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The Evolution and Application of Rail Profile Grinding

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Introduction:

The elimination of rail surface defects through the use of rotating grinding wheels, i.e. rail grinding, has been used by freight railroads since its introduction by the Pennsylvania Railroad in the late 1930's. That application used the first rail grinder cars for the elimination of corrugations, engine burns, and batter at rail ends. Subsequent applications of rail grinding extended rail grinding to almost all types of rail surface defects to include; corrugations, joint batter, weld batter, engine burns, flaking and shelling, as well as for the grinding of mill scale from new rail (1).

This traditional defect elimination or rail "rectification" remained the primary use of rail grinding from that early application in the 1930's until the 1980's. However, in recent years this traditional grinding practice has evolved from the defect elimination approach to the recently emerging rail "maintenance" or "preventive" grinding approaches. This latter approach does not allow for the development of any significant surface defects, but rather attempts to eliminate the development of these surface defects, before they emerge on the railhead. This is of particular interest to the heavy axle load environments, such as is common in North American freight railways, where rail exhibits a relatively short service life. This maintenance grinding offers the potential for increasing the life of rail, in such severe service applications.

This evolution from traditional grinding, to the emerging practices of profile control and maintenance grinding has resulted in a significant broadening of rail maintenance, and introduced the potential for increasing the service life (and thus reducing the cost) of rail in severe service track. Rail profile grinding is the technique that has been utilized to achieve this increase in rail service life.

This paper will present the fundamental concepts behind this technique of rail "profile grinding".

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Profile Grinding:

Rail profile grinding is the term that refers to the method of controlling and maintaining the shape of the railhead, it's "profile", through grinding of the head of the rail. This represents an evolutionary step beyond the traditional defect elimination grinding where the shape of the rail, either before or after grinding, was not a factor in the grinding process. In fact, as illustrated in Figure 1 (2), traditional defect elimination grinding flattens the railhead (1a), as opposed to profile grinding which grinds a specific contour or profile into the railhead (1b).

However elimination of the surface defects is usually a preliminary step in profile grinding, if they are present on the railhead. Thus, for rail with surface defects and plastic flow, profile grinding can be a three-step process, as illustrated in Figure 2. The initial step, consisting of one or more grinding passes, eliminates any surface defects present. The second step, again consisting of one or more passes, reshapes the deformed railhead. The third step, if necessary, grinds the final railhead profile.

By introducing a profile that is appropriate for a given track location, after the rail has been installed (thus eliminating the need to have a general purpose profile). An optimum rail shape can be designed for that track location and then ground into the rail. Through this control of the railhead shape, the locations of wheel/rail contact, and thus the interaction between the wheels and the railhead, can also be controlled. While this approach could be used in conjunction with wheel profile maintenance, North American application generally deals with the control of the railhead shape or "profile" only.

Rail profile grinding, as is currently practiced in North America, encompasses three general areas of rail maintenance:

a. Control of gage face wear of the high rail on curves and on tangents (as applicable).

b. Control of short wave corrugations, on the low rail on curves.

c. Control of gage corner surface fatigue, to include both spalling and shelling, on the high rail on curves.

While all three areas, can be addressed through the proper use of rail profile grinding, they generally cannot all be addressed simultaneously (3,4). Thus the profile that is best suited for the control of one of these maintenance areas, may not be the best for the other two problem areas, even though it may be possible to derive benefit in all three areas by proper profile selection. Therefore, in order to get the greatest benefit from this profile grinding it is necessary to prioritize the rail problems for a given track location and then select the optimum railhead profile for that problem location.

The evolution of implementation of rail profile grinding, in each of these three areas, will be presented, in the next three sections.

Evolution of Profile Grinding; Reduction in Rail Wear.

Rail profile grinding was first developed in the mining railroads of Western Australia during the late 1970's (5). These Western Australia mining railroads operated at North American axle loads and operating conditions, and as a result, their problems, and their subsequent solutions, were directly applicable to North American conditions.

The original development work was aimed at reducing the gage face wear of rail on light and moderate curvature track, through the optimization of the "steering" of conventional three-piece freight car trucks. This optimization was first analyzed using freight car curving models, to help define the optimum railhead profile, and then tested in actual service application (5). The result was the development of a set of asymmetric railhead profiles (i.e. asymmetric about the center line of the railhead), with a separate profile for the high and low rails of the same curve. In addition, for tangent track, where "hunting" wear was noted, special tangent profiles were developed to control this form of railhead wear, as well.

The initial profile grinding concept was designed to make use of the steering of the conventional three-piece freight car truck generated by the conicity of the wheelset (3). This behavior is illustrated in Figure 3, which illustrates the shifting of the wheelset "outward", towards the outer or high rail of the curve. This results in the outer wheel riding on the larger radius portion of its tread, and the inner wheel riding on the smaller radius portion of its tread. The difference between these radii, known as the "rolling radius differential", compensates for the difference in length, around the curve, between the high rail and the low rail. In addition, this rolling radius differential generates a longitudinal "creep" force (which is, in fact, a partial wheel slippage in the longitudinal direction), which tends to steer the truck into a radial position (with equally distributed misalignment of the two axles). The result of this is a degree of self-steering that reduces flanging on relatively shallow curves, and has the potential for eliminating flanging on curves less than 3 degrees (5).

In order to maximize this rolling radius differential, and still maintain sufficient wheel/rail contact area to avoid excessive contact stresses, the profile presented in Figure 4 was developed (5). This profile results in a shifting of the wheel/rail contact patch on the high rail toward the gage side of the railhead, while avoiding the gage corner to avoid surface fatigue at that location. On the low rail, the contact zone is moved towards the field side of the railhead, again avoiding any false flange contact. In this manner the rolling radius differential is maximized. The result is that the lateral forces generated by the three-piece truck while curving is reduced. In addition, lateral gage face wear is also reduced. In fact for shallow curves, i.e. the Australian case of curves less than 3 degrees, gage face wear is all but eliminated, as illustrated in Figure 5.

Subsequent field tests of the effect of profile grinding at FAST (6), measured the reduction in both lateral flanging forces and in gage face wear, for several different railhead profiles. In these tests, lateral force measurements were taken on a 4-degree test curve, with three different profiles and a control (non-profiled) railhead. Figure 6 presents these results, for operations above, below and right at balance speed for that curve. In all cases, profile grinding significantly reduced the measured lateral forces.

This reduction in lateral force, in turn, translates into a reduction in gage face wear. Even for curves where flanging is not eliminated, such as the 4 degree curve presented in Figure 7, a reduction in the rate of gage face wear was measured.

In the Australian case, where flanging was almost completely eliminated, significant increase in rail life were recorded (5). These are illustrated in Table 1.

Table 1

Increase in Rail Life by Profile Grinding

Curvature (Degrees)	Rail Life (MGT) No Grinding	Rail Life (MGT) Profile Grinding	Theoretical Increase (%)
1.5	255	465	82
2	225	390	73
2.33	195	330	69

In fact, use of profile grinding, as a means of controlling rail wear (application a above) resulted in a dramatic reduction in the projected rail requirements during the early 1980's (see Figure 8).

However, in extending the use of profile grinding to North American applications, the effect of the more severe curvatures and poorer wheel conditions, of North American railroads, resulted in a shift in emphasis of profile grinding away from wear reduction and towards first corrugation elimination and then towards fatigue control.

Control of Short Wave Corrugations

The second area of benefit to be derived from profile grinding is in the area of corrugation control. In the case of North American applications, this refers to the control of the heavy axle load short wave corrugations, found on the low rail of curves. These corrugations generally have wavelengths in the range of 12 to 24 inches on wood tie track (7).

These freight railroad corrugations are generally associated with the high contact stresses generated when the false flange of a worn wheel runs on the field side of the low rail, as illustrated in Figure 9. This contact, which is counter-formal (i.e. the curvature of the two bodies in contact, are opposite to each other), causes significantly higher wheel/rail contact stresses than the other (conformal) wheel/rail contact configurations (3).

This high contact stress, when located near the field side of the low rail, where there is little unstressed rail steel to retain the overstressed material, results in severe plastic deformations and correspondingly short wave corrugations (8). These corrugations can be of significant depth (over 0.60 inches, (4)) and result in severe wheel rail dynamic impact forces in the track structure.

The control of these corrugations has been considered by at least one North American railroad (3) to be the most important aspect of profile grinding of the rail. (This remains true as long as significant corrugations remain. Once these corrugations have been eliminated, other aspects of rail maintenance emerge as being "most" important.) While, several other techniques could be employed, either alone or in conjunction with profile grinding (such as control of wheel profile and of track gage), to control corrugations, the primary mechanism to be discussed here is rail profile grinding by itself.

By grinding the field side of the low rail, to shift the contact point towards the center of the railhead (such as from pint A to B in Figure), the high stress producing false flange contact is avoided. Rather a by a more tolerable conformal contact condition is established near the center of the wheel hollow and the top of the railhead.

The grinding pattern used for this type of profiling maximizes the metal removal on the extreme field side of the low rail, as illustrated by the shaded portion of Figure 9. Thus, it can be used in conjunction with the wear control profile described in the previous section and illustrated in Figure 4. However, the relative emphasis, in terms of the percentage of grinding motors and the amount of metal to be removed, must once again be determined by the relative priority of the railroad, and of the site being ground.

In the case of one major North American test application (3,4), the use of profile grinding to control the re-growth of corrugations was evaluated for several different types of grinding patterns. By measuring the average depth of corrugations, at periodic intervals after grinding, the corrugation re-growth curve shown in Figure 10 was developed. For both profiles used in the tests, corrugation re-growth was significantly slower than it had been using conventional (defect elimination) grinding patterns. This reduced growth rate could be used to extend the grinding cycle from the previous 6-month interval to an 8-month interval, an extension of 33% (4).

Alternately, it was observed during this test that more frequent grinding passes, could reduce the overall amount of grinding by eliminating the corrugations while they were relatively shallow. This comes about because of the non-linear nature of the corrugation growth curve (Figure 10). By grinding frequently, fewer grinding passes would be required over the life of the rail (9). This concept, which is illustrated in Figure 11, will be discussed in the later section on light grinding.

In the more recent applications of rail profile grinding, this specific grinding strategy is generally incorporated as part of the overall profile grinding activity. By controlling the contact zone on the field side of the low rail, the undesirable false flange contact can be eliminated, without affecting the remainder of the profiling objectives.

Control of Gage Corner Fatigue

The third area of benefit associated with rail profile grinding is in the control of rail surface fatigue, and in particular fatigue defects at the gauge corner of the railhead. This includes both surface fatigue defects, such as spalling, and subsurface fatigue defects, such as gage corner shelling.

In a severe flanging condition, such as on a sharp curve, single point contact between the throat of the wheel set and the gage corner of the rail will frequently result, particularly if the rail has a worn profile. This type of contact, which is illustrated in Figure 12, generates very high contact stresses in the region of the gage corner of the high rail. These high stresses can result in gage corner fatigue problems, to include cracking and spalling (10,11).

In order to relieve these high contact stresses, grinding of the gage corner of the rail, can shift the wheel/rail contact points, away from this corner contact and into a more central contact on the railhead. This shifting of the wheel/rail contact point is analogous to that discussed previously for the two other aspects of rail profile grinding. The grinding required to shift this contact away from the gage corner is illustrated in Figure 13. As can be seen in that figure, this requires grinding on the gage corner of the high rail. Supplemental grinding of the field side of the high rail, in a manner analogous to that discussed for wear control, aids in defining a suitable wheel/rail contact band.

This grinding of the gage corner can result in a decrease in both surface fatigue "spalling" and subsurface fatigue "shelling", by "wearing" away the surface fatigue damaged rail steel, and relocating the point of maximum rail stress, before fatigue damage can initiate. Figure 14 shows such a decrease in transverse defects (due to shells) as well as in overall fatigue defects, for one major North American railroad that utilized rail profile grinding to control gage corner fatigue from 1982 onward (12). Other instances of the control of rail fatigue defects by profile grinding have also been reported in Australia (13).

In the case of sharper curves, where flanging takes place, a second contact point between the flange of the wheel and the gage face of the rail can occur, thus generating "two-point" contact between the wheel and the rail. This change in wheel rail contact, from one point to two-point contact, can result in a deterioration in truck curving performance, and a corresponding increase in the wheel/rail flanging forces. This has been demonstrated in recent field tests on a major freight railroad (3). The result of this can be an increase in gage face wear, if no other action is taken. Therefore, this type of gage corner profile grinding should be used primarily in those areas where rail fatigue and not rail wear is the dominant rail failure mode.

However, it is noted that a limited amount of gage corner grinding, when combined with compensatory grinding to maximize the rolling radius differential, can be used as part of an overall profile grinding activity to control gage corner fatigue without increasing gage face wear (3,4). In fact, grinding of the gage corner of the high rail can be incorporated into the wear control pattern, previously illustrated in Figure 4. Thus, as in the case of corrugation control, this type of profile grinding can be combined with the previously defined profiles, as well. Once again, the degree of emphasis, and the corresponding amount of metal removal, varies as a function of the relative importance of this type of profile grinding and of the problems being addressed.

"Light" Grinding

As the concept of maintenance grinding becomes more widely used (and in fact is used by most major North American railroads), the benefits of more frequent grinding, and the elimination of rail surface defects as an early stage become increasingly apparent. This has already been observed previously, in the case of corrugation re-growth, where it was seen that grinding the corrugations at an early stage in their growth (and on a shallow portion of their growth curve) will result in a decreased rate of re-growth, i.e. a longer interval before the corrugations grow to an undesirable depth.

This concept has also been applied to rail surface fatigue types of defects (2). As can be seen in Figure 15, grinding of the surface defects (such as fatigue defects) while they are relatively shallow requires significantly less metal removal than that when the surface cracks have grown to a significant depth. In fact, grinding at this early stage can avoid the formation of corrugations or other surface defects entirely, provided that the grinding is carried out on a regular, ongoing basis. This concept, which has been referred to as preventive grinding (2), suggests that very light grinding passes (of the order of 0.002 inches in depth) taken at very frequent intervals (5 MGT for sharp curves) can prevent the emergence of these defects, and thus extend the life of the rail in track. The corresponding profile required to maintain this rail condition is once again, established by profile grinding. However in this case, rather than using heavy grinding to achieve the profile, the light, frequent grinds are used to install and maintain (with an emphasis on maintenance) this profile.

Economics of Rail Profile Grinding

The final issue to be addressed in this report is that of the economics of rail profile grinding. While rail profile grinding is still relatively new in its application, particularly in North America (having been introduced in the early 1980's) the question of the relative economic benefits of this technique of rail maintenance has only recently been addressed.

The economics of conventional rail grinding, such as corrugation grinding, has been previously established, with some analyses displaying return on investments (grinding costs) of over 400% (14).

Recent analyses of the economics of rail profile grinding (9,12) has examined the benefits associated with profile grinding aimed at extending the fatigue life of rail in heavy axle load mainline service. In such an environment, particularly in sharp curves, rail wear had been the traditional cause for rail replacement. However, increasing use of rail lubrication (12) has resulting in a shift in failure mode from rail wear, to fatigue, and in particular rail surface fatigue, such as shelling or spalling. Thus rail profile grinding can be used to extend the fatigue life of rail in these cases.

In the analysis of such heavy axle load traffic on a well lubricated 5-degree curve (12), the cost of frequent rail profile grinding (one profile pass every 15 MGT) was compared to the corresponding extension in fatigue life. This analysis, which is summarized in Table 2, indicates that under moderately heavy traffic conditions (25 MGT annual traffic), the return on investment (for rail grinding) was approximately 50%. For heavy traffic conditions (50 MGT annual tonnage), the return on investment (for rail grinding) was over 85%. In both cases, rail profile grinding, and its associated extension of rail life, was found to be economically viable.

An alternate analysis of rail profile grinding (15) suggests that for a major North American freight railroad, adoption of rail profile grinding can result in an overall cost savings of over 2 Million dollars, per year, due to a reduction in replacement rail requirements.

In both cases, the economic analysis suggests that profile grinding is an economically viable, as well as technically viable approach to rail maintenance.

Conclusion:

Rail profile grinding has emerged, in the last 10 years, as an effective approach for the control of rail fatigue and wear, through the use of controlled rail grinding. After initial application in the heavy haul mining railroads of Western Australia, it was quickly adopted by several North American freight railroads. Since the mid 1980's, rail profile grinding, in one form or another has been tried by all the major freight railroads. In many cases, it has been adopted as the primary rail grinding technique.

As noted in this report, rail profile grinding can be used to address several different classes of railhead problems; to include rail wear, corrugation control, and rail surface fatigue. While benefits can be obtained in all three areas by proper design of a rail profile, they may not necessarily be obtained simultaneously, in all cases. In addition, the relative benefits in each area will differ, as a function of the relative emphasis and effort placed in that area. This is readily evident by the differing effects of rail profiling, i.e. the trade off between gage corner grinding and lateral flanging force. Thus, it is extremely important that the rail problems to be addressed by profile grinding be defined and prioritized. In this manner, the patterns can be optimized to fit a railroad's problems, in the order of that railroad's priorities.

Proper trade off between differing rail problems and corresponding application of appropriate profile grinding techniques, can result in a customized grinding pattern, not only for each railroad, but potentially for each location on that railroad. In addition, the flexibility of the new generation of computerized rail grinders permits the preprogramming of a large number of grinding patterns, and the immediate selection of those patterns at a grinding site. This, in turn, permits the railroad to develop specialized profiles to address a series of rail problems, treating each problem with its own "optimum" pattern.

A comparison between three such "optimum" rail profiles, each of which is geared toward a specific rail problem, is presented in Figure 16 (4). In this example, Profile A addresses corrugations as its highest priority problem, Profile B treats gage face flanging force (and thus wear) as its greatest concern, and profile C considers gage corner fatigue as its highest priority. Note the difference in grinding emphasis (and thus metal removal) between these three profiles.

Finally, it must be noted that any rail profile deteriorates under traffic. This applies to the newly rolled rail profile, as well as to any ground profile. As a result, the desired railhead profile cannot be simply ground into track and "forgotten". Rather, it is necessary to periodically monitor the profile, and to regrind the railhead (maintain the profile), when the profile deteriorates to the point where it is no longer functioning properly. This deterioration has been reported to occur after between 15 and 20 MGT of heavy axle load traffic (4,6).

If this profile maintenance is not carried out, i.e. if the profile is allowed to deteriorate and is not restored, then the benefits of the ground profiles will no longer continue. Consequently, profile grinding must be considered an ongoing maintenance activity, with periodic "maintenance" grinding required to retain the optimum railhead profile. By maintaining such an ongoing program of profile maintenance, the full benefits of the profiles can be achieved, while at the same time, the total level of grinding required can be significantly less than that needed if the profiles were permitted to deteriorate completely, thus requiring extensive profile restoration.

References

1. Butler, R. W. et al., Criteria for Rail Grinding, Report of Special Committee No. 3, Proceedings of the Roadmasters and Maintenance of Way Association, 93rd Annual Conference, September 1981.

2. Kalousek, J., "Thorough Lubrication and Light Grinding Prevents Rail Corrugation", Second International Symposium on Wheel/Rail Lubrication, Memphis, TN, June 1987.

3. Lamson, S. T., "Rail Profile Grinding", Canadian Institute of Guided Ground Transport Report 82-7, November 1982.

4. Lamson, S. T., " Rail Profile Grinding; Phase II Test Report", Canadian Institute of Guided Ground Transport Report 84-14, February 1985.

5. Lamson, S. T., and Longson, B. H., "Development of Rail Profile Grinding at Hammersley Iron", Proceedings of the Second International Heavy Haul Railways Conference, Colorado Springs, CO, September 1982.

6. Walker, G. W., "Effects of Rail Profile Variation", Report from the Facility for Accelerated Service Testing (FAST), FRA/ORD-86-04, March 1986.

7. Zarembski, A. M., "Corrugation Behavior in the Freight Railroad Environment", Bulletin of the American Railway Engineering Association, Bulletin 712, Volume 88, October 1987.

8. Kalousek, J. and Klein, R., "Investigation into the Causes of Rail Corrugation", Bulletin of the American Railway Engineering Association, Bulletin 656, Volume 77, January-February 1976.

9. Zarembski, A. M., "The Economics of Rail Grinding and Rail Surface Maintenance", Proceedings of the Third International Heavy Haul Railways Conference, Vancouver, B. C., October 1986.

10. Worth, A. W., "Rail Profile Grinding Tests on CN Rail", CIGGT Technical Conference, May 1985.

11. Worth A. W., Hornaday, J. R., Jr., and Richards, P. R., "Prolonging Rail Life Through Grinding", Proceedings of the Third International Heavy Haul Railways Conference, Vancouver, B. C., October 1986.

12. Zarembski, A. M., "The Relationship Between Rail Grinding and Rail Lubrication", Second International Symposium on Wheel/Rail Lubrication, Memphis, TN, June 1987.

13. Marich, S. and Mass, U., "Higher Axle Loads are Feasible- Economics and Technology Agree", Proceedings of the Third International Heavy Haul Railways Conference, Vancouver, B. C., October 1986.

14. Zarembski, A. M., "The Impact of Rail Surface Defects", Railway Track and Structures, November 1984.

15. Lamson, S. and Roney, M. D., "Development of Rail Profile Grinding on CP Rail", Proceedings of the Third International Heavy Haul Railways Conference, Vancouver, B. C., October 1986.

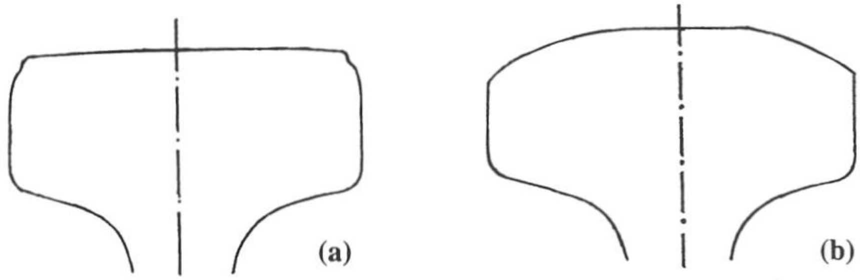


Figure 1. Ground Rail profile (2)
(a) "Flat" profile after defect elimination grinding
(b) "Contour" profile after profile grinding

By determining a profile that is appropriate for a given track location, an optimum rail shape can be designed and then ground into the rail after installation. Through this control of railhead shape the location of wheel/rail contact, and thus the interaction between the wheels and the railhead, can be controlled. This approach could be used in conjunction with wheel profile maintenance, but North

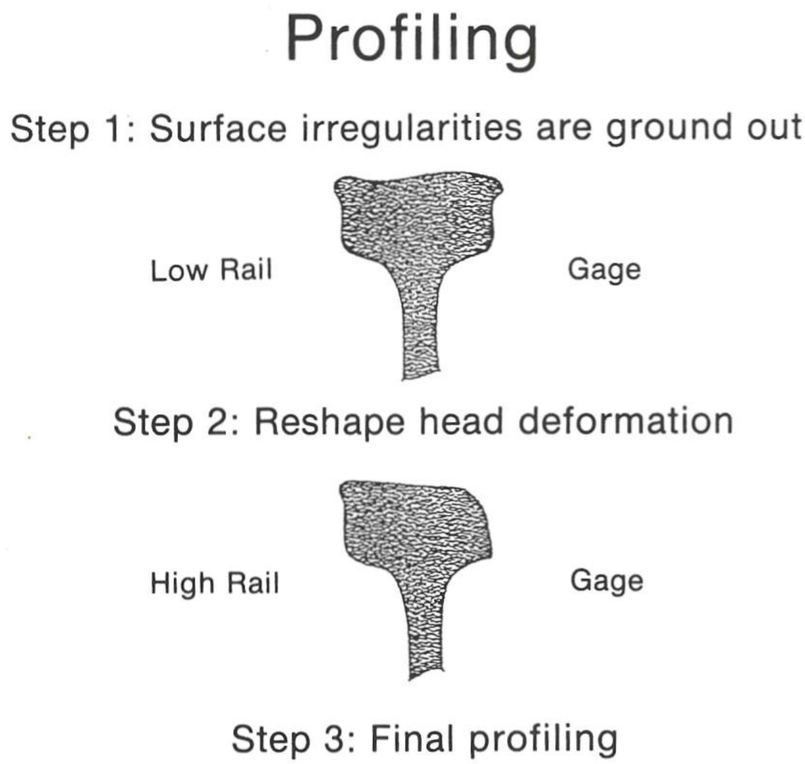


Figure 2. Three Steps of Profile Grinding

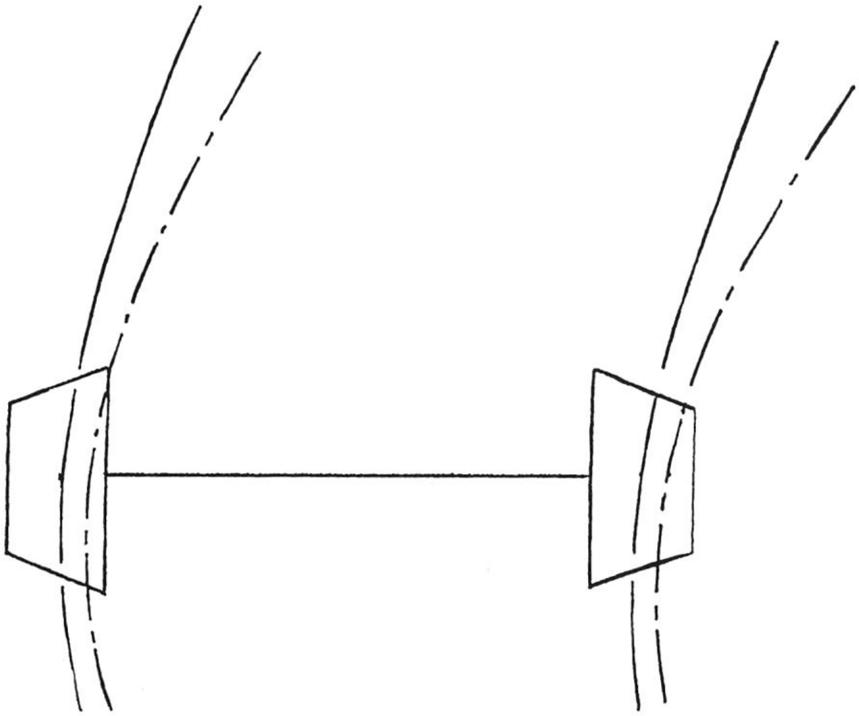


Figure 3. Curving Path of a Wheel Set (3).

contact. In this manner the rolling radius differential is emphasized and the lateral forces generated by the truck while curving are reduced. In addition, lateral gage face wear is also reduced. In fact, for shallow curves (in the Australian case for curves less than 3 degrees) gage face wear is all but eliminated, as illustrated in Figure 5.

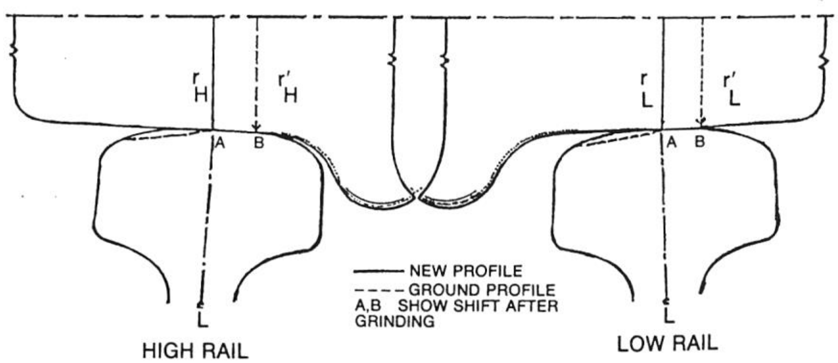


Figure 4. Effect of Grinding on Wheel/Rail Contact Positions (5)

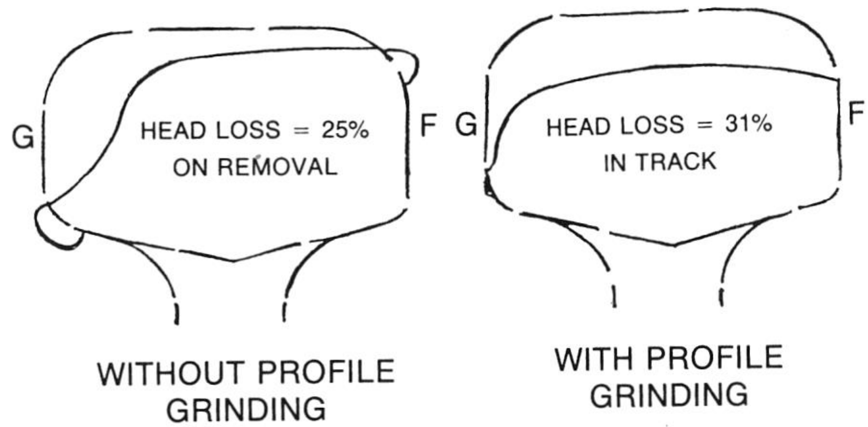


Figure 5. Worn Rail Sections, with and without Profile Grinding

Subsequent field tests of the effect of profile grinding at FAST (6) measured the reduction in both lateral flanging forces and gage face wear for several different railhead profiles. In these tests, lateral force measurements were taken on a 4 degree test curve with three different railhead profiles and a control (non-profiled) railhead. Figure 6 presents the results for operations above, below and at bal-

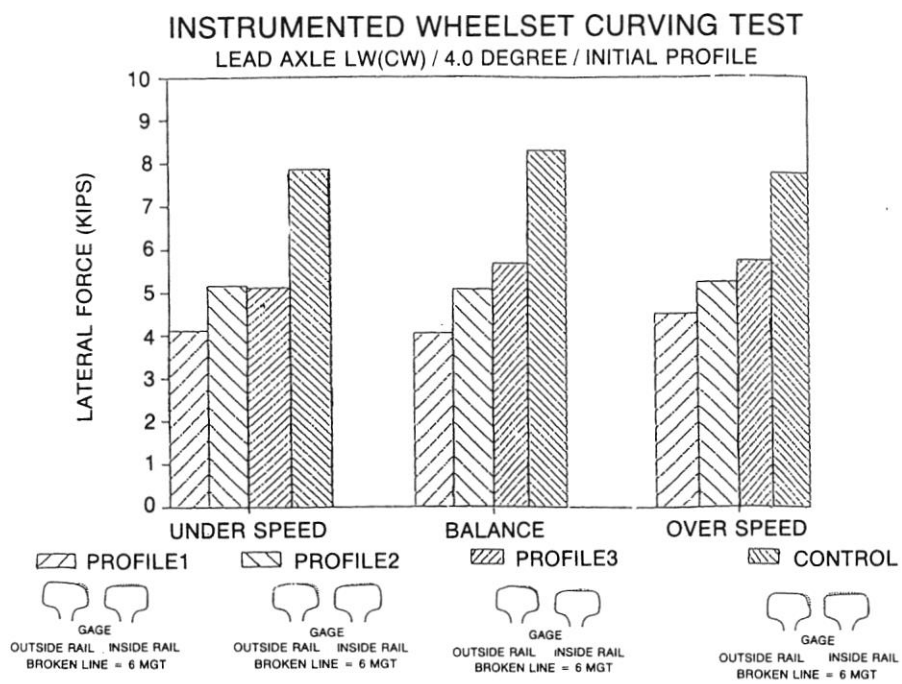


Figure 6. Lateral Wheel Forces–4.0° Curve. (6)

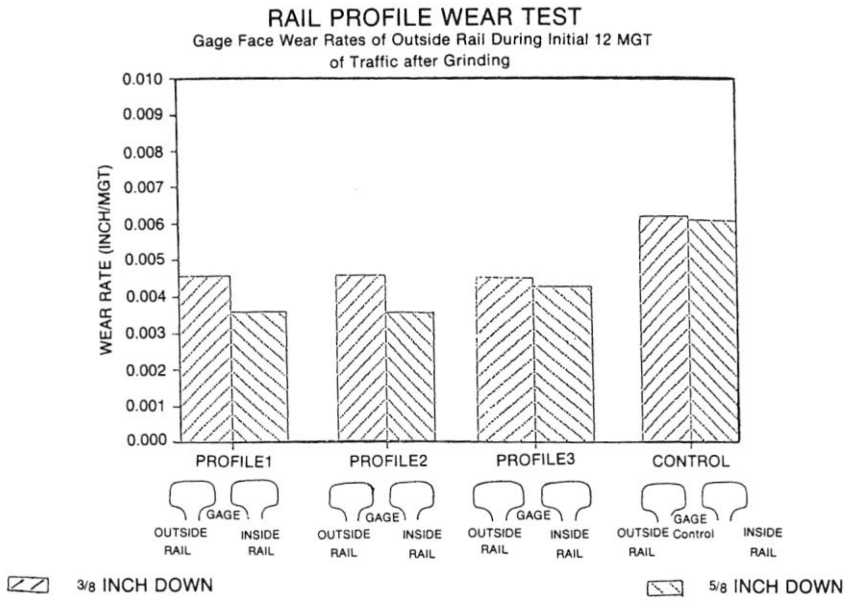


Figure 7. Outside Rail Gage Facewear—12 MGT. (6)

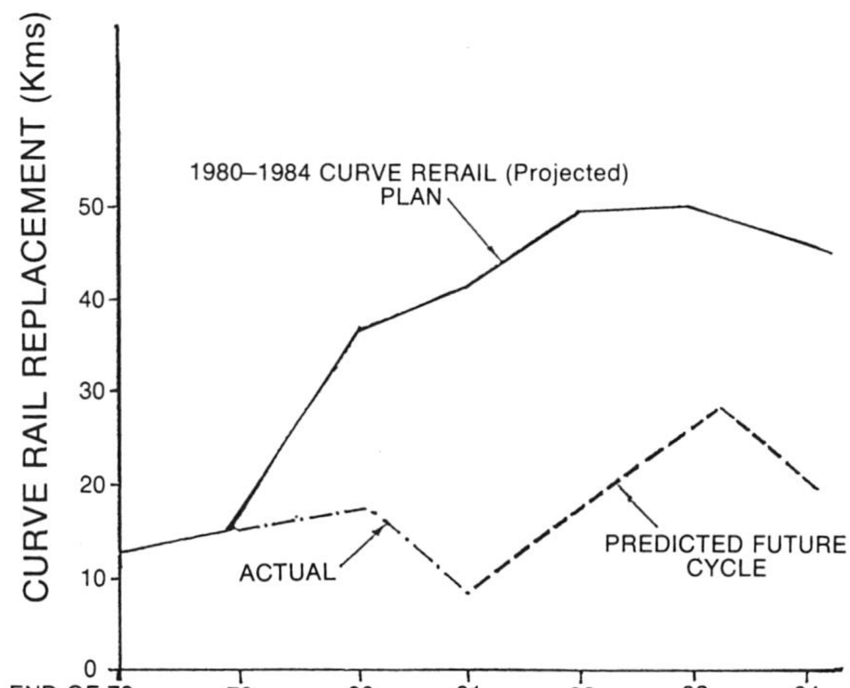
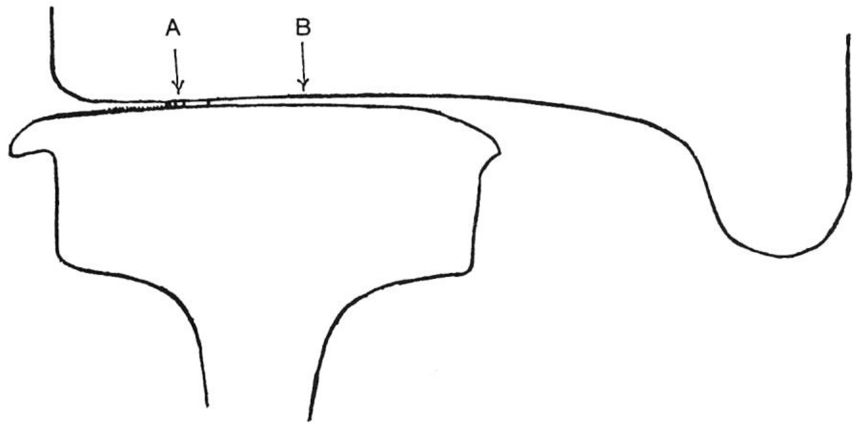


Figure 8. Effect of Profile Grinding on Curve Relay Requirements (5)



(WORN WHEEL/WORN RAIL/WIDE GAUGE)

Figure 9. False Flange Contact on Field Side of Low Rail (3)

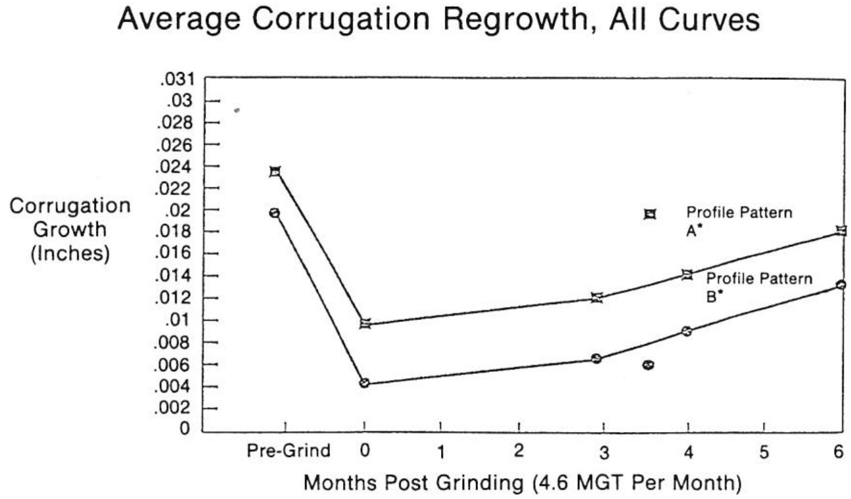


Figure 10. Corrugation Regrowth After Profile Grinding (4)

In the more recent applications of rail profile grinding, this specific grinding strategy is generally incorporated as part of the overall grinding activity. By controlling the contact zone on the field side of the low rail, the undesirable false flange contact can be eliminated without effecting the other profiling objectives.

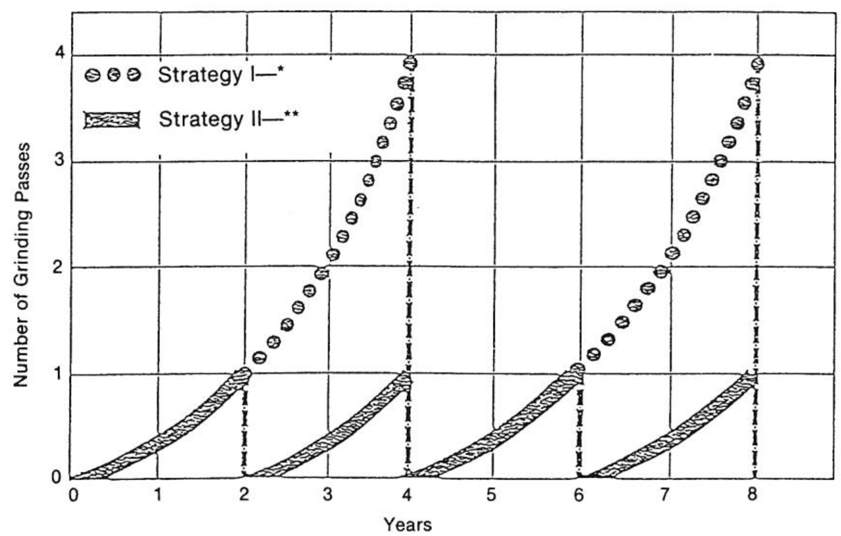


Figure 11. Corrugation Growth Rate Effect on Grinding Strategy (9)
***4 passes after each 4 years (8 passes over 8 years)**
****1 pass after each 2 years (4 passes over 8 years)**

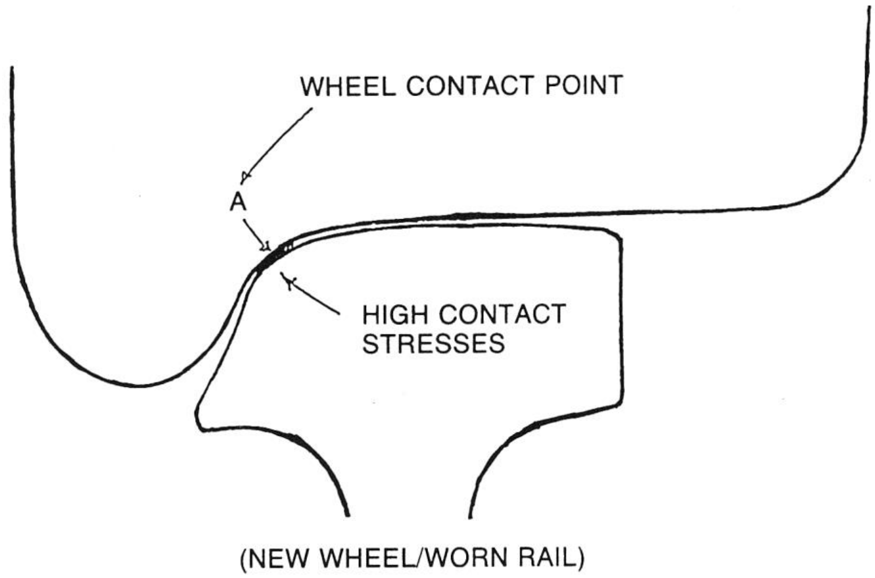


Figure 12. Single Point Contact between Gauge Corner of Rail and Wheel Flange Throat.

Table 2.

Contact Pressure Determined from Exercise of the AAR Curving Model

W/R Profile	Curvature 2°	4°	6°	8°
AAR1:20/132RE	191ksi	170ksi	160ksi	154ksi
flanging?	yes	yes	yes	yes
AAR1:20/136RE	182ksi	154ksi	134ksi	123ksi
flanging?	yes	yes	yes	yes
AAR1:20/Curve Worn	142ksi	127ksi	118ksi	113ksi
flanging?	yes	yes	yes	yes
AAR1/132RE	460ksi	329ksi	240ksi	220ksi
flanging?	no	no	yes	yes
AAR1/136RE	448ksi	421ksi	813ksi	224ksi
flanging?	no	no	no	no
AAR1/Curve Worn	327ksi	101ksi	92ksi	87ksi
flanging?	no	no	yes	yes

AAR1:20—Standard Wheel Profile
AAR1—"Heuman" Design Profile

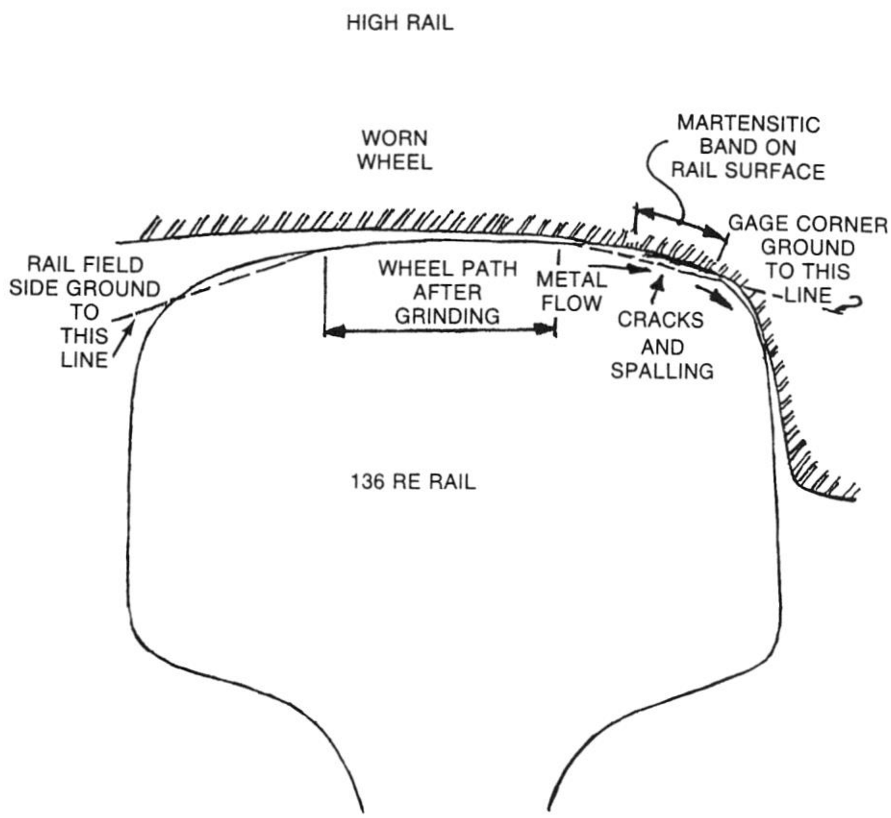


Figure 13. Gauge Corner Spalling and Profile Grinding to Relieve it.

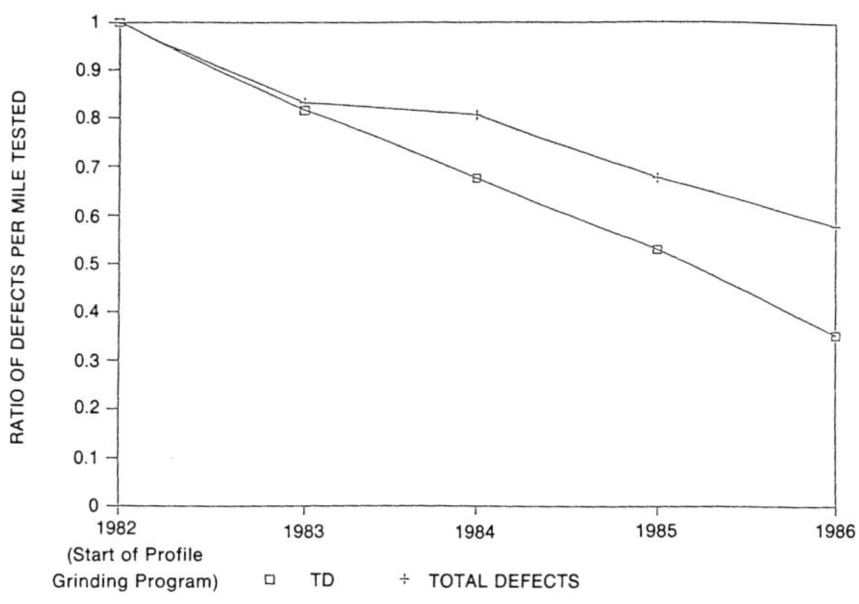


Figure 14. Rail Defects on Major North American Railroad (defects normalized by actual miles tested) (12)

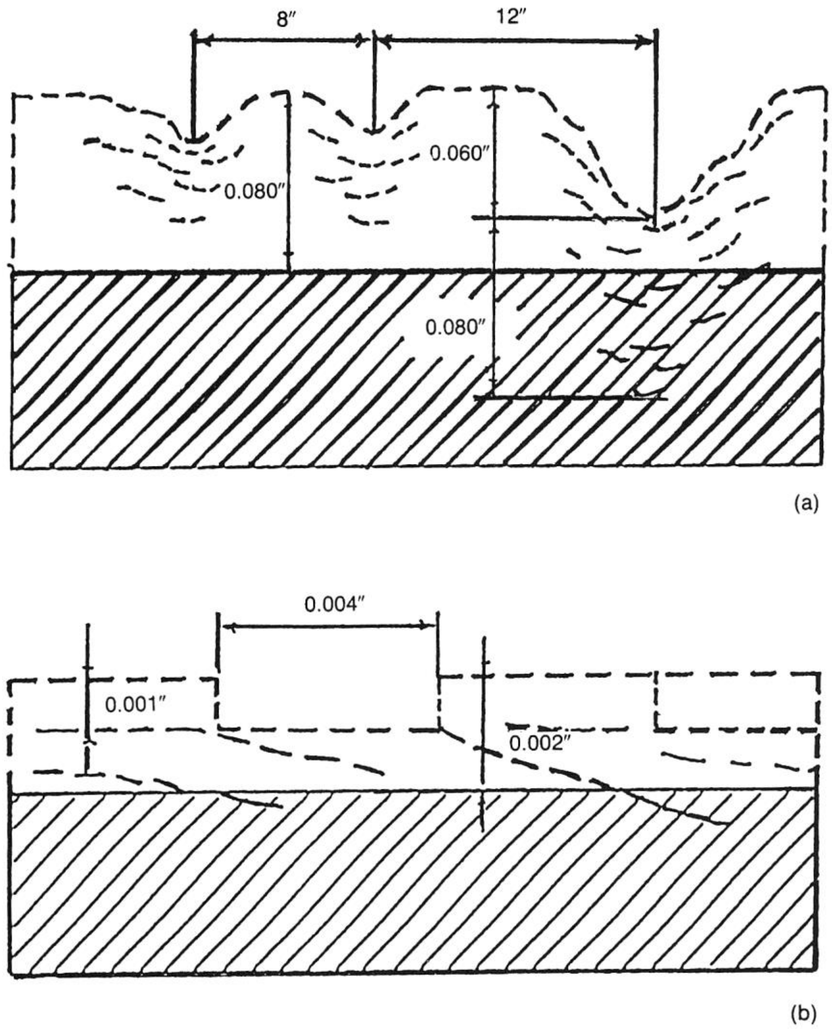


Figure 15. Rail Surface Cracks before
(a) Corrective Grinding
(b) Preventive Grinding (2)

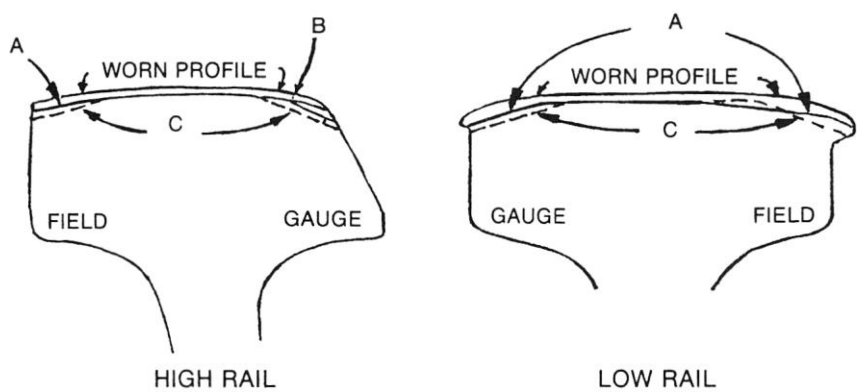


Figure 16. Conceptual Differences between Three Sets of Profiles (4)