Corrugation on low rails in curved track is a common and significant problem on North American railways. Research findings on probable causes are described and practical methods of keeping this problem under control are suggested. The role of wheel and rail contact stresses in the plastic deformation of rail surfaces, a necessary condition for corrugation development, is examined, and the use of high-strength steel and rail profile grinding to control rail corrugation through reducing or preventing rail surface plastic deformation is discussed. Results of recent field trials of rail corrugation control using a rail profile grinding technique are presented.

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rotate faster than the one on the low rail side. Because the wheelset is an integral component, this instantaneous rotational speed differential places the axle in torque until the torsional reaction becomes greater than the adhesion forces at the wheel and rail interface. The axle then twists back, resulting in wheel and rail slip. The stick-slip cycles set the axle into torsional vibrations which in turn perpetuate the stick-slip cycles, causing corrugation to increase.

The assumption of equal effective rolling radius on high and low rail sides does not hold, because, for a conical wheel tread in a flanging configuration, the wheel on the high side travels on a larger wheel radius. The stick-slip theory is, however, still valid if a torque of significant magnitude exists on the axle.

Various studies into the curving behavior of three-piece freight trucks have shown that large creep forces exist between wheel and rail interfaces, and that for a given wheelset, especially the leading one, the creep force orientation is such that a large torque is applied to the axle (3-5). Figure 1 shows an example of a force diagram for a leading wheelset as predicted by a steady-state, truck-curving computer model (6). The magnitude of torque on the axle is about 22,000 lb/ft in a 3-degree curve. Apart from the existence of a sufficiently large torque, the occurrence of stick-slip further requires that wheel and rail friction have a falling characteristic at high creepage and that the wheel and rail creepage condition be severe enough to give an operating point in the falling portion.

FIGURE 1 An example of force diagram for the leading wheelset in a curve.

Figure 2 shows some sample friction-creepage curves for various wheel and rail contact conditions. It is evident that a falling characteristic due to creep saturation occurs at a few percent creepage for all cases except those with water and oil contamination. However, most experimental results for the lower range of creepage, such as those in Figure 3, show a somewhat different characteristic. These indicate that creep saturation begins at about 1 percent creepage but show no falling characteristic up to 3 percent creepage.

FIGURE 2 Average friction-creep curve.

FIGURE 3 Comparison of the longitudinal traction/creep relationship of clean rollers and rollers wet with water.

Figure 4 shows the resultant creepage on low rail in a range of curves. These data are derived from computer simulation of the curving behavior of a three-piece freight truck with 35-ton axle load. Generally creepage increases with the degree of curvature and is about 1 percent in 8-degree curves.

FIGURE 4 Resultant creepage versus degree curve at balance speed.

mental work to verify the stick-slip theory. The results show that for a creepage condition greater than 1 percent, considerable vibration occurred, and in some cases a corrugation-like pattern appeared on the rail surface.

PLASTIC DEFORMATION

Stick-slip vibration may create periodic variation in the tangential force component at wheel and rail
contact. However, for this force to generate periodic plastic deformation as observed in typical North American corrugated rails, the force magnitude must exceed the elastic limit of the rail steel. Thus, it is necessary to know the magnitude and nature of the wheel-loading environment at the wheel and rail interface, as well as the resistance of the rail steel to plastic deformation under actual track operations. A sample calculation that illustrates the magnitude of the wheel-loading environment relative to the strength of the rail steel follows. For a 100-ton car with 36-in. diameter wheels, running at slightly under balance speed (1 in. over-super-elevation) in a 3-degree curve, the wheel loading on the low rail is:

1. Vertical:
   - Static wheel load: 32,000 lb
   - Vertical load transfer: 3,200 lb
   - Steady-state wheel load: 35,200 lb
   - Dynamic load factor (assumed): 10%
   - Dynamic wheel load: 38,720 lb

2. Compressive contact stress:
   - Average wheel and new rail (tread is slightly hollow with a concave radius of 30 in.)
     - 195,000 psi
   - New wheel and new rail (tread is 1 in)
     - 227,100 psi
   - Worn wheel and new rail (tread is hollow with false flange radius of 4 in.)
     - 430,400 psi

Both standard carbon and low-chrome alloy rails are used in North America. Carbon rails are used mainly in tangent track and shallow curves (e.g., less than 3 degrees). Low chrome rails are used in sharper curves as a measure against the more severe wheel-load environment. Yield strengths of standard carbon and chrome rails are about 75,000 psi and 90,000 psi, respectively. Even after taking into account a constraint factor of 1.7, these yield strengths are much lower than the estimated range of contact stresses (195,000 to 430,000 psi). Therefore, plastic deformation of rail would occur under the first wheel passage. For subsequent wheel passages, the residual stress created under earlier wheel passes improves the resistance of the rail steel to further plastic deformation. This phenomenon, called shakedown, has been the subject of intensive research in the field of contact mechanics. Johnson (8), in a recent comprehensive review of this subject, proposed an estimate for the elastic and shakedown limits applicable to rail steel in rolling contact as shown in Figure 5. According to this estimation, the shakedown limit for standard carbon and chrome rails, in the absence of tangential force, is 202,000 psi and 270,000 psi, respectively. However, if a tangential force of 0.275 times the vertical is also present, these shakedown limits are reduced to about 120,000 psi and 160,000 psi for standard carbon and chrome rails, respectively.

These estimates indicate that:

1. Standard carbon rails would be plastically deformed under the passage of most wheels, and
2. Chrome rails would be plastically deformed under the passage of new and worn (i.e., with false flange) wheels. For average wheels, the likelihood of plastic deformation is less than certain, because the shakedown limit under 0.275 creepage is only slightly below the contact stress.

For a track carrying 50 mgt of 32-ton axle loads per year, and assuming a wheel condition distribution of 15 percent new, 75 percent average, and 10 percent worn, the plastic deformation cycle for standard carbon rail and chrome rail would be about 1,500,000 and 300,000 times a year, respectively. Thus, curved track is generally too hostile an environment for the standard carbon and low allow rail steels currently in common use. These rails would likely corrugate in the presence of vibration.

**PRACTICAL SOLUTION**

The preceding discussion indicates that low rails in curves are subject to such a severe loading environment that unless hardened rails are used, there is potential for widespread corrugation. High wheel loads (due to heavy cars) and creepage (due to poor curving of three-piece trucks) place the present rail steel on the threshold of plastic deformation. With wheel and rail contact being steel on steel (low damping), and with limited adhesion (stick-slip), there is potential for vibration. Uniformly spaced tie support could add to the vibration problem as well. Knowing that these two factors, that is, plastic deformation and contact vibration, are essential in the development of corrugation, the solution obviously is to eliminate or reduce their severity. To achieve this goal when there is no option of replacing existing trucks with ones of steerable design, or replacing existing track with a continuously supported structure, or reducing axle load, the author believes the following remedial actions could be taken:

1. **Profile grinding.** At present, rail is ground periodically to remove corrugation. This grinding operation can be adapted to produce an optimal rail profile as well, without additional cost. The objective is to create a rail profile that conforms to existing wheel profiles, given the existing range of track gauge error. On the low rail, the primary aim is to ensure that the wheel and rail contact takes place away from the false flange should the wheel be worn and the track gauge widen. If this is achieved, a potential contact stress of 430,000 psi under worn wheels can be reduced to 195,000 psi, making the low...
rail less susceptible to plastic deformation. This technique will be described in the case study.

2. Grinding of new rail. The surface of new rail normally is not smooth. Apart from mill scales, there are irregularities with wavelengths from a few inches to several feet. An example is shown in Figure 6. This roughness can excite wheel and rail vibration at a time when the rail steel has not yet hardened to its potential. Early removal of surface roughness would reduce the initial plastic deformation and produce a smoother hardened rail surface at a later stage.

3. Superelevation. Track should be elevated at balance or at a slightly deficient level to avoid wheel load transfer to low rails. In a mixed-traffic situation, superelevation should be designed to accommodate the heavier traffic categories.

4. Heat-treated rail. Heat-treated rails such as the head-hardened type could be used to improve rail resistance to plastic deformation. With a yield strength (2 percent proof stress) of about 125,000 psi, they would be able to resist plastic deformation under most wheel loads except the false flange type. When used with a profile grinding program, which is effective in avoiding false flange contact, heat-treated rails would provide satisfactory resistance against plastic deformation, and hence rail corrugation.

5. Rail lubrication. The standard practice of lubricating the gauge face of the high rail effectively transfers some of the creepage from low rail to high rail. Figure 7 is a three-piece truck curving simulation result showing the reduction of longitudinal creepage and creep force on the low rail as the friction factor on the high rail gauge face decreases. This has the dual effects of reducing the likelihood of wheel slip and increasing the shake-down limit of the low rail. Daniels and Blume (9) reported a correlation study at FAST in which rail corrugation growth was much lower during the periods without lubrication (Figure 8). Because trackside lubricators are already being used on most railways, a field trial to validate this effect could be carried out quite readily.

There are also other measures that may be less readily achievable but are nonetheless feasible:

1. Wheel remachining. More frequent wheel inspection and remachining would reduce the percentage of defective wheels such as those with false flange or flat spots. If this action is coordinated with a program of profile grinding and the use of heat-treated rail, the problem of rail corrugation would be greatly reduced. For several years the Hamersley Iron and Mount Newman Mining Railways in Australia (33-ton axle loads) have been experiencing minimum rail corrugation problems using the preceding strategy.
2. Track gauge control. The biggest problem with timber track, as far as corrugation is concerned, is gauge widening, which causes false flange contact on low rails. The use of concrete ties solves this problem but introduces high dynamic loads because of large tie mass and stiff rail pad. For timber track, a practical solution could be to insert one steel tie, for example, every five tie spacings. The spacing, however, should not be uniform (i.e., not always one every five ties) as this may introduce a periodic stiffness variation. Gauge rod is another, perhaps less practical, option.

CASE STUDY: PROFILE GRINDING TEST ON CP RAIL - 1982 (10)

Outline

In May and June 1982, a rail profile grinding test was conducted on a section of curved track on the Canadian Pacific (CP) main line through the Rocky Mountains. The first objective was to reduce the problem of corrugation on low rails in curves. For this, two curves were selected: an 8-degree curve with severe corrugation (average depth 0.0595 in.) (1.44 mm) on the low rail (chrome), and a 2-degree curve with typical corrugation (average depth 0.0335 in.) (0.84 mm) on the low rail (standard carbon). Measurements of rail vibration under a 30-mph test train (three locomotives, five 100-ton cars) are shown in Figure 9. These indicate the severity of the problem, especially in the 8-degree curve.

Investigation

Track gauges and wheel profiles were surveyed in order to design a suitable rail profile to redress the problem of corrugation on low rails in curves. This survey revealed that in curves where rail corrugation occurs, the static track gauge is typically 0.25 in. wider than usual. Under traffic, there will be up to 0.25 in. of additional gauge widening due to lateral wheel forces (typical magnitude of 4 to 12 kips outward on both high and low rails). The survey of wheel profiles showed that there was a large percentage of wheels with about 0.25 in. flange wear, and a small but significant percentage of wheels having false flange (i.e., reversed tread radius on the field side). The combined effect of gauge widening and wheel wear creates an effective total gauge widening under wheel passage of about 0.50 to 0.75 in. (0.25 in. flange wear + 0.25 in. gauge face wear + up to 0.25 in. dynamic gauge widening). This led to a kind of false flange contact problem, as shown in Figure 10.

Design of the Ground Rail Profile

The preceding investigation led to the conclusion that false flange contact is a primary contributing factor to the problem of corrugation on low rails. To avoid false flange contact (without resorting to the remachining of worn wheels and the prevention of track gauge widening), the field side of the low rail must be ground down so that wheel and rail contact takes place only on the gauge side. Figure 11 shows diagrammatically what must be done. In reality, grinding of the field side had to be reduced because of the high cost of grinding and short track time. A cost-effective grinding program is one that

![Graph showing rail corrugation growth by lubrication condition: standard carbon rail, 5 degree curve, hardwood ties.](image1.png)

![Graph showing measurements of rail vibration.](image2.png)

![Diagram of wheel and rail contact geometry in curves with wide gauge.](image3.png)

![Diagram of proposed ground rail profile for curves on CP Rail.](image4.png)
removes only sufficient rail metal to avoid wheel and rail contact in the false flange area between grinding sessions. At the time of the next session, this grinding can be repeated, hence excessive grinding is not necessary each time.

Test Results

Corrugation regrowth was measured periodically after the test grinding. Figure 12 shows the corrugation levels in the 2-degree test curve 1 year after the test grinding. The rail had been subjected to a total of two profile grinding sessions. The open bars represent corrugation levels existing about 6 months (about 25 mgt) after conventional (symmetrical) grinding. The full bars represent corrugation levels 6 months after profile grinding. Except at 4 locations where minor increases occurred, the remaining 26 locations showed a significant reduction in rail corrugation levels.

Further Work

Following the previously described test, CP Rail adopted the designed profile rail as a provisional standard for the main line. A more comprehensive field test involving 12 curves is being carried out. The objective of this test is to further examine the performance of the designed rail profile and to explore its refinement.

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