

The work described in this document was performed by Transportation Technology Center, Inc.,
a wholly owned subsidiary of the Association of American Railroads.

Review of the Mechanism for the Formation of Thermal Mechanical Shells

Harry M. Tournay

Summary

A hypothesis developed under the Association of American Railroads' (AAR) Strategic Research Initiatives (SRI) Program for the root causes of formation of shells resulting in high impact wheels (HIW)¹ is supported by further evidence from an extended literature review. Although not specifically noted in the literature, the review suggests that the hypothesis may be used to explain crack propagation and resulting shelling mechanisms observed in rails.

The review confirms that wheel tread cracks result from surface tractions initiating material flow and a particular form of rolling contact fatigue termed ratcheting. It suggests that crack initiation should be avoided in order to prevent the development of HIW as there is no obvious practical strategy to suppress crack propagation and consequential shelling.

Also, the review indicates that instrumented wheelsets (IWS) may be used to measure the propensity for the formation of HIW. But an IWS does not provide information on the role of wear and friction on wheel tread crack formation. Consequently, it is proposed that a damage function similar to that developed for rails⁴ be further investigated; this is presented in a forthcoming *Technology Digest*.

Transportation Technology Center, Inc. was tasked to develop a conceptual freight car truck design to address current problems with the performance of current truck designs identified through the AAR SRI Program.

A major problem identified is that of HIWs. HIWs are a major cost factor in car operations, as well as a contributor to increased track costs and derailments. Car repair billing data shows that more than 400,000 wheels were removed in 2008 for HIWs in the North American industry, resulting in an estimated cost of more than \$500 million in 2008.



INTRODUCTION

Transportation Technology Center, Inc. (TTCI) was tasked to develop a conceptual freight car truck design to address problems with the performance of current truck designs identified through the AAR SRI Program.

A major problem identified and reported in this program¹ is that of HIWs resulting from thermal mechanical shelling. The formation of two crack bands observed on the treads of shelled wheels was associated with high tractions measured using an IWS. A hypothesis was presented¹ for the breakout of the material between these two crack bands to form shells and high impact wheels.

Available literature was reviewed and is presented in this *Technology Digest* (TD) to:

- Better understand the role of wear and friction coefficient in the formation of cracks on the wheel tread
- Suggest whether an IWS can be effectively used to predict the formation of surface cracks and HIW; the wheel encounters more varied friction and wear conditions than those modeled to date using a damage function for rail

A subsequent TD will describe the development of a damage function.

REVIEW

Much of the literature on surface crack formation resulting from rolling contact fatigue (RCF) is associated with the development of the so-called Whole Life Rail Model to predict the formation of head checks on rails on Network Rail.^{2,3,4} A useful overview of the phenomenon in both wheels and rails is also presented by Ekberg et al.⁵

Observations

The formation of surface cracks is associated with high tractions^{2,3,4,5} and the deformation of the surface of either wheel or rail, as Figure 1 shows.

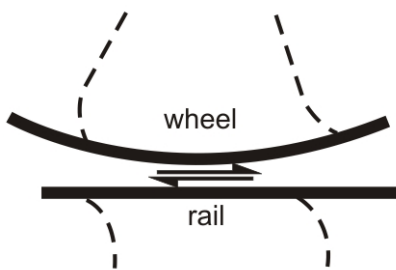


Figure 1. Schematic of Material Deformation Resulting from Surface Traction

Repeated applications of high tractions deform the surface material plastically in the direction of the dominant traction. If material hardening and residual stresses are not sufficient to prevent further accumulation of plastic strain, cracks will eventually form when the fracture strain of the material is exceeded, as Figure 2 shows.

Cracks initially grow into the wheel/rail at a shallow angle, corresponding to the texture of the plastically deformed surface material.⁵

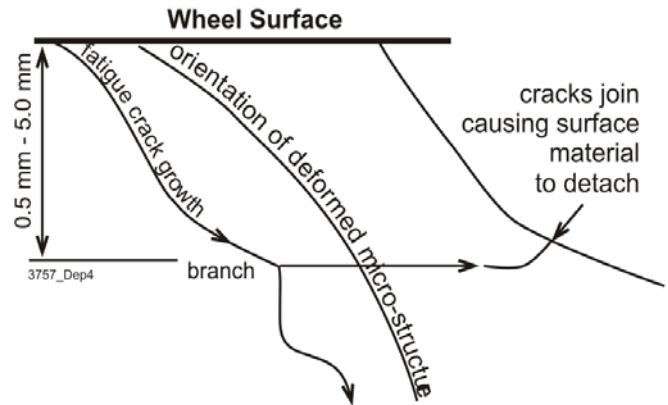


Figure 2. Schematic of Crack Initiation and Growth

In railway wheels, these cracks have been observed to branch and propagate in a circumferential direction at depths of between 0.0020 inch (0.5 mm) and 0.2 inch (5 mm). The extension of these cracks may lead to the breakout of material from the surface of the wheel or rail; this breakout appears to be more prevalent in wheels.

These observations lead to the conclusion that there are two mechanisms involved in the development of shelled treads:

- Crack initiation
- Crack propagation

Crack Initiation

There is general consensus on the mechanism for crack initiation described above. Two predictive models have been used:

- The shakedown theory attributed to K.L. Johnson⁶
- The theory relating the energy due to traction and creepage to crack formation and wear (the so-called T-gamma model) first proposed by Burstow⁴

The shakedown theory, based on that of Hertz, uses the applied normal loads, contact patch geometry, and material yield strength in shear, as well as the tractions across the contact patch to “map” anticipated regions of elastic, plastic, and ratcheting behavior (Figure 3). Although useful in suggesting the cause for, or likelihood of, crack formation, it provides no measure of the severity of surface cracking or to the role that wear might play in removing cracks as they form. Ekberg extended the theory to quantify the severity of shakedown (the so-called Ekberg function).⁵

The T-gamma approach uses the product of the net surface traction and the creepage between wheel and rail to define an energy function, or wear number $T\gamma$.⁴ This function is plotted against the so-called “damage index” (Figure 4), which is a nondimensional number equal to the proportion of the fatigue life of the material exhausted by that contact condition. For each load cycle at a point on the plot, the fatigue damage can be summed with failure said to occur when the sum exceeds unity; the reciprocal of the damage index gives the number of cycles to failure. This process is analogous to that described by an S-N fatigue curve.

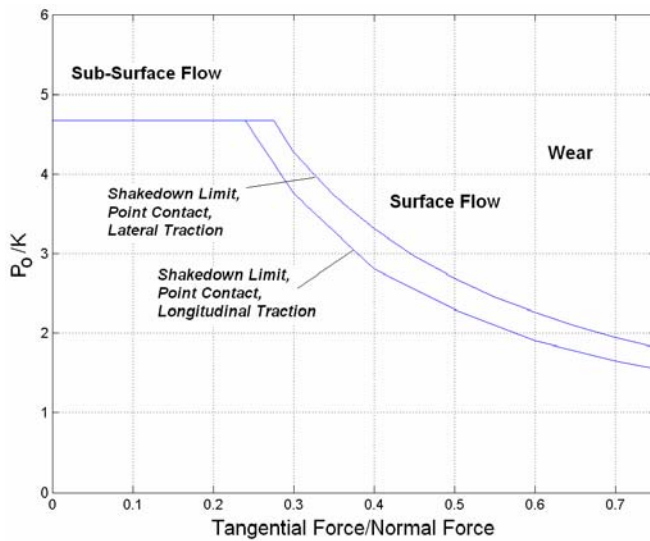


Figure 3. Shakedown Diagram

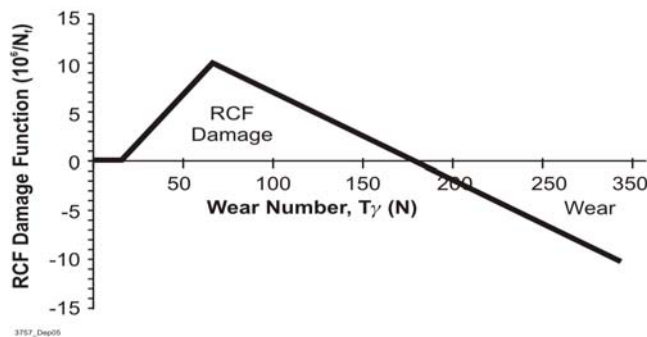


Figure 4. RCF Fatigue Damage Function

The damage function has three regions:

- Crack initiation
- A region where damage increases linearly with T_y to a peak value after which it reduces as wear increases
- A region where wear dominates and removes material faster than it is fatigued

The advantages of the damage function are:

- It can be used to predict the number of contact cycles to failure.
- It accounts for the role of wear in suppressing crack initiation.

Disadvantages of the damage function are:

- Generally, it needs to be “tuned” through experiment and/or observation as it is material specific.
- It does not describe the role of friction or friction modifiers in either promoting or suppressing crack initiation.
- It has been used to predict crack initiation in rail, where friction is relatively consistent as is vehicle condition; this is unlikely for freight wheels running on variable track in trucks with, generally, larger variations in tracking performance.

Crack Propagation

Crack propagation was a focus during the initial development of the Whole Life Rail Model.² Interest dwindled after it was established that the critical phase was crack initiation and that rail maintenance to avoid failure involved crack control at an early stage of development before branching occurred. Nevertheless, crack propagation was attributed, among others, to:

- “A complex stress field”⁴
- Direction of traction forces attributed to a driving wheel⁴
- Fluid entrapment resulting in:
 - Reduced crack face friction increasing crack driving forces
 - Trapped fluid distributing contact stresses within the material, preventing crack closure under normal loads
 - Trapped fluid causing hydraulic pressure, increasing the Mode I stress intensity factor for crack propagation

Interestingly, none of the models directly proposes the model suggested by the SRI hypothesis developed by TICI.¹ Further consideration of the SRI hypothesis and the mechanism of failure to form a HIW suggests:

- Crack initiation proceeds as suggested through the shakedown model: surface tractions in excess of shakedown result in ratcheting of the surface material and crack formation (Figure 5).

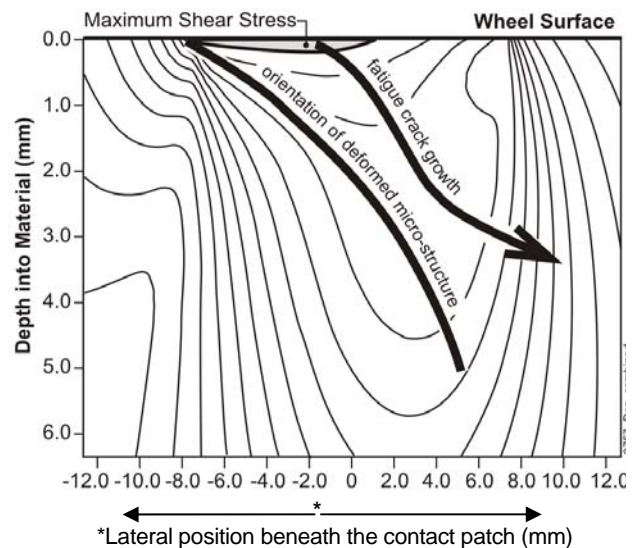


Figure 5. RCF Crack Initiation under Repeated Cycles of High Traction

As implied in the literature, this stress field is not sufficient to substantiate crack propagation; cracks must propagate away from the highest stressed region under steep stress gradients; complex fluid entrapment models are needed, and have been used, to describe propagation with residual stresses used to account for a change in the direction of crack propagation (Figure 2).

- The SRI hypothesis¹ suggests, however, that cracks can be propagated through load and contact cycles subject to low tractions or low friction conditions (Figure 6).

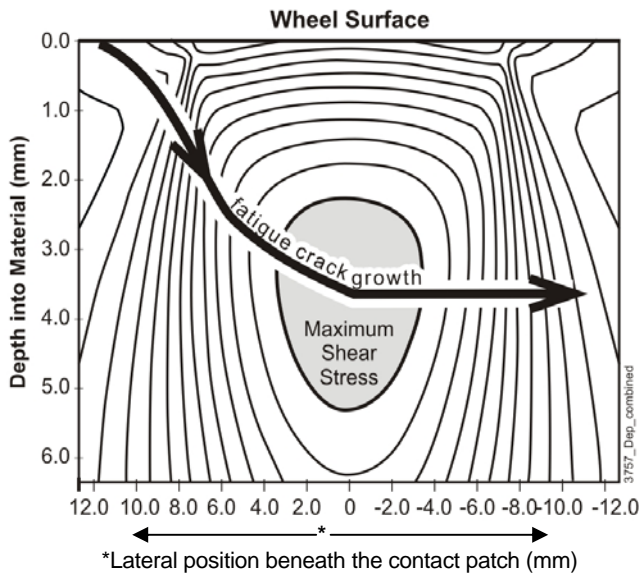


Figure 6. RCF Crack Propagation under Repeated Cycles of Low Traction

Under these conditions, the maximum Hertz shear stress lies beneath the surface of the contact patch; consequently, the maximum shear stress can, depending on the position of the contact patch and the magnitude of the tractions during a contact cycle:

- Occur close to the crack tip and promote crack propagation
- Provide an increasing stress gradient inducing propagation to an increasing depth
- Induce propagation circumferentially at approximately the depth of the maximum shear stress and, incidentally, at a depth of the measured average radial run-out of HIWs (0.05 inch, or 1.5 mm).¹

CONCLUSIONS

1. The hypothesis that cracks propagate from two surface crack bands, join together under the running surface of the tread, and break out to form shells and HIWs is strengthened by evidence presented in the literature.
2. The mechanism related to this failure mode is not specifically noted in the literature and may be the reason for other crack propagation and shelling mechanisms observed in wheel and rail contact.
3. Cracks initiate as a result of surface tractions initiating ratcheting.

4. Crack initiation should be avoided in order to avoid the development of HIW; there is no obvious strategy to suppress crack propagation; the number of contact cycles associated with low tractions, predominantly on tangent track, and the position of the contact patch suggests that suppression of crack propagation is not possible.
5. To establish whether IWS can be used to measure the propensity for the formation of HIW, the development of a damage function similar to $T\gamma$ should be investigated to establish the role of friction and wear in the formation of cracks on the tread surface.

RECOMMENDATIONS

A damage function should be developed for wheels to be used in conjunction with both NUCARS®* simulations and IWS tests, and this development should be made considering the following characteristics of a freight environment:

- Operations and equipment are less controlled and thus less conducive to controlled wear and damage observations as might be the case with passenger traffic in European environments.
- Freight wheels are particularly subject to differing curvatures and differing friction conditions.
- Ratcheting is also a function of wheel temperature, making it even more problematic.

A future TD will describe the development of a damage function for freight car wheels in North America.

REFERENCES

1. Tournay, H., S. Anankitpaiboon, and S. Cummings. September 2009. "A Mechanism for the Formation of Shells on Freight Car Wheels," *Technology Digest* TD-09-027, Association of American Railroads, Transportation Technology Center, Inc., Pueblo, Colo.
2. Beagles, A.E. et al. May 2003. "Whole Life Rail Model Application and Development — Six Month Progress Report," AEATR Report, AEATR-TEaM-2003-231 Issue 1.
3. Burstow, M.C. September 2004. "Whole Life Rail Model Application and Development for RSSB — Development of an RCF Damage Parameter," AEATR Report, AEATR-ES-2003-832 Issue 2.
4. Burstow, M.C. October 2003. "Whole Life Rail Model Application and Development for RSSB — Continued Development of an RCF Damage Parameter," AEATR Report, AEATR-ES-2004-880 Issue 1.
5. Ekberg, A. et al. March 2005. "Fatigue of railway wheels and rails under rolling contact and thermal loading — an overview," *Wear* 258, pp 1288-1300.
6. Johnson, K.L. October 4-8, 1999. "Rolling Contact Phenomena: Lecture 3: Shakedown in Rolling Contact," International Center for Mechanical Sciences, Udine, Italy.

*NUCARS is a registered trademark of Transportation Technology Center, Inc.