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# Rail Steel Requirements for Improving Wear in Heavy-Haul Service

by Kevin Sawley

## Summary

A literature and railroad survey done by Transportation Technology Center, Inc. (TTCI) indicates that most rails purchased in North America go to replace rails that have reached their wear limits, including natural wear and metal removed by grinding. New rail steels can offer significant life-cycle cost benefits if they have high resistence to wear and to rolling contact fatigue. Wear and rolling contact fatigue should reduce as the rail shear yield stress is increased. The yield stress of interest is that which develops in the work-hardened layers at the worn rail surface. Based on this, three potential ways to extend rail life are suggested.

1. **Improvements to premium rail steels.** This is the method adopted, for example, by Nippon Steel Corporation. The company's hypereutectoid grade of rail has thicker carbide lamellae, which increase the hardness of the work-hardened rail surface to give improved wear resistance. However, further improvements to conventional rails may be difficult to achieve.
2. **Use of less wear-resistant rail.** The J6 bainitic rail developed for the Association of American Railroads (AAR) by TTCI is less wear-resistant than premium rail, but shows high resistance to rolling contact fatigue. The rails could therefore be of value in track sites where premium rail is prone to surface damage and needs to be ground regularly. They may offer less benefit in sites where natural wear outweighs grinding wear.
3. **Use of very high hardness rail.** J6 rail has a hardness of 420 Bhn, but it is feasible to produce rail steels with much higher hardness and consequently better wear resistance. Other rail properties, however, are important; e.g., weldability, toughness, residual stress, and ease of sawing and drilling on site. Rails much above 420 Bhn may have good wear resistance, but are likely to be difficult to use in service. In addition, they are likely to be much more expensive than current rails.

Two of the three approaches to improved rails are already being addressed, and work needs to continue. The third approach, very high hardness rail, needs to be considered with care, as there is a danger of producing rail in the laboratory that is inappropriate for service use.

Rail is a major asset of North American railroads, with some 48.5 million tons installed. The replacement cost is approximately $27 billion, plus installation costs of the same order. These figures indicate that improved rail life has a major effect on railroad profitability.

**Suggested Distribution:**
- ☐ Maintenance of Way
- ☐ Planning & Analysis
- ☐ Track Maintenance
- ☐ Safety

Work performed by TTCI Transportation Technology Center, Inc.
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## INTRODUCTION

The United States Class 1 railroads, along with Canadian National and Canadian Pacific, own about 212,000 miles of track. Rail sections used vary, but assuming a nominal average of 130 pound per yard, the total weight of rail is about 48.5 million tons. Rail typically sells for between $500 and $600 per ton, giving a rail replacement cost of approximately $27 billion. Installation costs are roughly equivalent to rail purchase costs. These figures show that rail is a major capital asset of railroads, and that improved rail life could significantly increase railroad profitability

In North America, common practice is to install standard rail of typical hardness, 300 Bhn (Brinell), in tangent track and curved track up to about 2 to 3 degrees. At higher curvatures, premium rail of 340 to 390 Bhn is normally used. Rail life depends on many factors, including the conditions of the track and vehicles, lubrication practices, and grinding and track maintenance approaches. Typical rail life is shown in Exhibit 1.

Despite the relatively long lives shown in Exhibit 1, track costs could be further decreased by gaining longer rail life. This technology digest looks at options for rail steel development and recommends basic approaches for reducing rail life-cycle costs on heavy haul railroads.

| Track Curvature | Estimated Rail Life (million gross tons) |
|---|---|
| Tangent | 1,460 |
| 1 degree | 1,050 |
| 2 degree | 640 |
| 4 degree | 510 |
| 6 degree | 390 |
| 8 degree | 370 |
| 10 degree | 330 |

**Exhibit 1. Typical Current Rail Life**

## CURRENT RAIL STEELS

With few exceptions rails worldwide are made of plain carbon-manganese steels with pearlitic microstructures. In pearlite, alternating lamellae of iron and iron carbide are arranged in colonies, and lamella spacing has a large effect on hardness. Naturally cooled standard rails have a coarse spacing and relatively low hardness, about 300 Bhn. Control-cooled premium rails have finer spacing and thus higher hardness (340-390 Bhn).

A survey of the causes of rail purchase by four North American railroads yielded the information in Exhibit 2. The main cause of rail purchase is to replace rail that has reached its wear limits. Two railroads say this is the reason for 85 percent of rail purchases. It should be noted that wear includes natural wear (from wheel/rail contact) and metal removed by grinding to remove cracks, flakes, and spalls. New and upgraded lines notwithstanding, the other main cause of rail purchase is to replace rail that has reached defect limits. One railroad said that more 20 percent of rail went to replace rail with surface damage, but this cause was not mentioned by the other three railroads. From these figures, a requirement of any new rail steel is resistance to wear, surface damage, and rail defects.

| Percentage of rail purchased annually by railroad | A | B | C | D |
|---|---|---|---|---|
| Rail at wear limit | 25.3 | 85 | 58.8 | 85 |
| Rail at defect limits | 6.4 | 15 | 29.4 | 5 |
| Damaged rail | 1.7 | 0 | 7.8 | 0 |
| Rail with surface damage | 21.2 | 0 | 0 | 0 |
| New/upgrade lines | 44.9 | 0 | 3.9 | 10 |

**Exhibit 2. Reasons for Rail Purchase**

Regarding rail defects, a survey of six North American railroads from 1990 to 1995 identified the 10 most common defects shown in Exhibit 3, and their occurrence in defects per billion ton-miles. Some defects, such as piped rail and transverse defect, are related to steel quality, which is very good in modern rails. None of the defects is influenced directly by steel microstructure, but there is an indirect effect, in that microstructures that confer high fracture toughness enable cracks to grow to longer lengths before final fracture. Martensitic and bainitic steels, with higher toughness than pearlitic steels, will offer benefits by increasing the chance that defects will be found by inspection before sudden rail fracture.

## WEAR AND ROLLING CONTACT FATIGUE

From the above, the conclusion is that new rail steels offering significant life-cycle cost benefits over current rails need high resistance to wear and rolling contact fatigue (RCF). Research indicates that both wear and RCF progress by a process known as ratcheting, which is controlled by the same steel property, namely shear yield stress.

| Defect type | Occurrence in $10^9$ ton-miles |
|---|---|
| Transverse defect | 15.9 |
| Defective field weld | 11.1 |
| Bolt hole failure | 9.6 |
| Vertical split head | 6.5 |
| Defective plant weld | 5.0 |
| Head-web separation | 3.8 |
| Horizontal split head | 3.3 |
| Engine burn failure | 2.3 |
| Split web | 2.0 |
| Piped rail | 1.0 |

**Exhibit 3. Primary Defects in North American Track, 1990-1995**

Ratcheting is unidirectional shear of the metal near the rail surface under stresses produced in rolling contact. It is illustrated in Exhibit 4, which compares the bulk pearlite microstructure with that developed during rolling contact. Surface shear stresses deform the microstructure to give extreme surface flow. As the metal flows, it hardens. But eventually it can deform no more and metal flakes form. Under dry conditions the flakes lead to wear. When lubricant is introduced (water, oil, grease) the flakes crack further and deeper to produce pits and spalls. Ratcheting lessens, and therefore wear and RCF are reduced, as steel's shear yield stress (strength) increases.

The shear yield stress of interest is that which develops in the work-hardened surface layer at the strain rates applied by the wheel. This can be called the operating shear yield stress ($ø_{YS}$), and it depends on:

- The as-manufactured (bulk) yield stress.
- The work-hardening of the rail surface. The surface layer can be twice as hard as the bulk.
- The effect of strain rate. High strain rates raise yield stress. This could be a big effect at the very high strain rates in wheel/rail contact.

There is a lack of knowledge of the effect of microstructure on $ø_{YS}$. In particular, the effect of strain rate is little understood.

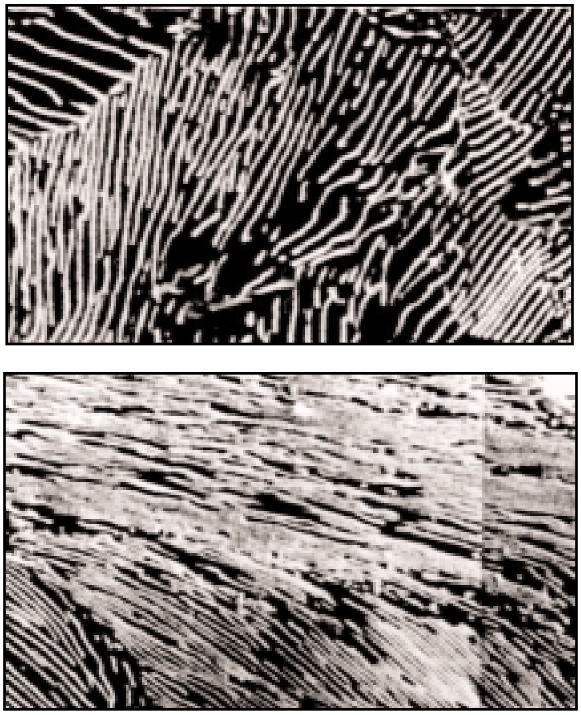

**Exhibit 4. Ratcheting in Pearlitic Steel at Rail Surface: (a) Bulk Structure, (b) Deformed Structure**

For steels with a given microstructure, $ø_{YS}$ rises with bulk hardness, giving the linear relationship between hardness and wear for the common pearlitic rail steels. (Wear falls as hardness rises.) Laboratory and service trials show that other steel microstructures do not follow the pearlitic wear-hardness relationship, and generally show worse and less predictable wear performance for a given bulk hardness. To avoid a trial and error approach to new rail steel developments, there is a need to develop better knowledge of the effect of microstructure on $ø_{YS}$.

This may likely best be done using small-scale laboratory wear tests of rolling/sliding cylinders, with accurate measurement of the surface/subsurface deformations and hardness profiles developed. Backed by modeling of the contact stresses produced, such tests should allow reasonable estimates of $ø_{YS}$. The effect of strain rate may also need to be assessed by comparing the deformation and hardness produced in test specimens and rails taken from service.

Finally, wear and RCF are linked, in that high wear rates can remove embryonic cracks before they reach a problem size. Thus for sites where rails are ground regularly to remove cracks, flakes, and spalls, adopting rails that give an increased wear rate can lead to longer life if grinding is reduced. This is shown in Exhibit 5 that gives estimated rail lives from a grinding test site with a 7.1-degree premium rail curve. Measurements over more than 150 million gross tons (MGT) have given both the metal removed by natural wear and by grinding. From these, the effect of more wear and less grinding on rail life can be calculated. (The figures in Exhibit 5 assume rail is replaced when 35 percent of the head is lost.) At this test site, which needs extensive grinding, the numbers indicate significantly increased life if RCF is reduced by increased wear.

| | Predicted life | |
|---|---|---|
| **Assuming** | **High rail** | **Low rail** |
| **Measured performance** | 465 MGT | 426 MGT |
| **25% more wear<br>50% less grinding** | 670 MGT | 749 MGT |
| **100% more wear<br>75% less grinding** | 659 MGT | 1032 MGT |

**Exhibit 5. Effect of Wear and Grinding on Rail Life**

## REDUCING RAIL LIFE-CYCLE COSTS

There are at least three approaches to reduce the life-cycle cost of rail.

- **Improvements to premium rail steels.** This is the method adopted, for example, by Nippon Steel Corporation with their hypereutectoid grade of rail. This rail has thicker carbide lamellae which increase the hardness of the work-hardened rail surface. It is claimed that this extra hardness gives much improved wear resistance. If confirmed, this is a notable success, but further improvements may be difficult to achieve.

- **Use of less wear-resistant rail.** The J6 bainitic rail developed for the AAR by TTCI and Oregon Graduate Institute is less wear-resistant than premium rail, but shows high resistance to RCF. The rails could therefore be of value in track sites where premium rail is prone to surface damage and needs to be ground regularly (see Exhibit 5). This rail may offer less benefit in sites where natural wear outweighs grinding wear.

- **Use of very high hardness rail.** J6 rail has a hardness of 420 Bhn, but it is feasible to produce rail steels with much higher hardness, and consequently better wear resistance. Other rail properties, however, are important; e.g., weldability, toughness, residual stress, and ease of sawing and drilling on site. Rails much above 420 Bhn may have good wear resistance, but they are likely to be difficult to use in service. In addition, they are likely to be much more expensive than current rails. While economic analysis suggests a sizable premium can be paid for guaranteed increases in rail life, with the volume of rail bought each year there is a need to first control costs tightly.

It can be seen that two of the three approaches to improved rails are already being addressed, and work needs to continue. The third approach, very high hardness rail, needs to be considered with care, as there is a danger of producing rail in the laboratory that is inappropriate for service use.

**Note: Please contact Kevin Sawley at (719) 584-0636 with questions or comments about this document.**
**E-mail:** **kevin_sawley@ttci.aar.com**
**Web site:** **www.ttci.aar.com**

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