TECHNOLOGY DIGEST
Timely Technology Transfer — 02-019

Deformation of Rail and Wheel Surfaces under High Adhesion Conditions

Huseyin Sehitoglu,* Yanyao Jiang,** and David Davis

Summary

As railroads introduce more powerful and higher adhesion locomotives, issues of rolling contact fatigue and control of wheel adhesion conditions become relevant. This *Technology Digest* describes theoretical analysis of deformation of rail and wheel surfaces under high adhesion conditions sponsored by the Transportation Technology Center, Inc. at the University of Illinois. More specifically, this work describes the elastic, plastic, and ratcheting behavior of wheel and rail under combined normal and shear tractions. A recently developed stress-strain model for rail and wheel materials was used in the simulations along with a three-dimensional finite element analysis. Use of this analysis methodology will allow development of guidelines for wheel and rail traction conditions that minimize running surface damage.

Findings from the current studies include:

- A rolling contact fatigue prediction methodology has been developed for railroad locomotive and car simulations.
- Modern high adhesion locomotives operate in the adhesion and contact pressure ranges where rolling contact fatigue may be an issue. However, lower total locomotive weight per train may mitigate the effects of higher wear.
- Steering trucks, with lower lateral tractions, should be beneficial to rail wear life and rolling contact fatigue.
- The study also includes additional data detailing the well-known fact that typical railroad freight traffic loading conditions exceed rail and wheel yield strengths and are in the plastic regime.

The Technology Scanning project of the Association of American Railroads' (AAR) Strategic Research Initiatives Program sponsored this research. The University of Illinois, Urbana, conducted the work under the AAR Affiliated Laboratory agreement. A goal of the Technology Scanning project is to bring new technologies to the railroad industry.

---

* Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign.

** Department of Mechanical Engineering, University of Nevada.

Suggested Distribution:

- ☐ Maintenance of Way
- ☐ Locomotive
- ☐ Track Maintenance
- ☐ Safety

Work performed by TTCI Transportation Technology Center, Inc.
a subsidiary of the Association of American Railroads

INTRODUCTION

The increases in railroad locomotive efficiency with higher adhesion levels have been recognized for some time.[1, 2] Adhesion is defined as the ratio of drawbar pull, or traction force, to the weight of the locomotive. The achievement of high adhesion levels through control of wheel creep can generate higher traction forces and permit heavier loads to be hauled in service with less total locomotive weight. Wheel creep is defined as the ratio of wheel sliding to rolling velocities. Currently, locomotive wheel and rail adhesion levels are nearing 50 percent under conditions of finite percentage of creep. Test results from Electro-Motive Division, shown in Figure 1, have identified that adhesion levels are dependent on the track conditions and the controlled creep levels.[1] By increasing the friction coefficient between the wheel and rail surfaces, higher shear tractions can be achieved. Other factors such as wheel and rail material properties and heat generation at the contact surfaces also affect the available adhesion and modify the curves in Figure 1.

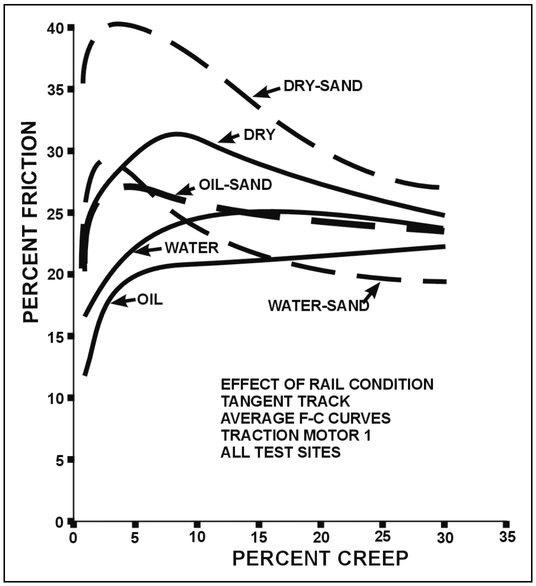

Figure 1. Effect of Controlled Creep on Adhesion Levels for Various Rail Conditions[1]

With the increasing use of higher adhesion levels, research is useful into the implications of high adhesion at the wheel and rail interface on plastic flow, ratcheting, and wear. Ratcheting is the incremental accumulation of shear strains on contact surfaces with each passage. When the ratcheting strain attains critical levels, the material may form a local shear band or intense local deformation. This can appear as wear, cracks, and spalls on the rail surface. A few experimental studies confirm that when the adhesion levels exceed 30 percent, the wear rates increase substantially.[3] Studied here is the elastic, plastic, and ratcheting behavior of contacting surfaces under combined normal and shear tractions in three-dimensional loading conditions. After illustrating the role of applied contact pressure, longitudinal traction levels on the material behavior regimes termed shakedown, plasticity, and ratcheting, we proceed to discuss ratcheting in detail. Numerical results from finite element simulations are also included to illustrate the shear strain accumulation and evolving residual stresses under high shear traction conditions.

Wheel/Rail Rolling Contact Fatigue

The elastic shakedown is the limit below which plastic deformation will not occur for rolling contact loading. This is also called the first yield.4 The results shown in Figure 2a represents the elastic shakedown diagram.[5,6,7] The vertical axis is the maximum hertzian contact stress (pressure) normalized by the rail (yield) strength in shear. The horizontal axis is the longitudinal tractive force normalized by the normal load. The role of lateral tractions is also shown in the same figure. Yielding first occurs below the surface when the tractive forces are small (left side of the diamond). In these simulations, we calculate the contact stresses and pressures from hertz theory using the circular contact geometry shown in Figure 2b. The primary focus of this work is on the role of longitudinal tractions. But, it is also noted that lateral tractions, Qy/P, have a modifying role on the results, as Figure 2a shows. The use of self-steering trucks is expected to reduce these lateral forces. In locomotive wheel and rail contact situations, the maximum hertzian pressure is of the order of 160 ksi, and the yield stress in shear (0.2% offset) is nearly 44 ksi for the case of pearlitic steels with fine lamellar structure. Therefore, the elastic shakedown is readily exceeded in wheel and rail loadings.

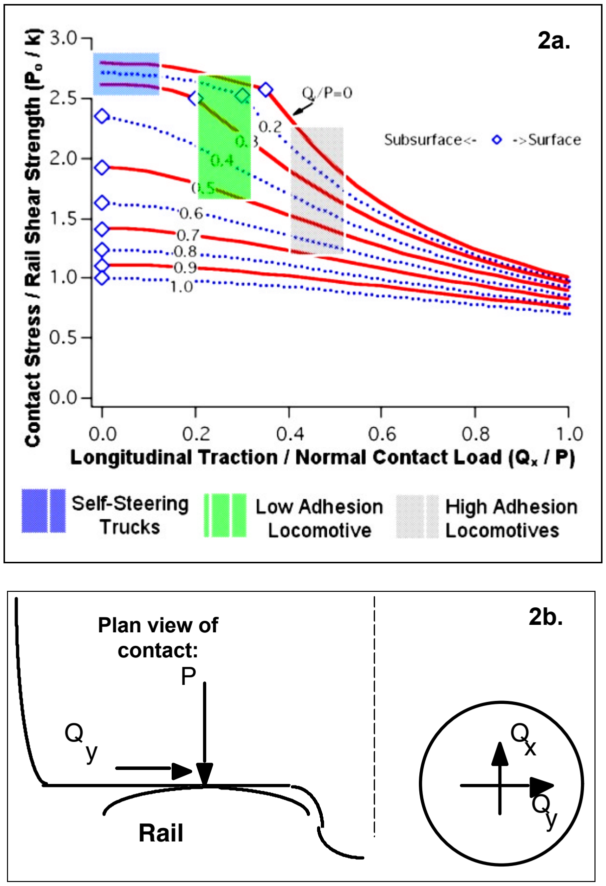

Figure 2. a) Elastic Shakedown Limits, b) Loading Nomenclature used in this Study[8]

The results in Figure 2a show that as the normalized longitudinal tractions exceed 0.4, there is a significant decrease in the normal load that can be sustained before the elastic limit is exceeded. Approximate regions of railroad operations for high and low adhesion locomotives and for self-steering trucks are superimposed for illustration purposes. Figure 2a suggests that steering trucks, with low longitudinal and lateral tractions, can sustain very high loads without causing adverse running surface effects to the rail. On the other end of the spectrum, it would suggest that high adhesions locomotives, with high longitudinal tractions, cannot sustain the same loads without affecting the surface of the rail. The elastic limit is exceeded in the first pass, plastic deformation takes place, and residual stresses are produced. These residual stresses are protective, in that after subsequent passes, the deformation becomes entirely elastic. This process is known as plastic shakedown. Figure 3 shows the plastic shakedown limits for the rolling contact with combined normal and tractive forces. The diamond markers represent the conditions in which persistent cyclic plastic deformation will occur subsurface or on surface.

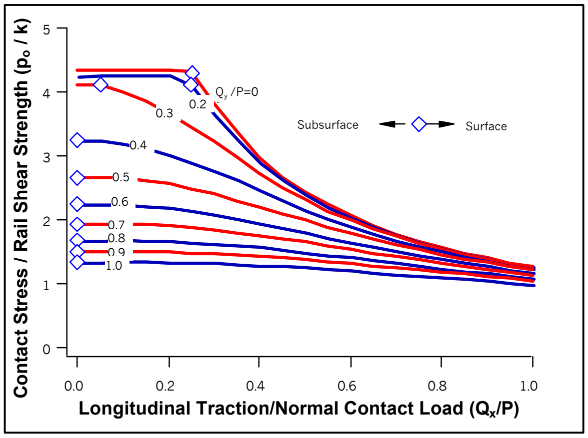

Figure 3. Plastic Shakedown Limits Showing Corresponding Hertzian Pressure and Shear Tractions[8]

Under the pure rolling contact condition (no tractive forces), initial plastic deformation occurs when the P_0/k (contact stress/rail shear strength) ratio is larger than 2.8 for 3-dimensional rolling contact with a circular contact patch (see Figure 2b). Repeated cyclic plastic deformation occurs when the P_0/k ratio is larger than 4.3 (see Figure 3). When a rolling load is higher than the elastic shakedown limit but lower than the plastic shakedown limit, cyclic plastic deformation will occur, but the duration of the cyclic plastic deformation is limited. After a certain number of rolling passes, elastic deformation resumes. As expected, the plastic shakedown limits are much higher than the elastic shakedown limits.[5]

When the plastic shakedown limits are exceeded, the contacting surfaces undergo strain accumulation. This strain accumulation is best illustrated with the deformed mesh given in Figure 4a giving a pattern similar to studies of many years ago using pine in drilled holes. The AREA Committee on Rail produced similar results experimentally using pins and drilled holes in rails.[6] The strain accumulation is confined to a zone of the order of the contact patch. Pearlitic steels have been used in rails for some time. This material has good low cycle fatigue and toughness properties and a good history of handling contact stresses in the plastic range. As wheel loads and levels of adhesion increase, it is useful to investigate what levels of increases could produce spallation, cracking, and ultimately, fracture. The analytical procedure for ratcheting/fatigue introduced by Sehitoglu-Jiang can be used to predict the passes to fatigue crack initiation for such cases.[5,6,7,8] Follow-on work will generate such predictions for current railroad operations.

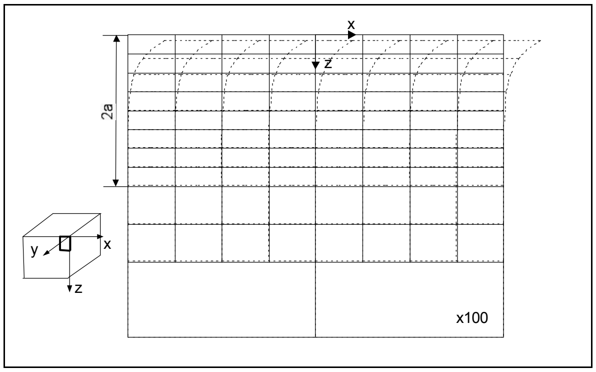

Figure 4a. Deformation of the Surface Layers on the Contact Surface in the Presence of Normal and Tractive Forces[8]

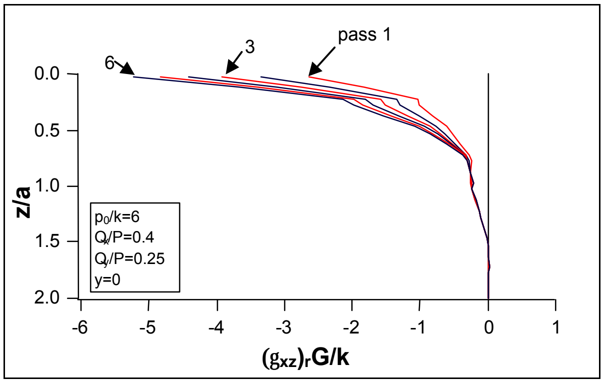

Figure 4b. Development of Residual Shear Strain $(xz)_r$ for p/k=6.0, Q/P=0.4, Q/P=0.25, y=0 (Reference 8)

In Figure 4b, the magnitude of the shear strains as a function of rolling passes is shown. The strains are normalized by the G/k term, where G is the shear modulus, and k is the rail shear strength. A value of 1 in the horizontal scale corresponds to yield strain. Note that the strain accumulation occurs every cycle; within six cycles, a shear strain of five times the yield strain is already built up. Under these conditions, the rail surface is expected to have a finite lifetime.

FUTURE WORK

The models developed will be used to define operating conditions that may cause running surface degradation. This information may be used to set operating guidelines and to develop rails with enhanced fatigue resistance.

References

1. Logston, C.F., Jr., and Itami, G.S., 1980, “Locomotive Friction-Creep Studies,” ASME, *Journal of Engineering for Industry*, Vol. 102, pp. 275-281.
2. K. Hou, J. Kalousek, H.S.Lamba, and R.T. Scott, 1998, ” Wear and Friction of Wheel/Rail Materials for High Adhesion Locomotives,” *Proc. 12th Wheelset Congress*, China Railway Society, pp. 44-52.
3. Kumar, S., Krishnamoorthy, P.K., and Rao, D.L.P., 1986, “Influence of Car Tonnage and Wheel Adhesion on Rail and Wheel Wear: A Laboratory Study,” ASME, *Journal of Engineering for Industry*, Vol. 108, pp. 48-58.
4. Johnson, K.L., 1985, *Contact Mechanics*, Cambridge University Press.
5. Jiang, Y. and Sehitoglu, H., 1996, “Rolling Contact Stress Analysis with the Application of a New Plasticity Model,” *Wear*, Vol. 191, 1996, pp. 35-44.
6. American Railway Engineering Association, Report of Committee on Rail, Vol. 12, 1911.
7. Jiang, Y. and Sehitoglu, H., 1999, “A Model for Rolling Contact Failure,” *Wear*, Vol. 224, pp. 38-49.
8. Jiang, Y., Biqiang Xu, and H. Sehitoglu, October 2002, Three-Dimensional Elastic-Plastic Stress Analysis of Rolling Contact,” *Journal of Tribology*, Vol. 124.

Note: Contact Dave Davis at (719) 584-0754 with questions or comments about this document.
E-mail: david_davis@ttci.aar.com
Visit TTCI’s website: http://www.ttci.aar.com