block cast iron.

| C  S  P  Mn  Cr  Ni  Mo  Cu  Si  V  Al  Ti |
|-----------------------------------------|
| 3.03 0.18 1.70 0.61 0.10 0.05 0.01 0.15 1.66 0.006 0.04 0.05 |
Thirteen tests were carried out, characterized by the following steps:

- Braking step: wheel disc against brake block disc in dry contact;
- Dry step: wheel disc against rail disc in dry contact;
- Wet step: wheel disc against rail disc in wet contact.

The three steps were applied in the sequence as listed; in some tests the first step only was applied, in other ones the first two steps only. In the wet step, water with 10% glycol was ejected towards the contact interface with a flow of $6 \times 10^{-6} \text{ m}^3/\text{s}$. The working conditions of each step are listed in Table 3; the sequence of the steps and the corresponding number of cycles is listed for each test in Table 4.

### Table 3. Working conditions during the tests

| Specimen | Braking step | Dry and wet step |
|----------|--------------|------------------|
|          | Wheel | Brake | Wheel | Rail |
| Rolling speed (rpm) | 175 | -175 | 373 | 502.5 |
| Diameter | 80 | 60 | 80 | 60 |
| Tangential speed (m/s) | 0.73 | -0.55 | 1.562 | 1.579 |
| Sliding speed $v_\tau$ (m/s) | 1.28 | 0.017 |
| Contact width (mm) | 15 | 15 |
| Contact load $F$ (N) | 2000 | 8636 |
| Contact Hertz pressure (MPa) | 529 | 1100 |

### Table 4. Sequence of steps in the tests.

| Step      | Braking | Dry | Wet |
|-----------|---------|-----|-----|
|           | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 | Test 8 | Test 9 | Test 10 | Test 11 | Test 12 | Test 13 |
| Braking   | 7300   | 8000 | 8000 | 2000 | 4000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 |
| Dry       | -      | -    | -    | -    | -    | 10000 | 10000 | 10000 | 10000 | 10000 | 10000 | 10000 | 10000 |
| Wet       | -      | -    | -    | -    | -    | -    | -    | -    | 24000 | 20000 | 15000 | 10000 | 5000 |

The coefficient of friction was measured during the tests by elaboration of the torque signal coming from a sensor mounted between the displaceable specimen shaft and the transmission, according to the procedure detailed by Mazzù et al. (2015a). The temperature on the contact surface of the specimens during the braking step was checked by means of a thermographic camera following the procedure detailed by Faccoli et al. (2019a). The weight variation of the specimens was measured by means of a precision balance with a resolution of $0.001 \text{ g}$ after cleaning in a bath of ethanol with ultrasonic vibrations; the weight measurements were taken before the tests and at the end of each step.

At the end of the tests, the wheel discs were cut along the mid plane orthogonally to the contact surface. The disc sections were ground, mechanically polished to a $1 \mu\text{m}$ finish, etched with 2% Nital and examined with a Leica DMI 5000 M light optical microscope. The deformation under the contact surface and the crack morphology were investigated and the damage mechanisms were identified.

The Vickers hardness was measured on the wheel disc sections at varying distances from the contact surface to evaluate the steel work-hardening phenomenon and correlate it with the deformation beneath the contact surface. The tests were carried out using a $1000 \text{ g}$ load and a dwell time of $15 \text{ s}$, in compliance with ASTM E384.
3. Experimental results

3.1. Non-destructive measurements

Figure 2 shows the weight loss as a function of the number of cycles for all the rolling contact tests.

Figure 2. Weight loss: a) wheel specimens in tests with braking step; b) brake specimens in tests with braking step; c) wheel specimens in tests with braking and dry step; d) rail specimens in tests with braking and dry step; e) wheel specimens in tests with braking, dry and wet step; f) rail specimens in tests with braking, dry and wet step.

Figure 2a and Figure 2b show the weight loss measured in the wheel and in the brake specimens at the end of the tests with the braking step only. Both discs lost weight during the tests and the weight loss increases with the number of cycles due to progressive wear. As expected, the brake discs had a much higher weight loss compared with the paired wheel discs due to their lower hardness, as reported by Bhushan (2001). Figure 2c and Figure 2d show the weight loss measured in the wheel and in the rail specimens at the end of the tests with the braking and the dry step. The weight of all of the ER7 discs decreased after each step as a consequence of wear. Figure 2e and Figure 2f show the weight loss measured in the wheel and in the rail specimens at the end of the tests with the braking, the dry and the wet step. The weight loss of both the wheel and the rail discs show a similar trend, in particular it increases quickly above 27000 total cycles (the last 15000 cycles in wet contact), due to the occurrence of severe shelling.

Figure 3 shows the variation of the coefficient of friction during Test 9. This diagram is representative of what happened in each step of all of the tests. In the braking step, the coefficient of friction started from a value around 0.54 but it rapidly decreased, down to about 0.25 at the end of the braking step. Even in the other tests, during the braking phase the coefficient of friction stabilized between 0.25 and 0.3 after about 500-600 cycles, whatever the total duration of the braking step. In the dry step, the coefficient of friction rapidly rose up to 0.5-0.55, e.g. the same value it had at the beginning of the braking step. Finally, when water was added to the contact, it fell down to 0.2-0.25, due to the lubrication effect of the water.

The temperature of the wheel disc surface was monitored during the braking step by analyzing the thermographic images near the contact region. The wheel disc surface reached and then maintained a temperature of about 230 °C after around 1750 cycles in all of the braking tests, corresponding to the temperature of the wheel rim during stop braking previously estimated by Faccoli et al. (2019a).

3.2. Destructive analyses

Figure 4 shows some representative cross-sections of the wheel discs after some of the tests with the braking step only; in particular, the subsurface state after 2000, 4000 and 8000 cycles is visible. The wheel steel is clearly strained near the contact surface; this evidence is compatible with the coefficient of friction measured during the braking step. In some regions, layers of cast iron detached from the brake specimens and stuck to the wheel ones are visible. These layers, probably, are continuously attached and removed during the braking step, as witnessed by some cracks inside the cast iron layer. Also some surface cracks involving the steel layer are visible, likely due to the plastic strain accumulation (ratcheting). There are no relevant differences in the general appearance between the three micrographs, meaning that these phenomena are substantially stabilized after 2000 cycles or less.

Figure 5 shows two representative cross-sections of the wheel steel discs after the tests with the braking and the dry step. The plasticized depth is much thicker than after the braking step, in agreement with the higher coefficient of friction.
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friction and with the longer duration of the dry step. Even the surface cracks that were found are longer, and in some cases they are filled by wear debris, likely detached from the brake, the wheel and the rail specimens during the previous steps. The brake material was almost completely removed during the wheel-rail sliding contact in the dry step, as only few traces were found at the end of the tests.

![Figure 4](image-url) Micrographs of ER7 disc sections of the tests lasting for 2000, 4000 and 8000 cycles.

![Figure 5](image-url) Micrographs of ER7 disc sections at the end of the tests with braking and dry steps.

Figure 6 shows some representative cross-sections of the wheel specimens after the tests with the braking, the dry and the wet step; the micrographs refer to tests of different duration of the wet step. After 5000 cycles in wet contact...
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Figure 4. Micrographs of ER7 disc sections of the tests lasting for 2000, 4000 and 8000 cycles.

Figure 5. Micrographs of ER7 disc sections at the end of the tests with braking and dry steps.

Figure 6 shows some representative cross-sections of the wheel specimens after the tests with the braking, the dry and the wet step; the micrographs refer to tests of different duration of the wet step. After 5000 cycles in wet contact (17000 total cycles) many inclined surface cracks are visible; some of these propagated into the bulk. After 10000 cycles in wet contact (22000 total cycles) some isolated cracks had a further propagation into the bulk followed by kinking towards the surface, sign of incipient shelling. After 15000 cycles in wet contact (27000 total cycles), the propagation into the bulk and the subsequent kinking had proceeded further leading to crack path interconnection. The further crack propagation lead to severe shelling in the longest test with wet contact. This kind of crack propagation was observed in real tread braked wheels, as shown on the bottom-right of Figure 6, and it is typical of fluid-driven rolling contact fatigue, as shown, for instance, by Faccoli et al. (2017), Mazzù et al. (2015a) and Makino et al. (2012).

Figure 7a shows the Vickers hardness profiles on the cross-section of the ER7 discs at the end of the tests with the braking step only, for different test durations. The maximum hardness is close to the contact surface where the plastic deformation is more severe, and then the hardness gradually decreases at increasing distance from the surface, because of the smaller deformation, down to the undeformed steel value. The maximum hardness was slightly higher in the discs cycled for 4000 and 8000 cycles than that for 2000 cycles because of the higher accumulation of plastic strain. The depth of the hardened layer is almost the same in all the discs (~ 0.65 mm). Figure 7b shows a similar result on the cross-section of the wheel specimen after a test with the braking and the dry step. Again, an increase of hardness...
can be observed under the contact surface, but the maximum hardness is higher than at the end of the braking tests: this is consistent with the pattern of deformation shown in Figure 4 and Figure 5. The depth of the hardened layer is almost the same as in the discs after the braking tests (~ 0.65 mm).

4. Damage assessment

All these experimental evidences allow describing the damage mechanisms occurring at the wheel specimens. During the braking step of the tests, the temperature rise due to braking friction is not high enough to produce relevant microstructural changes in the wheel steel; however, it probably promotes the adhesion of the brake material on the wheel disc. Indeed, as a result of the ploughing action of the wheel steel disc asperities and the heating of the contact surfaces, fragments of cast iron are first removed and then stuck to the wheel specimen, forming a discontinuous “third body” layer. This layer is visible by the naked eye on the wheel disc contact surface at the end of the braking step due to the darker color of the cast iron compared with the steel, and is likely responsible of the reduction of the coefficient of friction between the brake and wheel specimens. Ratcheting and strain hardening occur in a surface layer of the wheel specimen, leading to the formation of small and shallow cracks. Simultaneously, the “third body” layer is continuously deposited and removed on the wheel disc; its detachment, probably, in some cases involves also the steel surface and contributes to the initiation of surface cracks. In addition, the wear debris of both materials leads to the abrasive wear of the disc surfaces.

The deposition of the third body layer of brake block material on the wheel is also documented in the works of Vernersson et al. (1998) and Vernersson (1999). In these papers, full-scale block braking experiments were performed, testing various brake block materials against wheels in ER7 steel, both in stop braking and drag braking condition. Material transfer from cast iron blocks to the wheel tread was observed in stop braking experiments, but it was not examined in depth; however, it was reported that the transferred material was not well bonded to the wheel surface and it was easily detached from the surface during cycling. It is reasonable to infer that similar phenomena also occur in a real wheel during stop braking, even though they cannot be easily observed because the brake material transfer and removal occur subsequently at each wheel revolution.

During the subsequent dry contact between the wheel and the rail specimen, the third body layer is almost completely removed in about a thousand of cycles, as witnessed by the rapid rise of the coefficient of friction. Due to the increased coefficient of friction, ratcheting becomes more severe, involving a thicker layer and causing a further strain hardening. The surface cracks propagated further. Only traces of the third body layer are left on the contact surface and, probably, inside the surface cracks in form of wear debris.

When water is added at the wheel-rail contact surface, the previously originated cracks begin to propagate towards the bulk, due to the pressurization of the fluid entrapped inside them at each load passage. These cracks initially propagate obliquely from the surface to a certain depth following the plastic deformed material, then some of them deviate towards the surface, causing coalescence with other cracks and shelling.
Therefore, wear is the main damage mechanism of the wheel discs until crack kinking occurs; in this phase the weight loss is gradual, as it is due to a continuous removal of small particles. Subsequently, RCF prevails leading to shelling and consequently to a sudden increase of the weight loss. Competitive damage mechanisms were often observed in the wheel steel discs, as also shown by Mazzù et al. (2015b).

Given these evidences, surface crack growth under wet contact is clearly the key mechanism leading to severe shelling. Understanding and evaluating the threshold over which surface cracks begin to propagate is therefore a key issue for preventing fatal damage. The problem was approached by Fracture Mechanics: in particular, Finite Element (FE) models were used for calculating the applied Stress Intensity Factor (SIF) at the tip of a surface crack, to be compared with the material propagation threshold.

Figure 8 shows the FE model: it is built with two-dimensional plane strain elastic elements and represents the central region of the rolling path. The model includes a flat fixed block, representing the wheel specimen, and a moving body with a circular contact surface, representing the rail specimen. The radius of the moving body was set to 15 mm, equal to the equivalent radius of the couple of tested discs. The fixed contacting body contains a crack inclined of 20° to the contact surface, according to Figure 6, with a 1.5 \( \mu \)m opening on the surface. According to the procedure detailed by Ghafoori-Ahangar and Verreman (2019), the crack tip is modeled through the “quarter point” technique. The applied SIF in mode I \( (K_I) \) and mode II \( (K_{II}) \) are obtained from the displacements of the quarter nodes on the crack face of the collapsed elements, according to the Williams equations:

![Figure 8. FE model of the two contacting bodies, the lower one with a surface crack.](image)

![Figure 9. Deformed mesh around the crack tip at an instant of the load passage simulation, amplified 10 times.](image)
\[
\begin{align*}
K_I &= (v_1 - v_2) \frac{E \sqrt{\pi r}}{8(1-n^2)} \\
K_{II} &= (u_1 - u_2) \frac{E \sqrt{\pi r}}{8(1-n^2)}
\end{align*}
\]

where \( E \) is the elastic modulus, \( n \) the coefficient of Poisson, \( v_1 \) and \( v_2 \) the Crack Opening Displacements (COD) and \( u_1 \) and \( u_2 \) the Crack Shearing Displacements (CSD) of the two quarter nodes on the crack face, \( r \) the distance of the same nodes from the crack tip. The condition of wet contact was simulated by a fluid cavity interaction, which forces the internal crack volume to be constant, as it was filled by incompressible fluid. The contact load was set in order to generate a Hertz pressure \( p = 1100 \) MPa and contact half-width \( b = 0.29 \) mm, the same as in the experimental tests. Frictionless contact interaction was imposed between the crack faces, in order to take into account the lubrication effect of the entrapped fluid. Four models were built for crack depth \( z \) varying from 40 \( \mu \)m to 70 \( \mu \)m.

Figure 9 shows the deformed model around the crack tip at an instant of the load passage over the crack mouth, amplified 10 times. The effect of the entrapped fluid, which is pressurized and causes positive COD, is evident.

In order to compare the applied SIF with the material propagation threshold, the equivalent mixed mode SIF \( K_{eff} \) was determined according to the maximum tangential stress criterion of Erdogan and Sih (1963):

\[
K_{eff} = \frac{1}{2} \cos \frac{\theta}{2} [K_I (1 + \cos \theta) - 3K_{II} \sin \theta]
\]

where \( K_I \) and \( K_{II} \) are the instantaneous mode I and mode II SIF respectively, and \( \theta \) is the propagation direction. The equivalent SIF range \( \Delta K_{eff} \) during a load passage was calculated by the following equation:

\[
\Delta K_{eff} = \max_{\theta} \left( K_{eff \max}(\theta) - K_{eff \min}(\theta) \right)
\]

where \( K_{eff \max}(\theta) \) and \( K_{eff \min}(\theta) \) are the maximum and minimum equivalent SIF respectively for a given \( \theta \) during a load passage; therefore, \( \Delta K_{eff} \) is calculated for the angle \( \theta \) that maximizes the equivalent SIF range.

![Graphs showing mode I, mode II and equivalent SIF](image)

Figure 10. a) Mode I, mode II and equivalent SIF (calculated for \( \theta = 57^\circ \)) during a load passage for a crack with \( z = 50 \) \( \mu \)m, with \( e \) being the distance of the contact point from the crack mouth; b) Equivalent SIF range during a load passage for varying crack depth, compared with the propagation threshold of the ER7 steel.
Figure 10a shows the calculated SIFs during a load passage for a crack with tip depth $z = 50 \, \mu m$, where the equivalent SIF $K_{eff}$ was calculated for $\theta = 57^\circ$; $e$ is the distance of the contact point to the crack mouth. $K_i$ is approximately zero for almost all the load passage, except for the phase when the crack mouth is closed and the entrapped fluid is pressurized. $K_{ii}$ is reversed during the load passage and has a larger range. The peak of $K_i$ is almost simultaneous with the negative peak of $K_{ii}$. Figure 10b shows the variation of the equivalent SIF range $\Delta K_{eff}$ against the crack tip depth $z$, compared with the experimental propagation threshold $\Delta K_{th}$ of the ER7 steel, which was determined by Faccoli et al. (2019b). The intersection of the curves allows determining the critical crack depth, e.g. the crack depth over which propagation has to be expected in condition of wet contact: it results about 52 $\mu m$.

5. Conclusions

The effect of tread braking on the damage of railway wheels in ER7 steel was simulated by means of bi-disc tests on specimens subjected to dry contact with cast iron brake block specimens, dry contact with rail steel specimens and wet contact with rail steel specimens. The material state evolution was evaluated by means of non-destructive analyses (weight loss, surface temperature, coefficient of friction) and destructive analyses (subsurface hardness profile and microstructural analysis). Wear, ratcheting, surface cracking and material transfer from the cast iron specimens were the main phenomena observed on the wheel steel specimens during the wheel-brake contact phase. Again wear and increased ratcheting and surface cracking were observed in subsequent dry contact with the rail specimen; the cast iron stuck in the previous phase was almost completely removed. Again wear and shelling due to fluid-driven surface crack propagation, were observed in the final wet contact with the rail specimen.

The most severe damage mechanism, e.g. crack propagation in wet contact due to the pressurization of the fluid entrapped inside the cracks, was assessed by means of a finite element model of a body with a surface crack filled by incompressible fluid, subjected to the load of a passing contacting body. The range of the equivalent stress intensity factor was obtained and compared with the experimental propagation threshold, determining the critical crack depth over which shelling has to be expected.

This methodology of damage assessment could be extended to full-scale wheels for determining the maximum allowable crack depth for preventing severe shelling and consequently scheduling the wheel maintenance, according to the damage tolerant design concept.

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