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# Review of Rail Research on British Rail

C. O. Frederick and E. G. Jones

**The rail research program of British Railways, which is aimed at understanding and reducing the severity of various mechanisms of rail failure, is described. An important part of the work is the measurement and prediction of rail stresses and the study of force-free temperature for continuous welded rail. To reduce failure problems, it is necessary to develop laboratory-based techniques to assess the performance of rail steels and welds. This requires a knowledge of the dynamic and static stress environment of the rails and computer programs to calculate these stresses. The study of failures includes the study of Thermit and flash-butt weld failures, tache ovale defects, star cracks at bolt holes, and squat defects. It has been found that the majority of Thermit weld failures can be attributed to poor welding practice. Flash-butt weld failures are much less frequent but may become more of a problem as the more wear-resistant rail steels are introduced into welded track. The need to develop better steels for switch and crossing work has provided an impetus to develop a weldable austenitic manganese steel and also bainitic steels of high strength and toughness. These developments are reviewed.**

Rail research should reflect the future objectives and problems of the railways concerned. British Railways (BR) is a high-speed railway, and this has tended to cause rather special problems. In addition, the move to continuously welded rail (CWR), while solving some problems, has created new ones—all of which has provided the impetus for research.

The thermal stresses in long, welded rails are, of course, invisible and are commonly overlooked; nevertheless, they are large and very significant in controlling the modes of failure. In designing a railway with CWR, it is always necessary to choose the force-free temperature with care. Too high a force-free temperature will assist the rapid growth of transverse fatigue cracks and brittle fracture of the rail in winter, whereas too low a force-free temperature will create a buckling problem in the hot weather of summer. After a spate of buckling incidents in 1969, BR raised the force-free rail temperature by 5.5°C to improve track stability. Subsequently, an investigation was conducted into the factors that affect track buckling with a view toward improving track design. The rise in force-free rail temperature may explain why there has been an increase in transverse rail defects in recent years. There have, however, been other problems, two of which are closely associated with high-speed lines: squats and short pitch corrugations.

The current maximum strict axle load on BR is 250 kN. This is higher than on most European railways and lower than U.S. values, which can exceed 298 kN. Rail-crushing and side-wear problems are much less severe in the United Kingdom than in the United States. Nevertheless, rail side wear still limits rail life on curves. For large-radius, high-speed curves, where use of the correct transverse rail profile is important to good riding, it has been necessary to prohibit the practice of transposing side-worn rails. Thus, there are incentives to use more wear-resistant rail. The standard BR rail steel [710-MPa ultimate tensile strength (UTS)] is somewhat less wear resistant than the standard U.S. compositions. However, BR is using an increasing quantity of wear-resistant Union Internationale des Chemins de Fer (UIC) grades (880-MPa UTS) and 1 percent chromium rails (1080-MPa UTS) in sharply curved situations. These rail steels bring with them some welding problems and slightly less toughness. There is a need for simultaneous improvements in wear resistance, toughness, and weldability.

The BR rail research program has sought to establish an understanding of and to lessen the existing problems and also to look to the future to see what might be achieved by new rail steels. This paper is an account of some of the main lines of investigation.

## FORCE-FREE RAIL TEMPERATURE

### Track Buckling

The force-free rail temperature is defined as the rail temperature at which long welded rail experiences zero resultant longitudinal force. This temperature is determined by the procedures used to install the welded rail. In deciding this temperature, it is desirable to have an understanding of track-buckling behavior. Some early experiments in track buckling were done in Mousehole Tunnel between 1956 and 1959 (1). At first, the buckling theories could only account for the behavior of an infinite sinusoidal irregularity in straight track (2). More recently, a more advanced theory has been developed that allows for an individual irregularity on straight and curved track (3). This is an important advance because it shows for the first time the importance of the longitudinal restraint between the rails and the sleepers. If this restraint is large, it helps to prevent feeding of rail compression into the buckling zone as a misalignment develops. The new theory also shows that there is a fairly clearly defined value of the maximum rise in rail temperature at which thermal buckling will not occur despite the presence of misalignments. This "safe" maximum increase in rail temperature is shown in Figure 1, where it can be seen that, in the curve for temperature increase versus deflection, there is first a peak followed by a trough. The height of the peak is very sensitive to misalignments, but the height of the trough is insensitive to these and provides a better design limit.

The calculated variation in the safe temperature increase with lateral and longitudinal resistance for standard BR track components is shown in Figure 2. Buckling experiments have recently been under way at Old Dalby to check these predictions. The value at which buckling took place was always above the calculated safe temperature increase and was sensitive to rail straightness. After the first experiment, the rail developed a permanent lateral set. Even when the track and rails were laid apparently straight, the built-in set in the rail strongly influenced the buckling behavior.

### Rolling Out

There have been many observations of BR in-service rails experiencing a general drop in force-free rail temperature, a phenomenon referred to as "rolling out". This should be distinguished from changes in the distribution of force-free temperature along the track, which is caused by creep of the rail along the track associated with movement through the fastenings or movement of the sleepers in the ballast. The rolling-out effect is caused by the rails becoming longer. The magnitude of this effect has been measured by taking out 240-m lengths of rail, measuring their length, and then replacing them. Reductions in force-free temperature of approximately 6°C in a year have been measured for new rails. It is thought that this effect will stabilize and considerably lessen over the years. Nevertheless, it means that a higher initial rail tension is required to prevent track buckling (1°C is equivalent to 1.7 Mg for 56-kg/m rail).

## RAIL STRESSES

### Wheel-Rail Contact

It is fitting to start an investigation of rail behavior by considering the stress environment of the rail steel. Clearly, the highest stresses come from wheel-rail contact force. These stresses, however, are very dependent on the precise profiles of wheel and rail. Iterative computer programs have been written to calculate the shape of the contact area for different wheel-rail-profile contact arrangements. Contact at the gauge corner will tend to produce an elliptical contact patch that is long and thin, whereas contact of worn wheel and rail near the rail center line tends to produce a wide and short contact patch. These programs must be iterative, since the dimensions of the contact patch depend on the out-of-plane surface deflections. It is customary to assume elastic material behavior and to assume that the surface deflections are those of a semi-infinite half-plane. The latter assumption is somewhat dubious for gauge-corner contact. Since it is well known that rails plastically deform, it may be thought that the assumption of elastic behavior is also dubious. However, the plastic deformation of rails is something that occurs slowly

Figure 1. Typical buckling response.

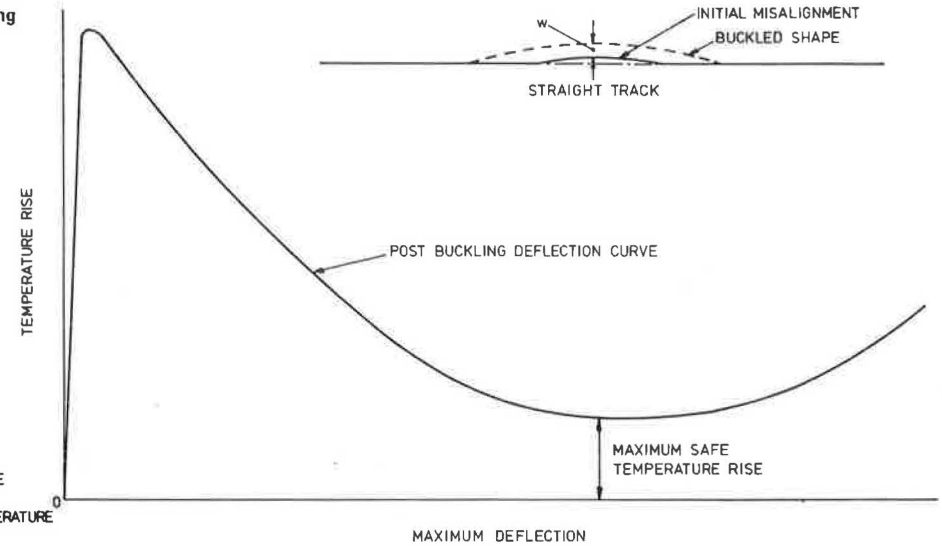
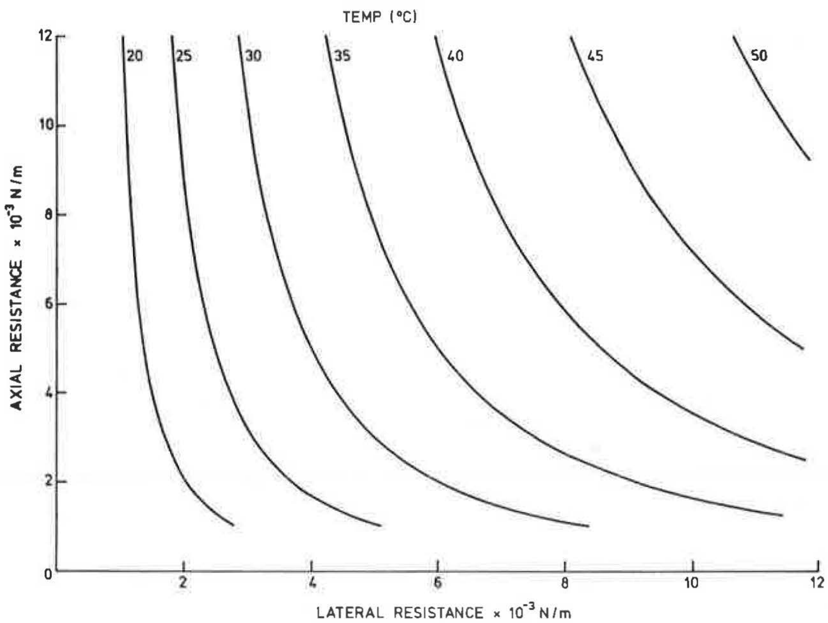



Figure 2. Maximum safe temperature rise for standard BR components.




under many thousands of cycles, and the plastic deformation that occurs under one cycle is almost certainly negligible compared with the elastic strains.

Calculations of the Hertzian stresses caused by wheel-rail contact do not usually allow for flexure of the rail as a beam, nor do they allow for phenomena such as bending of the railhead as a beam supported by the rail web. To investigate these effects, it is usually necessary to resort to finite-element analyses of some sort. These analyses allow the true shape of the rail to be included but make crude assumptions for stresses and strains that occur in the immediate contact zone. When conventional three-dimensional finite elements are used, the computation rapidly becomes very large because of the large number of unknowns. The Research and Development Division of the British Railways Board has found the most promising analysis method to be one that combines finite elements and Fourier techniques (4). This analysis divides the rail up into longitudinal prisms of quadrilateral cross section. Although the loading must itself be expressed in Fourier harmonics along the rail, a good representation of a localized load is possible. This program has been used successfully to analyze the effect of off-center vertical loads on strains in the rail web (see Figure 3).

In the past, lateral forces have been measured for experimental purposes by measuring the bending of the rail web at two positions that are vertically one above the other. This arrangement is, however, affected by off-center vertical loads (5), and this can be demonstrated by using the computer program. In the future, it should be possible to design improved load-measuring systems by using an array of gauges and a small on-line computer.

## Dynamic Load Variations

In calculating stresses in rails, it is usually necessary to consider dynamic wheel loads. Dynamic variations in load are especially important at high speeds or when the wheels have formed flats. There are very few data on wheel and rail roughness, but it is clear from calcu-

Figure 3. Calculated rail stresses for off-center vertical load: vertical stresses on the rail web.

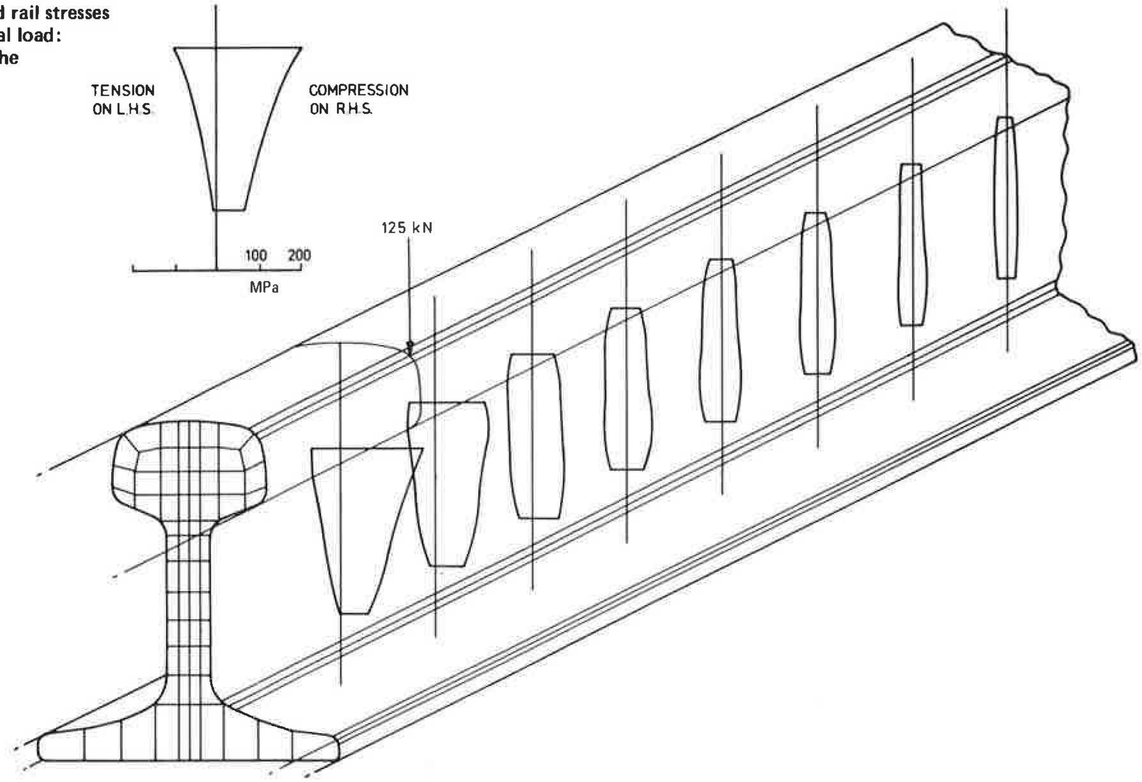
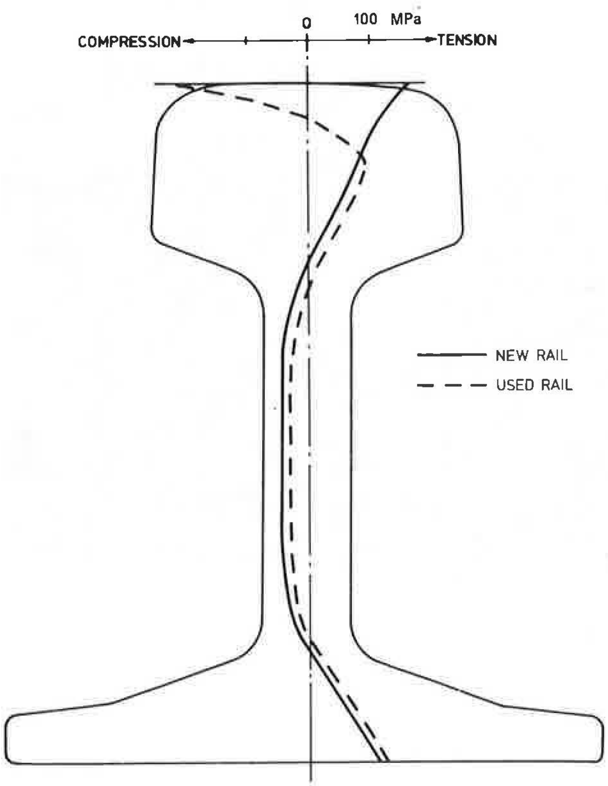



Figure 4. Longitudinal residual stresses in new and used rail on rail centerline.




lations that contact forces can vary substantially with very small levels of roughness (6). These variations are so large because the wheel-rail contact spring is so stiff and because the rail inertia is significant at high frequencies of oscillation. When longitudinal profiles have been measured by using an inertial trolley, it has been found that rail roughness usually decreases under the influence of traffic unless some phenomenon such as corrugation is at work. It is worth noting that, at high speeds, wheel-rail contact forces can be expected to increase if rail weight is increased; thus, mechanisms of rail surface damage are likely to get worse with heavier rails.

## Tensile Stresses in Railhead

In considering rail fracture, it is especially important to consider the extreme values of tensile stress in the railhead, since failures rarely initiate in the rail foot (the exceptions in the United Kingdom being defective welds or cracking from corrosion pitting or chair gall). The highest tensile stresses are attributable to a combination of the effects of cold-weather contraction and wheel-flat impact. Thus, the tensile stresses caused by hogging of the rail at either side of the point of impact are more important than the stresses immediately under the point of impact. There has been a substantial program of research to study wheel-flat impact (7), and it has been found that the resultant hogging bending waves propagate very rapidly along the rail and lessen only slowly with distance. As a result, all of the rail will experience to some extent the hogging stresses caused by a wheel flat, although the maximum stresses occur where the quasistatic procession wave is combined with the dynamic effect.

The dynamic testing of rails reflects the importance of tensile stresses in the railhead and is described later in this paper.

## Residual Stresses

Recently, there has been an increased interest in residual stresses among BR researchers. It is well known that European rails show high residual tensile stresses

Figure 5. Computer algorithm for correction of an irregular weld.

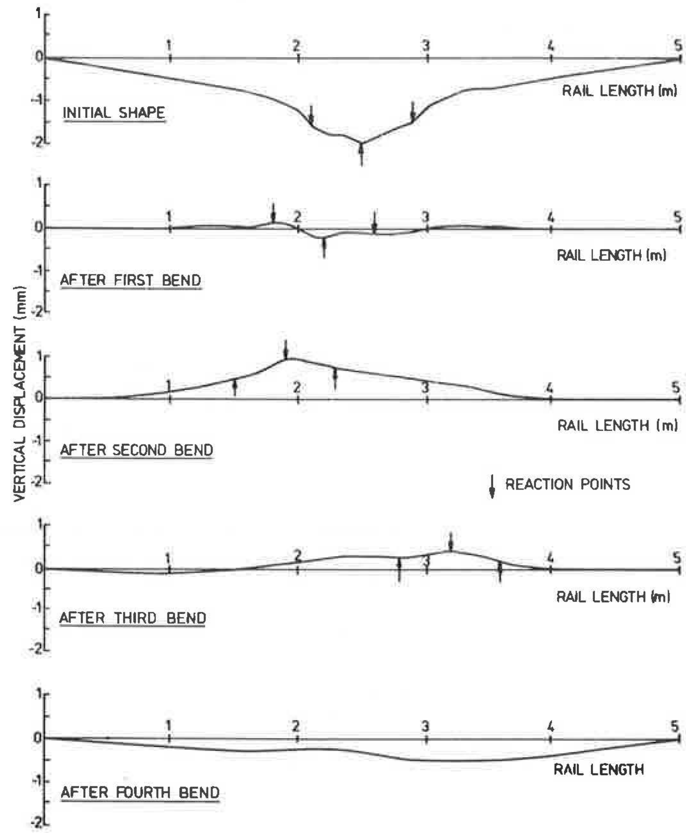



Table 1. Physical properties of rail steels.

| Material | Coefficient of Linear Expansion ($^\circ C^{-1} \times 10^6$) | Young's Modulus (GPa) -15°C | 20°C | 50°C |
|---|---|---|---|---|
| BS 11 normal quality | 11.25 | 216 | 213 | 211 |
| UIC grade B | 11.4 | 211 | 208 | 206 |
| 1 percent chromium | 11.8 | 216 | 213 | 212 |
| Cast LCAMS | 17.0 | 181 | 180 | 178 |
| Rolled LCAMS | 17.1 | 201 | 200 | 197 |
| Bainitic[a] | 11.6 | 211 | 209 | 207 |

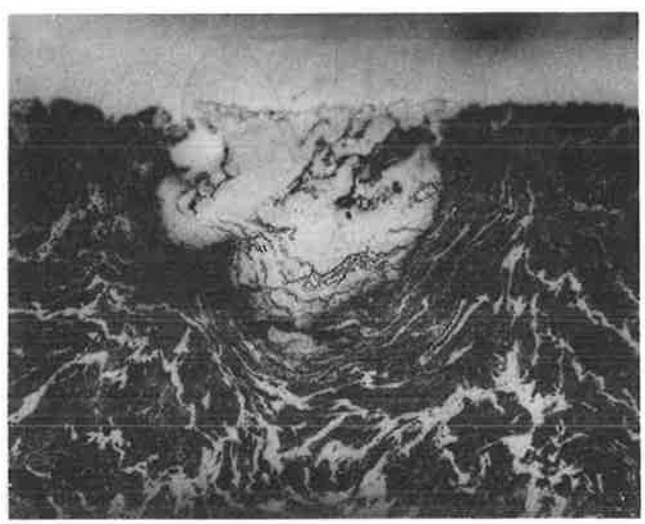
[a]Composition (percentage by weight) = 0.16 carbon, 0.19 silicon, 1.01 manganese, 0.23 sulfur, 0.025 phosphorus, 1.40 chromium, and 0.53 molybdenum.

in the railhead after manufacture and that these stresses are modified by traffic loads (8) so that the longitudinal residual stresses near the running surface are converted from tensile to compressive stresses (see Figure 4). According to German researchers (9), the original residual tensile stresses are caused by the roller straightening process. These residual stresses in the railhead are undesirable because (a) they must increase the magnitude of the rolling-out process and (b) they will probably increase the tendency of cracks to propagate downward across the rail section rather than parallel to the rail surface.

Alternative systems of rail straightening are being examined, and the possibility of a computer-controlled gag press is being considered. Such a device would require a preliminary measurement of longitudinal rail profiles (vertical or lateral) followed by a traverse of one or more automatically controlled presses that obey pressing instructions worked out according to a computer algorithm. Such a system would not produce large residual tensile stresses in the head of the rail.

Work is proceeding to identify suitable computer algorithms. Figure 5 shows the effect of one computer algorithm in correcting an irregular vertical weld profile.

Figure 6. White phase embedded in rail running surface.



## Physical Properties

Thermal stresses in CWR are, of course, dependent on the temperature change from the force-free condition, but they are also dependent on the product of Young's modulus and the coefficient of expansion. There are slight differences (±5 percent) in the values used in different countries for the coefficients of expansion of pearlitic rail steels. These differences could be very significant when it comes to selecting a rail steel. We decided, therefore, to obtain some reliable comparative data. The results, which are given in Table 1, seem to show that any variations between pearlitic and bainitic steels are unimportant, although these two steels are very different from austenitic steels.

## LIMITS ON RAIL LIFE

### Sleeper Condition

The bulk of rails withdrawn from BR service are withdrawn as a consequence of the normal track relaying pattern. The commonest determinant of relaying priority is poor sleeper condition, since there are still many lines with timber sleepers. It has been found that rails removed from straight or slightly curved track for this reason are no longer suitable for use in high-speed lines because of rail-end batter, corrosion, galling of the rail seating area, or localized loss of railhead profile. Nevertheless, the 710-MPa UTS rail steel in current use performs adequately with long-lived sleepers and gives a life of more than 20 years in most lines. More sharply curved track, however, presents a very different picture, and the life of 710-MPa UTS rail can be much less than 2 years. This has led to some use of 900-MPa UTS rail steels. The use of these steels is currently restricted by welding problems and to some extent by availability. Chromium rail steel with 1080-MPa UTS has so far been used on a very restricted experimental basis.

### Corrugation

Corrugatory wear on both straight and curved track leads to a shortening of service life and, although its appearance has been reported since the 19th century, the causes are still not understood. The incidence of this phenomenon on BR is increasing, and at present the only remedy is periodic grinding, which obviously will lead to a shortening of rail life. The effect of corrugations on general track deterioration is slowly emerging and is giving cause for concern.

The loosening of iron shoulders cast into concrete sleepers has been observed where rails are severely corrugated, and it is also thought that the corrugations may shorten the fatigue life of the rail. The steel at the crests of corrugations is often severely deformed plastically, and small cracks have been observed that follow the same direction as the plastically deformed grain boundaries. In a joint exercise with Speno International SA to study the effectiveness of rail grinding, it was found that ground rails subsequently developed squat defects, which may well have initiated from cracks that were not completely removed in grinding (10).

Corrugations on high-speed lines usually exhibit patches of "white phase" on the crests. This is very similar in appearance to martensite and is very hard. The possibility that corrugations worsen because of differential rates of wear or corrosion is currently being examined. In this context, the presence of white phase could be important, since it is frequently observed on BR rails. White phase could also play a role in surface-initiated fatigue mechanisms since, as Figure 6 shows, hard pieces of white phase can become embedded in the surface and cause severe plastic deformation (11). These investigations are still exploratory, and the importance of white phase in surface damage mechanisms has still to be ascertained.

### Rail Fracture

Sometimes rail fracture causes premature withdrawal of rails from service. In a passenger-carrying system, safety is of the greatest concern, and so some forms of fracture are regarded as more serious than others. The most dangerous forms are those in which a piece of the running surface is removed. In general, a single transverse fracture in CWR is not so dangerous and is usually detected promptly by its effect on track circuits.

In plain track, the following fracture types are of prime interest:

1. Squat fractures—surface defects initiated by rolling-contact fatigue that propagate at a shallow angle and then turn down to form transverse fractures (see Figure 7);
2. Tache ovales—in the United Kingdom, hydrogen-flake-initiated fatigue fractures in the center of the railhead;
3. Star cracks—fatigue-initiated cracks that start in the bore of fish bolt holes;
4. Wheel burns—isolated depressions in the running surface of the rail that lead to (a) high dynamic stresses and subsequent fatigue cracking or (b) continuous transformation of the running surface of the rail, causing hardened microstructures with subsequent fatigue or brittle fracture; and
5. Weld fractures—Thermit weld failures, which generally initiate from a lack-of-fusion defect, and flash-butt failures, which initiate from "flat spots" (entrapped oxide plates on the weld center line).

In all of these fracture types, final fracture is always by brittle cleavage and causes either a complete transverse fracture through the rail or detachment of a portion of the railhead. A star-crack fracture often removes part of the running surface. Tache ovales and wheel burns are particularly dangerous when they initiate at multiple sites at short intervals along the rail.

## TESTING OF RAIL STEELS

As demonstrated above, the service life of rail is reduced by wear, rolling-contact fatigue, fatigue, and brittle fracture. To improve service performance, it first becomes necessary to understand how these mechanisms are induced and how rail steels respond.

The assessment techniques used by BR in the evaluation of rail steels have been described in detail elsewhere (12). The basic approach adopted has been to quantify the environment that the rail is subjected to and then use the data so obtained to define a suitable laboratory test. This allows quicker and cheaper evaluation of possible improved materials. This approach also lends itself to gaining an understanding of how the metallurgical structures of rail steels are affected by the various detrimental environmental mechanisms and leads to a materials design concept.

### Laboratory Assessment of Fatigue Life

The occurrence of the squat type of defect in BR track has required the development of laboratory assessment methods for failure under rolling-contact fatigue. Preliminary work to date has been carried out on Amsler twin-disc-type machines and small-diameter specimens. Initial experiments indicated that a liquid contaminant (water in this case) was necessary to induce failures. The work to date has been concerned with studying the effect of different creepages—i.e., the percentage of sliding between the two rollers—and contact stresses on the failure rates of a range of rail steels.

In the Amsler tests, it is customary to fix the load and creepage $\gamma$, thereby generating in the test certain levels of contact stress $\sigma_c$ and traction force T. For normal-grade BR rail steel (710 MPa), it was found that cycles to failure N depended approximately on the square of the contact stress. When the creep rate was varied with a range of steels, it was found that the shortest lives occurred at a creep rate of 0.3 percent for all steels. It is thought that this minimum is associated with zero traction at zero creep and, when creep is plotted against the parameter NT for a given contact stress, the minimum disappears. Figure 8 shows a plot of $NT\sigma_c^2$ versus creep for a range of steels. These results tend to indicate a relationship of the following form:

$$N = (1/T\sigma_c^2)\,f(\gamma) \qquad (1)$$

where the function f depends on the steel. Since the work is at an early stage, this result can only be viewed as provisional; it may be a function of the test machine and the limited variation in possible specimen geometries. Specimens of narrow width deform plastically at the loads used so that the original geometry and contact stress are lost. Work is continuing to determine the effect of geometry on contact stress and may lead to a requirement for a larger-scale test rig.

Figure 7. Longitudinal vertical section through a typical squat defect.

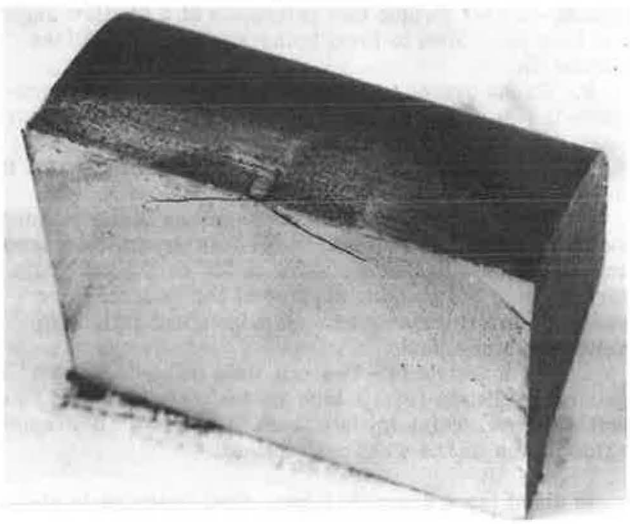
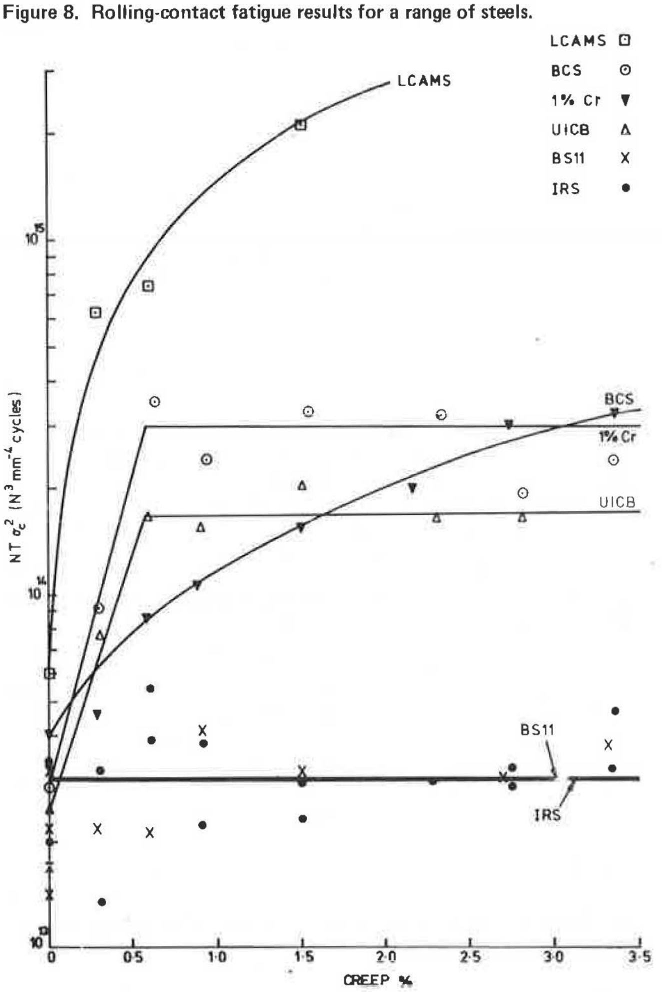


Figure 8. Rolling-contact fatigue results for a range of steels.




Research on rail wear has continued, but a change of direction has taken place. Previous work was aimed at producing semiquantitative relations between laboratory-generated wear data and service experience and attempting to relate wear performance over a wide range of test conditions to a single property parameter. More recent work has been aimed at relating wear to the conditions that exist in the wheel-rail contact zone. A nonlinear curving theory that predicts the forces, creep rates, and contact-zone sizes for a given set of conditions has been developed (13). Current work is aimed at developing an extension to this theory that will lead to wear-rate predictions. Several hypotheses that relate wear rate to traction force T, creep rate $\gamma$, and either the contact-zone width 2b or the contact-zone area are under investigation.

A series of laboratory tests performed by using a small-scale Amsler wear-testing machine and a range of creep conditions (1-10 percent) and contact stresses (500-1300 MPa) indicated that two regimes of wear were operating. These regimes were termed mild and severe and were characterized by the debris. Wear rates in the severe regime were found to be dependent on both contact stress and creep rate, whereas in the mild regime wear rate could be independent of creep rate. Correlations were then attempted between wear rates and expressions such as $(T\gamma^n/2b)$. In the mild-wear regime, where there was no interdependence on creep rate, no correlation was obtained. In the severe-wear regime, when combined wear rates (the total wear rate of both rollers) were considered, it was found that neither of the two parameters—$(T\gamma/2b)$ or $(T\gamma^2/2b)$—gave a satisfactory relationship. However, when the value of n = 1.5 was substituted, a better relationship was obtained (see Figure 9).

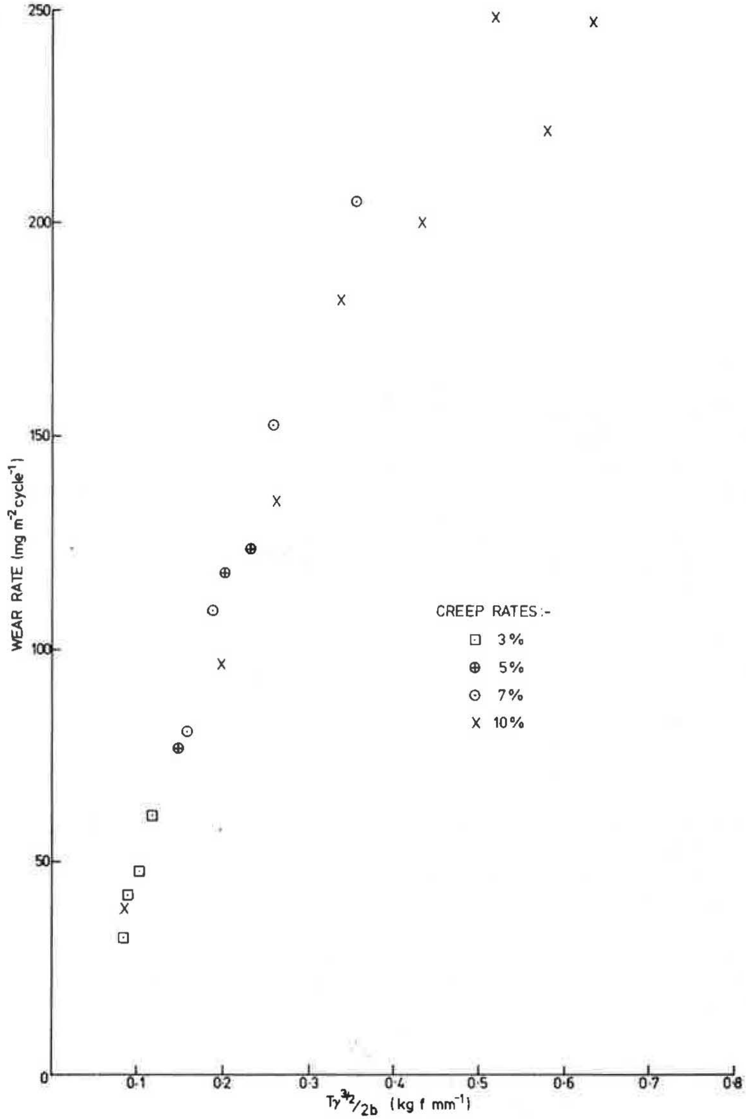
Currently, the effect of contact-zone geometries on wear for given contact stresses is unknown, and therefore the general validity of the wear parameters cannot be established. Further work will investigate this geometry effect and also explore whether the relations apply to other rail steels.

## Toughness of Rail Steels

The toughness of steels depends on ambient temperature and rate of load application and, to a large extent, the effects of these two parameters are interchangeable. The lowest toughness can be expected at the highest rate of loading and the lowest ambient temperature. It has been estimated that for BR these are 100 GPa/s and -15°C, although clearly there will be rare occasions when these values will be surpassed. The rate of load application corresponds to the impact of a wheel flat.

Most steels show a transition in toughness from a lower to an upper plateau as the temperature rises.

Figure 9. Wear rate versus ($T\gamma^{3/2}/2b$).




Most pearlitic rail steels, including the UIC grades and 1 percent chromium steel, are on the lower plateau at normal ambient temperatures and slow rates of loading so that the reductions in toughness caused by higher loading rates and lower temperatures are not very large, although they can be significant. When a new, tougher rail steel is produced, however, it is usually found to be in the transition region so that loading rate and temperature are significant. The fracture-tough rail steel developed jointly by BR and the British Steel Corporation is in this category (12).

The effective toughness of rails is affected by residual stresses and also by the size of the specimen. As a result, to measure toughness it is now the practice to test both small specimens and full-section rails. To generate the necessary high loading rates for full-sized specimens, a drop-weight test facility is used. Before testing, a notch and a fatigue crack are formed 6 mm deep across the head of the rail. The rail is tested in bending with the head in tension to simulate wheel-flat loading on a rail with a head defect. Strain gauges are used to identify the load at which the crack begins to run. The drop-weight test facility has also been used in the laboratory to simulate the dynamic loads caused by a wheel flat.

## WELDING OF RAILS

### Procedures

Considerable effort has been applied to improving the service performance of welds in rails (14). BR uses three basic weld procedures. Flash-butt and Thermit welding are used for producing butt joints, and build-up repair is being increasingly applied because of increases in the number of defects in the rail running surface and the rising cost of replacing rails. In this method, the defects are usually repaired by grinding and building up the surface with metal arc-welding deposit.

### Causes of Defects

Until comparatively recent times, the only rail steel used on BR in considerable quantity was the 710-MPa grade. In the two butt-welding processes this material presents few problems; failures are largely confined to Thermit welds. A survey of all Thermit weld failures carried out in 1971 and 1972 indicated that 80 percent of all failures were attributed to operator errors. These failures resulted from (a) lack of fusion, generally in the foot and lower web area (50 percent of all failures); (b) hot tears, usually in the head area (7 percent of all failures); and

Table 2. Composition of commercial rail steels.

| Grade | Minimum UTS (MPa) | Composition (percentage by weight) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Carbon | Silicon | Manganese | Sulfur | Phosphorus | Chromium |
| Normal-quality BS 11 | 710 | 0.45-0.60 | 0.05-0.35 | 0.95-1.25 | 0.050 max | 0.050 max | - |
| UIC grade A | 880 | 0.60-0.75 | 0.50 max | 0.80-1.30 | 0.050 max | 0.050 max | - |
| UIC grade B | 880 | 0.50-0.70 | 0.50 max | 1.30-1.70 | 0.050 max | 0.050 max | - |
| One percent chromium | 1080 | 0.68-0.78 | 0.35 max | 1.10-1.40 | 0.04 max | 0.03 max | 1.00-1.30 |

(c) porosity (6 percent of all failures).

Lack-of-fusion defects are considered to result from poor rail-end preparation, inadequate rail gap, use of oxidizing flame during preheating, and cold additions to the Thermit reaction. Hot tears emanate from premature release of rail tensors, or clamp slip on rail tensors, and porosity results from the use of damp or contaminated molds or luting sand. All of these can be attributed to operator deficiency. As a result of the investigation, a major change in the Thermit process was introduced on BR. From an aluminothermic quick-welding process referred to as the SmW process, which requires 6-7 min of preheating, BR went to a quick-welding process called the SkV process, which requires 1-2 min of preheating, thus reducing the operator dependency involved in preheating [these processes are derived from a German company and marketed by Thermit Welding (GB), Ltd.] The other aspects of operator deficiencies were covered by retraining and adequate supervision of welders in the field. The performance of the SkV weld is currently being evaluated by a further survey of weld failures. Supplies of Thermit consumables are rigidly inspected under a BR specification that ensures a regular supply of consistent consumables.

The failure rate of flash-butt welds is much lower than that of Thermit welds: 0.1/1000 compared to 1.0/1000 for 710-MPa steel. However, investigation of flash-butt-weld failures indicates that 80 percent can be attributed to welding machine and post-weld-treatment deficiencies (40 percent of failures result from incomplete fusion and 40 percent from postweld treatments such as weld trimming and arc spots). Some of the faults can be remedied by good housekeeping; incomplete-fusion defects, however, arise because of machine malfunction or incorrect machine settings that are either electrical or mechanical in action. This type of defect becomes more evident in the welding of higher-strength rail steel.

## Higher-Strength Steels

The non-heat-treated, higher-strength rail steels—UIC grades A and B and 1 percent chromium—rely on higher alloy content to develop the higher strength and wear resistance that are their desirable features. However, the higher alloy content also reduces the weldability of these steels, which may require special processes and procedures to produce satisfactory butt and repair welds. Table 2 gives the composition ranges of commercially available rail steels.

### UIC Grade A

UIC grade A steel relies on an increase in carbon content to raise its strength level to the 880-MPa minimum value specified, compared with the 710 MPa for normal-grade steel.

Flash welds made with the settings used for normal-grade steel gave good results. Metallographic sections of the heat-affected zones (HAZs) were fully pearlitic in microstructure, and the mechanical properties were satisfactory. Some flat spots—i.e., small oxidized areas that are the remains of arc craters—have been found on the weld line. These can initiate fatigue cracking and subsequent complete transverse fracture of the welds and must therefore be minimized by optimization of the machine controls.

Thermit welds were also found to be satisfactory with fully pearlitic HAZ microstructure and good mechanical properties. Samples put in track showed some "cupping" (local wear) in the weld zone, but this was attributable to the use of a Z80 Thermit portion—i.e., one with 795-MPa tensile strength—whereas a Z90 (880-MPa) strength would now be recommended as matching the rail steel properties.

### UIC Grade B

UIC grade B steel derives its extra strength from a 0.1 percent increase in carbon content and an increase of 0.45 percent in manganese content compared with the normal-grade steel. The manganese has a considerable effect on the transformation time, which has to be allowed for during welding. Segregation of manganese aggravates this problem and can lead to the formation of small bands of hard microstructures in HAZs.

In flash welding this steel, difficulties were encountered in optimizing the flash-welder control settings to (a) reduce the flat spots on the weld center line and (b) obtain consistent mechanical properties in commercial production. Flash welding in FB 113A section rail with the optimized machine settings gave cooling rates that were generally slow enough to avoid the formation of hard microstructural phases, although isolated cases of these phases were observed. To minimize the occurrence of flat spots and to maintain good mechanical properties, it was necessary to set machine controls to give (a) an adequate power to flash off the rail, (b) a low enough voltage to avoid deep craters, (c) a high acceleration to avoid oxidation, and (d) a correct flashing distance.

It was also found to be necessary to carry out the investigation on full 18-m-length rails since a considerable variation in results was obtained when welds were made with "shorts", apparently because of power losses through earth leakage. It was concluded that with adequate care and supervision satisfactory welds could be produced in this grade of steel with the current flash-welding machines but that future machines should incorporate feedback control systems.

For the Thermit welding of UIC grade B steel, it was necessary to ensure that a good sound weld with a matched weld metal and nonhardened HAZ was produced. The soundness of welds was attained by use of the SkV short-preheat Thermit process (15), and a Z90 (880-MPa tensile strength) portion was used to give a weld metal that matched the rail in tensile strength and wear resistance. Cooling rates of welds made in FB 113A section rail by using this process were measured at about 20°C/min between 800°C and 400°C. Considered in relation to the continuous cooling transformation diagram for this steel, this would appear to give adequate protection against undesirable hard phases in weld HAZs. However, since these cooling rates were determined under ideal laboratory conditions whereas in-service ambient rail temperatures could be much lower, the effect of muffle cooling was determined. An insulated muffle placed over the welded joint after weld trimming (completed 6 min after weld tapping) reduced the cooling rate from 20°C/min to about 10°C/min in the 800°C-400°C range. Welds produced by using this process and proportion and muffle cooling were free from defects and had good mechanical properties. Further work must be done on the effect of adverse weather conditions and the use of muffle cooling.

### One Percent Chromium Steel

The high tensile strength (1080 MPa) of 1 percent chromium steel is generated by the use of as much as 0.78 percent carbon and the addition of as much as 1.4 percent chromium; the alloy additions again had to be allowed for in welding such a steel.

Flash welding was carried out, and machine control settings similar to those used for UIC grade B steel were found to produce welds of good quality. However, the normal cooling rate for flash welds (46°C/min in FB 113A section) produce hardened microstructures in the weld HAZ. Several procedures for retarding the cooling rate were investigated. Direct postheating in the welding machine reduced the cooling rate; about 4 min of postheating was required to produce a satisfactory cooling rate. Muffle cooling was found to be inadequate, but a special flame heating rig in which the joint was heated for 5 min retarded the cooling rate to about 28°C/min. This last treatment gave fully pearlitic microstructures in the HAZs and gave the best and most satisfactory mechanical properties. This procedure reduces delay time in production by not occupying the welder as in direct postheating.

For the Thermit welding of this steel, the SkV short-preheat process is used, and a special high-strength portion has been developed by Thermit Welding (GB), Ltd., to produce matched weld properties. Metallographic examination and mechanical testing indicated that fully pearlitic HAZ microstructures were obtained. However, as with the UIC grade B steel, the recommended practice in service is to use muffle cooling to counter possible effects from adverse weather conditions.

### Repair Welding of Rails

Normal-quality rails that have isolated defects in the railhead are often repaired on BR by using the metal arc process, and codes of practice have been issued for the repair of defects such as isolated wheel burns and squats. Work is continuing to extend the procedures to cover the higher-strength rail steels and is aimed at determining preheat levels, the suitability of consumables, preparation geometry, welding techniques, and finishing methods.

Work is also being carried out to explore the use of semiautomatic processes for rail repair, and an evaluation of welding machines and consumables is currently under way. A longer-term objective in this area is the development of fully automatic machines for the repair of railhead defects.

## NEW DEVELOPMENTS IN RAIL STEELS

The higher-strength pearlitic steels discussed previously are likely to be sufficiently resistant to wear and fatigue to satisfy BR needs for plain line rails in the foreseeable future. However, the loading environment is more severe in switch and crossing work, and further improvements in rail steels are needed.

BR currently uses a range of crossing types. For the severest locations, cast austenitic manganese steel (AMS) crossings are used. For the less severe locations, the crossing types listed below are used:

1. Bolted AMS crossings (machined from FB 113A section AMS rails),
2. Bolted BS 11 normal-grade crossings (machined from FB 113A section rail), and
3. Semiwelded BS 11 normal-grade crossings (the vees are produced by electroslag welding FB 113A section rail, and wings are attached by bolting).

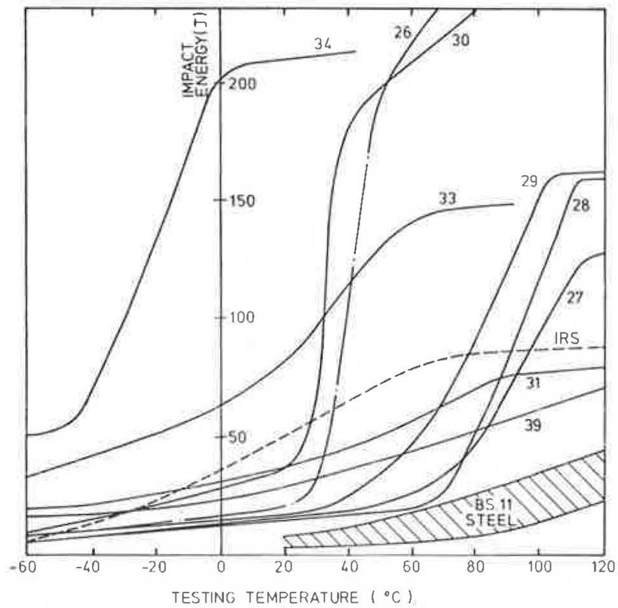
These various types of crossings generally perform adequately in service but have deficiencies of various kinds that could be overcome or minimized by material or fabrication changes. Cast AMS crossings are difficult to produce without casting defects, which lead to structural failure, and the alloy in current use is virtually unweldable. Furthermore, rolled AMS crossings are prone to fatigue cracking that results from the damage produced when the bolt holes are drilled. BS 11 normal-grade crossings deform quickly in heavy-traffic locations because of inadequacies in material strength. There is a need, therefore, for crossing materials that can be produced without defects and are weldable and of adequate strength. Two material developments have led to new fabrication procedures and modifications to existing fabrication procedures.

The problems of casting defects and poor weldability with AMS arise from the high coefficient of expansion and the thermal instability of the conventional Hadfield alloy. The coefficient of expansion of the alloy is much higher than that for the pearlitic rail steels; this, coupled with the narrow range of freezing and the long, narrow castings needed for crossings, results in gross shrinkage cavities and hot tears in the finished product.

The original Hadfield alloy has a carbon range of 1.1-1.4 percent and is used in the water-quenched condition. Subsequent heating above 300°C in welding processes results in carbide precipitation and severe embrittlement of the otherwise high-toughness alloy.

The testing of an experimental series of alloys of varying carbon and manganese levels (16) has shown that they are thermally stable—i.e., there is very little carbide precipitation and resultant embrittlement, providing the carbon level is below 0.9 percent. The decrease in tensile strength properties that results from this reduced carbon content can be offset by increasing the level of manganese. The work has indicated that good mechanical properties and thermal stability can be achieved within the composition ranges 0.7-0.8 percent carbon and 14-17 percent manganese. This composition is now referred to as low-carbon austenitic manganese steel (LCAMS). Commercial quantities of rails have been produced in this alloy, and flash and Thermit welding procedures and consumables have been developed for butt welding of rails in CWR. The high coefficient of expansion of this alloy still limits the use of long, welded rails to locations that have small variations in rail temperature, such as tunnels. However, in the manufacture of crossings, the improved weldability of the alloy lends itself to the production of (a) semiwelded crossing vees and (b) shorter-cast crossing centers with welded-on legs. The development work on semiwelded vees, which is being pursued jointly with Thomas Ward (Railway Engineers), Ltd., is nearing completion, and crossings that incorporate such vees will shortly be installed in track for service evaluation. The production of short-cast crossing centers will relieve the casting defect

Figure 10. Charpy impact curves for bainitic steels.




problem considerably, and welding techniques for the attachment of legs have been developed. Trial track installations will be made for service evaluation.

The remaining problem in the use of LCAMS is the need to weld it to pearlitic rail steels. The alloy contents of the two steels result in the formation of very brittle phases when fusion welding is attempted. Practical solutions are still being sought.

The limitations of LCAMS prompted a search for alternative materials with the desirable properties of LCAMS, such as high strength, impact resistance, and fracture toughness, but without the undesirable properties (the material would have an acceptable coefficient of expansion and could be welded to pearlitic rail steels). The work of Irvine and Pickering (17, p. 292) indicated that such properties could be obtained in the as-rolled condition by an air-cooled, low-carbon bainitic steel. These structures are achieved by the suppression of the ferrite-pearlite transformation, which is best achieved by additions of molybdenum and boron.

Although some data were available on the mechanical properties of some low-carbon molybdenum-boron steels, no systematic study of the effect of carbon, manganese, and chromium on mechanical properties had been carried out. These alloy additions depress the bainitic transformation temperature and thereby improve the tensile properties. An experimental molybdenum-boron alloy series with suitably varying levels of carbon, manganese, and chromium has been produced and tested (18). Tensile strengths as high as 1525 MPa have been achieved, and the fatigue limits were all higher than those of normal-grade steel. The Charpy impact curves were generally much higher than those for normal-grade steels and, in some cases, higher than those previously developed for fracture-tough rail steel (see Figure 10). Work is currently proceeding to evaluate the extent to which these properties can be maintained in commercial production.

## CONCLUSIONS

Although the main trend of rail research must be toward improved steels and a better choice of steels and operating practices, it is clear that many problems are still inadequately understood and as such difficult to quantify. It is clear that in the future greater priority must be given to understanding the wear and fatigue mechanisms that act at the surface of rails and how these mechanisms interact. Until this is done, the practicality of defining an optimum steel for a particular set of circumstances must be questionable.

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# Dilemma of Direct-Fixation Fastening Systems

W. R. Hamilton

**A short, nontechnical discussion of the shortcomings of present direct-fixation fastening systems is presented. The state of the art is reviewed, and some suggestions are made on corrective solutions to existing problems.**

The phenomenon of the modern railroad track is a mixture of ingenuity, experience, and long trial and error. From the early years of the rail bolted to the flat stone sleepers to the modern integrated structure, there has always been a delicate balance between the mechanical and track design improvements. The problem, however, has always been the same: how to keep the train on the track and provide a low-maintenance running surface. The balance between the track and the train was radically tipped by the dieselization of the railroads and the economics of the maintenance of way so that the track no longer could support the loading forces or provide longevity of running surfaces.

This problem will ultimately be solved as problems in the railroad industry have always been solved. Fortunately, the industry now recognizes the folly of deferred maintenance and acknowledges the track-train relationship as a total system that must be treated as a whole if all of its parts are to operate successfully.

Today, with aid from the federal government, there are literally hundreds of research programs being undertaken in the academic and scientific community. The interface between rail and wheel is being studied; ballast, subgrade, and tie performance is being analyzed; and rail metallurgy is at the moment extremely important. Research in all of these areas can add dramatically to our fund of knowledge and greatly assist in future development of the railroad system.

One area included in these studies, and in my opinion a most important one, is the interface between the tie and the rail, the rail-fastening system. It is not the intent of this paper to analyze mathematically or theoretically the performance of this area of the structure but merely to point out, in general terms, the effect of the fastening system on the performance of the total track structure.

In the broadest sense, the rail-fastening system can be defined as a device that can accurately position two rails with respect to each other and with respect to the earth below them. More specifically, rail-fastening systems are generally considered to concern the method used to affix the rails to the ties. Further, this device should have the capability to selectively absorb or transmit the various loads imposed on the track structure by the rail-wheel contact of passing trains. Without this capability, the remainder of the structure may be subjected to damaging forces that will require additional maintenance and perhaps shorten the life of the structure. However, without the input rail-wheel forces, the structure will also remain relatively inert. We may therefore assume that the fastening device will experience only those forces generated statically by thermal changes in the rail and dynamically by the wheel rolling over the rail.

If one conceptualizes in three dimensions a wheel moving along a rail, it can be seen that many forces are working in all three planes, the longitudinal, the vertical, and the lateral. There are three longitudinal forces. One is the static or thermal force, and the other two are dynamic and are caused by the wave action of the track and the drafting and braking forces of the train. The lateral force created by the wheel has now become a major concern in overturning rail and wheel climbing. The vertical forces are created in a downward direction by the wheel load and converted into an uplift force through the wave action of the track. Imposed on this is the vibration effect caused by the wheel on the rail. This effect has been much ignored because most vibration is short lived and of a greatly varying nature in terms of amplitude and frequency. It does, however, occur in the longitudinal, vertical, and lateral planes; in the lateral plane, it occurs more in curves than in tangent track.

Quantifying the various track loads is beyond the scope of this paper. Available data on the magnitude of longitudinal track loadings, for example, are highly variable. Each researcher has made measurements that he or she believes to be correct but that rarely agree with those made by fellow resarchers. In a