CHAPTER 3 RAILS

3.1 THE USE OF STEEL IN TRACK ENGINEERING

Rails, rail fastenings, base plates, distance blocks, the high tensile wire used to prestress concrete sleepers, sometimes even the sleepers themselves, are all made from one form or another of iron and steel. It may be said as with many other things which are commonplace in modern life that the railway could not exist without iron. The great variety of types of article produced from iron are only possible because of certain fundamental peculiarities in the way iron behaves when heated. These peculiarities also bring with them problems if iron or its derivatives are carelessly heated or cooled. To understand and appreciate the behaviour of steel rails and other parts made of iron and steel in relation to the processes used in the laying and maintenance of railway track, we need to understand the metallurgical behaviour of these materials and how they are produced.

3.2 THE PRODUCTION OF IRON

In the traditional method of smelting iron, iron ore (which is in principle iron oxide) is mixed with carbon (either coke or in early days charcoal), and a flux (usually limestone), and the mixture is heated in a blast furnace. The carbon/coke burns to produce carbon monoxide (CO) and heat. CO is a highly reducing gas which readily reduces the iron oxides to iron. The iron melts due to the high temperatures generated as the coke burns in the blast of hot air. Other impurities present are caught up by the flux to form a slag (which being less dense than iron floats on the surface). The slag also protects the iron from further re-oxidisation. The molten iron is tapped off at appropriate intervals. The pig iron which results after solidification will contain an appreciable quantity of carbon left over from the smelting process. As the iron cools and solidifies, what happens to this carbon which is mixed with it?

Before answering this question, we need to know a little about the behaviour of pure elemental iron when heated and cooled. Pure iron exists at room temperature in a crystalline form known as Alpha Iron. In that form it is only moderately hard and ductile, and it is also magnetic. When heated magnetism is lost at 769°C, and at 910°C the crystalline structure is transformed to a form known as Gamma Iron. The iron undergoes a volume change as a result of the rearrangement of the atoms in the crystals. It also becomes softer, and more ductile. The process is reversed if the iron is allowed to cool slowly to its original temperature.

As the liquid iron from the blast-furnace solidifies it takes up the gamma form, and in this form can take up to 1.7% carbon into solid solution to form austenite. The excess carbon can combine with iron to form the chemical compound cementite (Fe_3C). With carbon levels of 3% and above, and dependant on the cooling rate, free graphite will be precipitated from the solidifying liquid at the same time as the formation of austenite and cementite. On further cooling the austenite itself transforms to alpha iron (a low carbon content phase) called ferrite, and a lamellar phase called pearlite, which is made up of alternate laths of ferrite and cementite.

When final cooling has been achieved and dependant on cooling rates and other elements other present, particularly silicon, pig iron can have a structure of pearlite and graphite (grey iron) or, pearlite and cementite (white iron) or, pearlite, graphite, and cementite (mottled iron). Blast furnace pig iron is generally not suitable for the production of castings and further remelting and refining is required.

3.3 THE PRODUCTION OF STEEL

Steel is an alloy of the element iron with a very small percentage of carbon and elements such as manganese. Steel is made from pig iron by heating it once more until it is molten, and then blowing oxygen through the melt which combines with some of the carbon to reduce the proportion of this element in the alloy. To produce steel, the carbon content must be brought below the percentage at which free graphite will form in the austenitic phase (i.e., less than 3%).

With a carbon content as high as 2%, the steel consists of granules of cementite in a matrix of pearlite. As the carbon content decreases towards 0.8%, the proportion of free cementite in the alloy reduces until at 0.8% the steel if slowly cooled through the austenitic-pearlitic transformation, consists entirely of pearlite. Below this carbon content, the steel takes the form of a mixture of granules of ferrite, and granules of pearlite.

Since cementite is a compound which is both much harder and more brittle than ferrite, the hardness and brittleness of the resulting steel will be related to the proportion of cementite, and hence to the proportion of carbon. Steel with 1.3% carbon would be used to make something like a file or a razor. The wire used in the tendons of prestressed concrete sleepers would be made from steel with from 0.8 to 0.9% carbon, while rolled steel joists are made from steel containing only about 0.10-0.20% carbon.

Normal and wear resisting rail steels of Grades R220 and R260 contain 0.50% to 0.82% by weight of carbon. Hence the rail steels usually used are referred to as pearlitic steels, with a medium to high carbon content.

3.4 RAIL MANUFACTURE

Until the mid-1970s, after conversion from pig iron to steel, the steel was traditionally formed into an ingot, made by pouring the molten steel into a mould and allowing it to cool slowly. In producing a rail, the steel was then passed through two further processes. In the first, the ingot was reheated until white hot and then rolled out into a strip having a rectangular cross-section, and about three to four times as long as the original ingot. This strip was then cut into sections called blooms, which were either further processed immediately or allowed to cool for storage. The final process involved again heating the bloom to white heat and further rolling it through a series of specially shaped rollers to produce the final rail section. A bloom which started off around four metres long rolled out to at least around 36 metres of finished rail.

3.4.1 Modern Steelmaking Processes

Current steelmaking technology takes two short cuts. The first short cut is to convey the newly smelted iron directly from the blast furnace to the converter in liquid form instead of running it into moulds and allowing it to cool to the ambient temperature. The ladle in which this is done is a large and very heavy steel cylinder with a refractory lining, usually mounted on a railway truck. The weight of this so-called “Torpedo ladle” is such as to involve axle weights of 45 tonnes making such traffic (on the internal tracks of steelworks only) the heaviest rail borne freight in the UK. The main effect of this modernisation of technology is to eliminate the energy loss involved in cooling and reheating the raw iron. The second short cut is more significant from the track engineer’s point of view. It is to make blooms directly from the converted steel by means of the continuous casting process.

In the continuous casting process, molten steel is fed into a tundish with openings in the bottom leading to a corresponding number of rectangular tubes into which the molten steel flows. These tubes, in which the initial solidification of the outer skin of the steel takes place, define the ultimate cross-sectional shape of the bloom. The remainder of the process is concerned with the controlled cooling, straightening, and cutting of the blooms.

3.4.2 Continuous casting and elimination of piping defects

The continuous casting process saves both the energy required to reheat the ingot, and that required to roll the ingot into blooms. The importance of this process change rests also on the elimination of the possibility that a defect known as “Piping” will be present in the finished rail. Piping occurs because when liquid steel is poured into an ingot mould, cooling and solidification set in immediately. The parts of the ingot which cool quickest are the sides, which are in contact with the cold walls of the mould, and even more so, the free surface at the top of the mould which is in contact with the atmosphere. Quite quickly, a skin of solid steel starts to form on these surfaces, and as soon as that happens, the exterior form and dimensions of the ingot are determined. However, as the molten steel continues to cool, it shrinks. (When water freezes into ice, an expansion takes place (vide icebergs), but with steel, shrinkage continues through the solidification process.) Since the centre of the ingot cools and solidifies last, liquid steel is constantly being drawn towards the colder outward regions until at last the originally level top surface of the ingot is sucked inwards in a kind of solid vortex, and in the middle of this surface a narrow tube or pipe leads down into the upper part of the ingot. As a result of this phenomenon, the upper 10% or so of the ingot was always useless for rolling, and it was cut off and fed back into the stock of refined steel. Even so, sometimes the vortex extended further down the ingot than usual, and when this happened, it persisted through the bloom and rail rolling processes to finish as a very narrow pipe shaped void in the body of the rail. Continuous casting (concast) eliminated this type of defect completely.

3.4.3 The significance of the rolling process

Hot working by rolling ingot or concast blooms produces many benefits to the properties of steel. The grain structure is refined, the orientated cast structure is destroyed, the metal becomes more homogeneous, diffusion of segregated alloy additions is promoted, undesirable brittle films are broken up, cracks, blow holes and porosity (provided they are unoxidised) are welded up, and toughness and ductility are enhanced. Some directionability of properties is incurred, the better properties being along the rolling direction.

3.4.4 Other constituents of steel and hardness grades

According to EN 13674 (derived in part from the earlier BS 11), the commonly specified grades of rail steel will contain proportions by mass of elements other than iron as shown in Table 3.1. The three EN 13674 steel grades most commonly found in the UK rail network are Grade 220, 260 and 350HT. Since 2004, over 90% of new rail installed in the UK has been R260 grade, which is also the most widely used grade in continental Europe. A small proportion of UK installations are made in R350HT, HP335, and other premium wear resistant steels. Other than cast austenitic manganese steel crossings, virtually all new switches and crossings in the UK are produced from R260 rail.

In a steel grade designation, e.g., Grade 260, the number 260 refers to the hardness of steel. This is hardness measured using the Brinell Test. In this test, a tungsten carbide indenter is pressed into the surface of the test piece using an appropriate specified force. The diameter of the impression so produced is then measured and the Brinell Hardness Number, HBW, derived from:

$$HBW = 2P/\pi D(D - \sqrt{(D^2 - d^2)})$$

where load P is in kgf, indenter diameter D in mm, and impression diameter d in mm.

TABLE 3.1 Chemical Composition of Rail Steels

Grade	UK Rail Specification - % by weight in solid phase				
	Carbon	Silicon	Manganese	Phosphorous	Sulphur
220	0.48-0.62	0.18-0.62	0.95-1.30	0.030 max	0.030 max
260	0.60-0.82	0.13-0.60	0.65-1.25	0.030 max	0.030 max
350HT	0.70-0.82	0.13-0.60	0.65-1.25	0.025 max	0.030 max

Carbon has already been discussed.

Phosphorus and sulphur are present as impurities, mainly because they form a proportion of the naturally occurring ore from which iron is smelted, and it is difficult to eliminate them altogether in the smelting and refining process.

Silicon is also present in most steels, arising from the refractory materials used in lining blast furnaces and steel converters. Siliceous materials are also generally present in most ores of iron. Generally, silicon at controlled levels is beneficial to the properties of steel and is added deliberately to liquid steel prior to ingot or continuous casting to remove excess oxygen from the steel. This process is called “killing” the steel and is most essential.

The other common element used for ‘killing’ liquid steel is aluminium, however silicon is preferred for rail steel production, as oxides of silicon which solidify as inclusions in the solidified steel are less harmful than aluminium derivatives for subsequent service performance.

By contrast, sulphur is a highly damaging impurity. The reason for this is that at the high temperatures involved in steelmaking, sulphur combines chemically with the iron to form iron sulphide (FeS). This compound is soluble in molten steel, but it is virtually incapable of forming a solid solution with it. Consequently, as the molten steel solidifies, so the FeS is rejected from the solid part of the ingot and is ultimately deposited as a thin layer along the steel grain boundaries. Steel so impaired is virtually useless.

To prevent the formation of FeS, manganese (Mn) is added to the steel at the conversion stage. The sulphur then forms manganese sulphide (MnS) in preference to FeS. This has two effects, both of which are because MnS is insoluble in molten steel. The first is that most of the MnS floats off the surface of the melt in the slag. The second is that the remaining MnS forms independent globules which are distributed throughout the steel and solidify in this form. MnS has none of the damaging qualities of FeS.

Manganese combines readily in solution with austenite and ferrite, and forms a stable carbide similar to cementite, so that it has no ill effects on the properties of the steel. Moreover, it increases the depth of hardening of the steel and improves strength and toughness. These valuable properties are reflected in the comparatively high proportions of this element which are allowed in rail steel.

3.4.5 Nitrogen and hydrogen - two other undesirable impurities

Both these impurities make the steel brittle, but in different ways.

The gas nitrogen which forms four fifths of the atmosphere tends to be absorbed by molten steel during the manufacturing process. This was particularly so when steel was made in Bessemer converters because the “blast” used was air. In the more modern “basic oxygen process” pure oxygen rather than air is blown through the melt when making steel, thus removing nitrogen from the blast.

If nitrogen dissolves in the liquid steel its small atomic size means that the nitrogen atoms are located between the iron and carbon atoms making up the bulk of the steel, hence the nitrogen is called an interstitial atom. The nitrogen atoms increase the strength of the steel but there is a corresponding reduction in ductility. This phenomenon accounts for the reduced carbon level specified for Acid Bessemer rail steel (0.4 - 0.5% C) compared to Open Hearth rail steel (0.5 - 0.6% C). The reduced carbon level in the Acid Bessemer steel is compensated for by the nitrogen content.

Water (either as vapour or chemically combined as for example in rust) can come into contact with steel at various times during the purification process. The hydrogen formed by the breakdown of water during steel making is in the form of atomic hydrogen which, being the smallest of all elemental atoms, is again an interstitial atom and moves freely by diffusion within liquid and solidified steel. Solidified steel contains many cavities (on a microscopic and sub microscopic level) and the hydrogen atoms diffuse preferentially to those sites, and form molecular hydrogen which then, as more hydrogen molecules gather in the cavity, exert an increasing pressure on the metal surrounding the cavity. If sufficient hydrogen is present in the steel the build-up of pressure causes small fractures to occur within the steel, known as hydrogen flakes or shatter cracks. These small fractures can then, under the influence of the various forces acting on the rail in service, initiate fatigue cracks which grow and finally cause a brittle fracture of the rail to occur. This type of failure with its characteristic fracture features is known as a Tache Ovale. Higher strength steels are more prone to hydrogen embrittlement than low strength steels, so that the higher strength wear resisting rail steels require more careful control procedures to reduce the risk of its occurrence.

Modern steelmaking techniques, combined with controlled cooling of the finished product, reduce the hydrogen content of modern rails to one or two parts per million and hydrogen flakes or shatter cracks are now very rare in such rail steels. However, this type of defect can still occur, particularly in older pre-1974 rail, and must continue to be guarded against.

3.4.6 Heating and cooling defects

One of the most important and fascinating features of the behaviour of steel, and one which has been a major contributor towards its economic and cultural importance, is the fact that if a piece of ordinary carbon steel is made red hot and then plunged into water, it becomes extremely hard. In this condition it is possible to grind a sharp edge onto the article which will remain sharp for a much longer time in use than would be possible with the same article cooled slowly.

The process of cooling hot metal very quickly is called “quenching”. Quenching may be done, not only with cold water, but in oil, or by a blast of cold air, and in many other ways and at many different temperatures. In metallurgical terms, it has already been explained that steel above a temperature of 910°C consists of austenite based on the crystalline structure known as gamma iron, and that it changes to ferrite and/or pearlite based on alpha iron as it cools slowly to normal temperature. When it is rapidly quenched, the iron crystals still change from the gamma form to the alpha form, but the carbon atoms no longer have sufficient time to combine with iron atoms as cementite, and hence the formation of pearlite is no longer possible.

The surplus carbon atoms become trapped in the crystalline structure and distort it. The amount and type of distortion depends on the proportion of carbon in the steel, but in all cases the resultant steel becomes harder than either pearlite or austenite. If sufficient carbon is present in the alloy an extremely hard material is produced known as martensite. This appears under the microscope as a uniform mass of needle shaped crystals, although in fact they are more like discs.

The problem with martensite is that not only is it very hard, but it is also very brittle. In the making of, for example, steel tools, the finished product can be made less brittle, at some sacrifice of hardness, by the process of tempering. This involves reheating the steel slightly so as to encourage the carbon atoms to rearrange themselves. During tempering the fully martensitic structure progressively changes towards the equilibrium structure of ferrite and cementite.

Rail steel contains sufficient carbon for a fully martensitic structure to develop if it is cooled rapidly enough. However, in the manufacture of rails, the normal objective is to achieve a fully pearlitic structure, and it is an important part of the rail maker's skill to ensure that at each stage in the processing, the product is allowed to cool slowly enough to ensure a return to the desired crystal structure.

Once in track, rails sometimes have to be made very hot (e.g., for welding), and sometimes get very hot by accident (as in wheelburns). What then happens, if the rail gets hot enough to change to the austenitic structure and is then carelessly allowed to cool very quickly, is that martensite forms in place of pearlite/ferrite in the heat affected zone. This will soon crack under traffic, leading to a complete rail fracture. This is unavoidable with wheel burns because the volume of steel affected is so small by comparison with the rest of the rail, and the damage will normally be done before it can be corrected. In alumino-thermic welding this type of damage can be prevented by suitable measures to control the rate of cooling of the weld.

3.4.7 Getting austenitic steel at normal temperatures

Plain carbon steel, whilst it has many good qualities, is by no means an ideal material. The realisation of this fact meant that, concurrently with the development of the processes for its mass production as described above, much research was devoted to iron alloys having desirable properties, such as hardness combined with toughness, or freedom from rusting, which ordinary carbon steel does not possess.

One of the results of this research was the discovery by Sir Robert Hadfield in 1882 that by adding a comparatively large dose (around 12.5%) of manganese to high carbon steel (i.e., steel containing about 1.2% of carbon), it was possible to make the austenitic structure possessed by the alloy at high temperatures stable through the quenching process so that for the first time austenitic steel was available at normal ambient temperatures. It has been found that in this form the steel is extremely tough and shock resistant. In the "raw" state austenitic manganese steel (AMS) is relatively soft (its Brinell Hardness is around 200, which is slightly softer than R220 and R260 rail grades), but in use it very quickly becomes extremely hard indeed (Brinell Hardness of around 400 to 550). This rapid development of hardness when worked makes it necessary to use special techniques if it is desired to machine AMS. AMS is extensively used by railways around the world in the form of castings, to make monobloc crossings. It is also possible to make it into rolled rails, and these were formerly extensively used in sharp curves subject to heavy side wear, and for making switches and stock rails for use in situations of exceptionally heavy traffic. However, the difficulties involved in manufacture, tendencies to develop certain kinds of defects, and the availability of other hard rail steels has led to the decline of use of AMS in its rolled form.

The alumino-thermic process is commonly used to weld together two pieces of rail in the track. In this process the weld is made by pouring molten metal around the ends of the rails to be joined. From the account of the metallurgy of steel already given it should be clear that one of the conditions for a successful weld is that after pouring, the weld must be allowed to cool slowly enough for the austenitic-pearlitic transformation to take place. Furthermore, the chemical composition and crystallographic structure of the two rail steels should not be too dissimilar. Whilst most common pearlitic rail steels can readily be welded to one another, and also to bainitic steel (see 3.4.8 below), it is not possible to weld AMS components, such as castings or rolled rail, directly to pearlitic or bainitic steel rails. However, developments in welding techniques (described more fully in Chapter 4) have been made to create acceptable welds between cast AMS crossings and pearlitic rails.

3.4.8 Bainitic steel

Bainitic steel is yet another phase or arrangement of atoms of carbon and iron which can be produced by certain types of controlled quenching from the austenitic phase, or by the additions of the elements boron and molybdenum, which modify the transformation behaviour from the austenite phase. In this instance the austenite-pearlite transformation is suppressed, and the austenite transforms to bainite under natural cooling. Additions of chromium, nickel and copper can also be made to the alloy to tailor the properties to meet the requirements of the service environment. Bainite is somewhat similar to pearlite, in that it consists of alternate layers of cementite and ferrite, but the grain is very much finer, and the toughness and hardness much increased, qualities which are valuable where rail is required to withstand heavy abrasion and impacts. Since bainite is a phase rather than a separate chemical compound it is possible for its chemistry to be very similar to that possessed by a pearlitic rail and, subject to appropriate control of the cooling rate, a successful alumino-thermic weld between pearlitic and bainitic rail steels is possible.

Following extensive development work, common crossings with a bainitic steel centre-block were introduced in the UK from the late 1980s, initially with good results. Over time however the crossings exhibited a propensity to unexpected rapid brittle fracture and virtually all were replaced with AMS units.

Internationally, research and development work to achieve a fuller understanding of the behaviour of bainitic steels and their various crystalline structures has continued. In 2021 several rail manufacturers offer premium bainitic rail, primarily for specialist applications within switches and crossings, with up to 10 years and 1,000MGT of service experience.

3.5 THE FUNCTIONS OF A RAIL AND HOW THESE DETERMINE ITS SHAPE

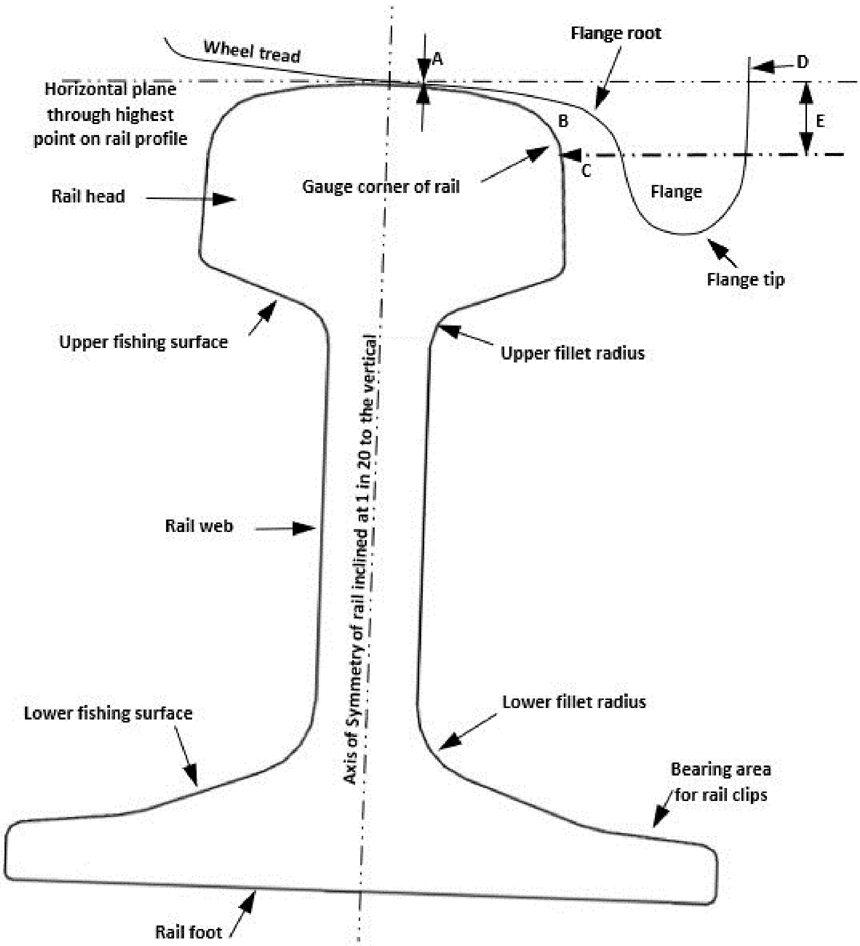
As was explained in Chapter 1, the original function of the rail was to act as a hard and unyielding surface to carry a rigid tyred wheel without rutting or abrasion, and this remains a prime function of a rail to this day. The other prime functions are to act as a beam and thereby transmit the wheel loads to the sleepers, and to act with the tread and flange of the wheel tyre in steering the vehicle in the desired direction.

The shape of the rail that has become standardised for all modern main line railways is the Flat Bottom (FB) rail (sometimes called Vignoles rail after its inventor). The bullhead (BH) rail which was once universal in the UK is now limited to slower speed, specialist locations, and heritage railways. Use of BH rail on London Underground is being phased out and remaining sections are limited to some areas of deep tube lines. A few notes on its development and the reasons for changes will be found in Chapter 1. For the sake of any reader who may be unfamiliar with the terminology, Figure 3.1 shows a typical cross section of a wheelset on a railway track, with the names given to the different components. The reasons for the shapes of the various parts of the rail are discussed below, with particular reference to the EN 13674-1 56E1 rail section (previously BS 113A), the dimensional details of which are shown in Figure 3.2. below.

Considering first the shape of the rail head, note the subtle combination of curves of three radii varying from quite sharp to very flat. These are designed to fit with the shape of the wheel tyre, to form a combination which will both have good riding qualities and minimise contact stresses. One of the features of a well-matched combination of wheel tyre and rail head is that, when the axis of the wheel set coincides with the longitudinal axis of the track, and the rail is at its correct inclination, the point of contact between the two is very close to the centre of the rail. This is very desirable from the point of view of the rail, since it minimises the twisting effect which an eccentrically applied wheel load would have on the rail, and by keeping the wheel/rail contact area away from the gauge corner the likelihood of gauge corner shelling and head check fatigue damage is reduced. Side wear is also reduced. It also implies a practical limit to the overall width of the rail head, and even the heaviest rail sections in use have head widths very little greater than those of 56E1 rail.

The 56E1 rail head has sides which slope at 1:20. This is to compensate for the 1:20 inwards slope of the rail, and not only makes it simpler to control gauge, but ensures that when side wear takes place, the associated gauge widening is minimised.

Even when rails are welded into CWR, it is occasionally necessary to join them together by fishplates and the lower faces of the head and the inner parts of the upper faces of the foot are designed so as to maximise the efficiency of the fishplate in transmitting the longitudinal forces associated with the bending of the rail end under wheel loads, and to allow wear on the mating surfaces to be taken up by re tightening the fishbolts.



NOTES:-

A: Point of contact between wheel and rail

B: Flange clearance 8mm approximately

C: Track gauge measured between vertical inner faces of rail: 1432mm

D: Back to back gauge measured between vertical inner faces of wheel tyres

E: Plane of measurement of gauge below plane of rail running table 16mm (Network Rail); 14mm (London Underground)

Figure 3.1 Standard wheel profile running in its central position on 1432 mm gauge track with EN 13674-1 56E1 rail

The design of the fishing surfaces also ensures alignment of the rail ends without any contact between the rail web and the fishplates. When it is necessary to install insulated fishplates in CWR, the fishing surfaces are also called upon to transmit the thermal loads from the rail into the fishplate and vice versa.

The thick, sturdy web of the 56E1 rail is designed to give the rail adequate shear strength to guard against fatigue failures, particularly around fishbolt holes even under the impact loading imposed by the heaviest axle loads passing over dipped joints. Another feature to note here is the generous radii of the transitions between the head and web and between the web and foot. These fillet radii as they are called are necessary because the guidance forces on curves may be of the order of 35% of the axle load. (Lateral loadings are discussed in more detail in section 2.7 above.). The direction of application of the resultant wheel load and the asymmetry of the point of application of the wheel loads, results in the development of secondary stresses within the rail itself, particularly at the fillets between the head, web, and foot, and the large fillet radii of the 56E1 rail are designed to keep down these secondary stresses, again to guard against the possibility of fatigue failure.

Finally, we come to the foot of the rail, which is broad to give stability to the rail against roll over, remembering that the steering forces mentioned above produce significant torsional forces which have to be resisted by the clips which secure the rail to the sleeper. The rail is made flat underneath to distribute the wheel reaction evenly over the surface of the baseplate. The reason for the slope of the inner portion of the upper surface of the foot has already been mentioned. The much flatter slope of the surface towards the outer edge of the foot is provided as a table upon which the rail clips may engage, and the surface is planar rather than cylindrical to enable precise control over the deflection of the clip, to simplify the shape of any insert provided between the clip and the rail, and to minimise contact stresses between clip and rail.

In addition to its primary functions the rail has secondary functions, notably that it may convey return traction current, and that it may carry electric currents for signalling purposes, usually as some form of “track circuit”.

3.5.1 The Rail as a Beam

In most modern applications the rail is supported at discrete intervals by sleepers. In the case of concrete sleepers, thin resilient pads, typically 5mm- 10mm thick, lie between the rail and sleeper; where timber sleepers are used a steel baseplate lies between them. On bridges, baseplates may be positioned directly onto bridge girders. Thus, the rail can be seen to be acting as a beam and indeed its transverse section is similar to that of an I-beam.

As explained in Chapter 1, the loads from train wheels produce bending moments and shear forces in the rail. The bending moments cause longitudinal compressive and tensile stresses which are mainly concentrated in the head and foot of the rail whilst the shear forces produce shear stresses which occur mainly in the web. It is the need to provide adequate resistance against bending (referred to as resistance moment) which determines the required areas of the head and foot of the rail, and its overall depth.

It is to be noted at this point that even if the rail is continuously supported, as for instance in slab track, the track form almost always possesses a degree of vertical resilience (e.g., in the form of a continuous rail pad). In this case also, the stiffness of the rail distributes the point load from the wheel over a determinable length of support and bending moments and shearing forces arise from this distribution of load. Even with continuously supported rail, the rail’s size must be commensurate with its function as a beam.

Even in jointed track a rail will be continuous over 24 or more supports. Characteristically for a continuous beam over many supports carrying rolling loads, the rails are subject to repeated reversals of bending and shear stress. These stress reversals are a source of metal fatigue. To combat this, they are limited to an allowable level which takes into account CWR thermal stress and residual stresses caused by the manufacturing process and wheel/rail contact.

A further factor to be taken into account is that over the course of time the rail head gets worn away by wheels on its top surface and galled by abrasive contact with baseplate or sleeper on its underside. Corrosion (especially of the rail foot) leads to loss of rail section, and surface pitting may itself reduce the fatigue resistance of the rail. In wet tunnels severe localised head loss may occur due to dripping water. This too will reduce the cross section of the rail, but more significantly the resulting running surface irregularity will cause higher than usual dynamic loads. These features have to be taken into account when determining rail removal criteria.

Once these allowances have been made, the strength and the moment of inertia and depth of rail required in any particular situation may be determined by considering the bending moments produced by the known wheel loads, (suitably factored to take account of the effects of impact forces produced by track irregularities). The calculation of the bending moment has to take account of the spacing of the sleepers and the fact that the sleepers themselves sink into the ballast as the wheel passes and recover afterwards. A method of doing this is explained in Chapter 2. It should be noted that the strength of rail steel required is also likely to be influenced by wear resistance requirements and the need to combat rolling contact fatigue problems.

3.6 USE OF RAILS IN THE UK

3.6.1 Rail Sections

EN 13674 contains descriptions of a wide range of FB and related special rail sections in use or manufactured with in Europe. The standard is in 4 parts:

- Part 1, EN 13674-1 describes FB rail sections of 46kg/m and heavier;
- Part 2, EN 13674-2 describes special switch and crossing rail sections designed to be used alongside the FB sections described in part 1;
- Part 3, EN 13674-3 describes special check rail sections (but specifically excludes guard rails);
- Part 4, EN 13674-4 describes FB rail sections of 27kg/m and heavier up to but not including 46kg/m.

Two standard rail sections are widely used in modern UK main line and heavy metro systems, 56E1 and 60E1.

60E1, which as its name indicates has a mass of 60kg/m, is employed in the UK and on continental railways for premier higher speed and more heavily trafficked lines. The principal dimensions of this rail are shown in Figure 3.4.

56E1 rail shown in Figure 3.2 and as modified by Figure 3.3 is a UK development of the 54E1 rail more widely used in continental Europe. Prior to the introduction of 60E1 rail into UK use, 56E1 was the standard UK FB rail and was previously known by the code BS11-113A, where:

"BS11" was the original British Standard now largely incorporated within EN13674

"113" indicates the mass of rail in lbs per yard

"A" indicates that the sides of the rail head are inclined outwards at 1:20

The geometrical properties of 56E1 rail are given in Table 3.2. Earlier FB rail used in the UK includes rail of 98lb, 109lb, and 113lb/yard, as well as 54E1 (previously described in the UK as BS11-110A).

TABLE 3.2 Area, calculated mass, and properties for 56E1 railway rails in metricated units. (Reproduced from Table 11 of BS 11-1985)

Areas -	**Head**	**2882.83 mm^2 (40.12% of whole area)**
	Web	**1711.93 mm^2 (23.83% of whole area)**
	Foot	**2589.74 mm^2 (36.05% of whole area)**
	Whole Section	**7184.50 mm^2**
Calculated mass		**56.398 kg/m**
Moment of inertia I(xx)		**2332.4 cm^4**
Section modulus Z(xx)		**277.95 cm^3**
Distance - top of rail to neutral axis		**83.914 mm**

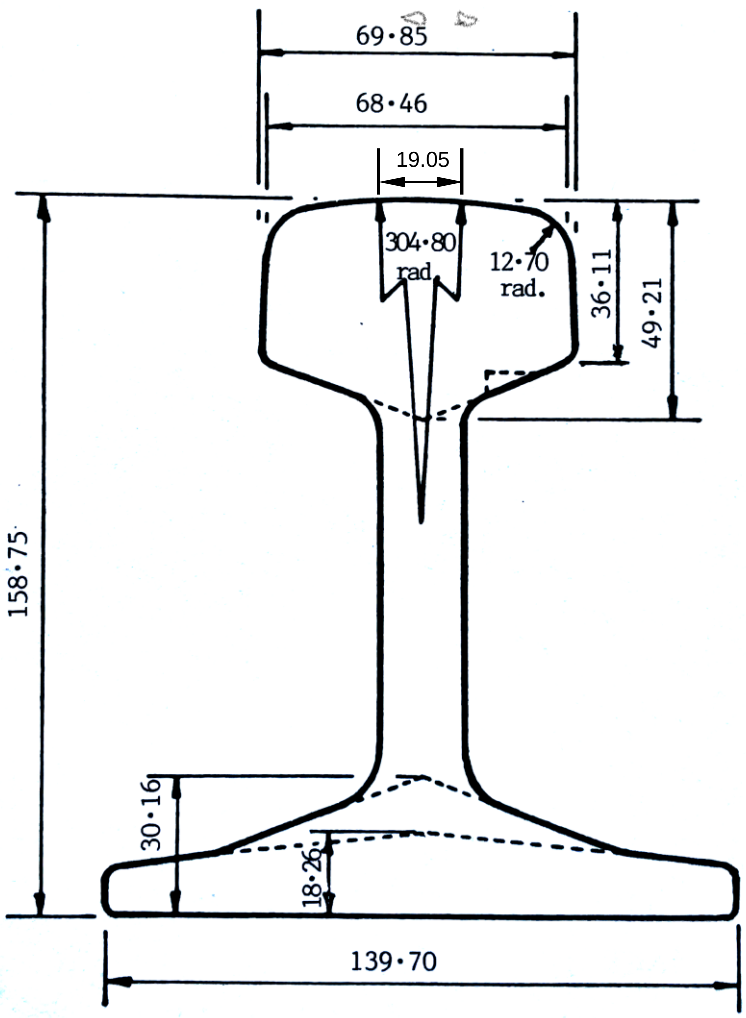


Figure 3.2 BS113A Rail Section pre-1993

At the time when CWR track on concrete sleepers became the standard the 54E1 (BS110A) rail was adopted as the standard UK rail. Following a tragic accident in late 1967 involving much loss of life and attributed to a rail end failure involving this rail, concern was expressed that the web of 54E1 rail was too thin at the rail centreline. After some consideration it was decided to thicken up the web with parallel sides rather than the curves of the original section and this became BS113A rail. This change added approximately three lbs per yard to the mass of the rail, which was otherwise identical to 54E1 (BS110A) rail.

A further adjustment to BS113A rail section was made in 1993 to reduce the width of the central band at the crown of the rail (with a radius of 304.800mm) from 19.05mm to 12mm. The difference will be observed by comparing Figure 3.3 below, with Figure 3.2. above. The effect of this change was to significantly reduce the average crown radius, hence increasing the effective conicity of the wheel-rail combination. This improves the lateral dynamic stability of bogies on straight track without degrading performance in curves. Initial wheel-rail contact stresses are however slightly increased.

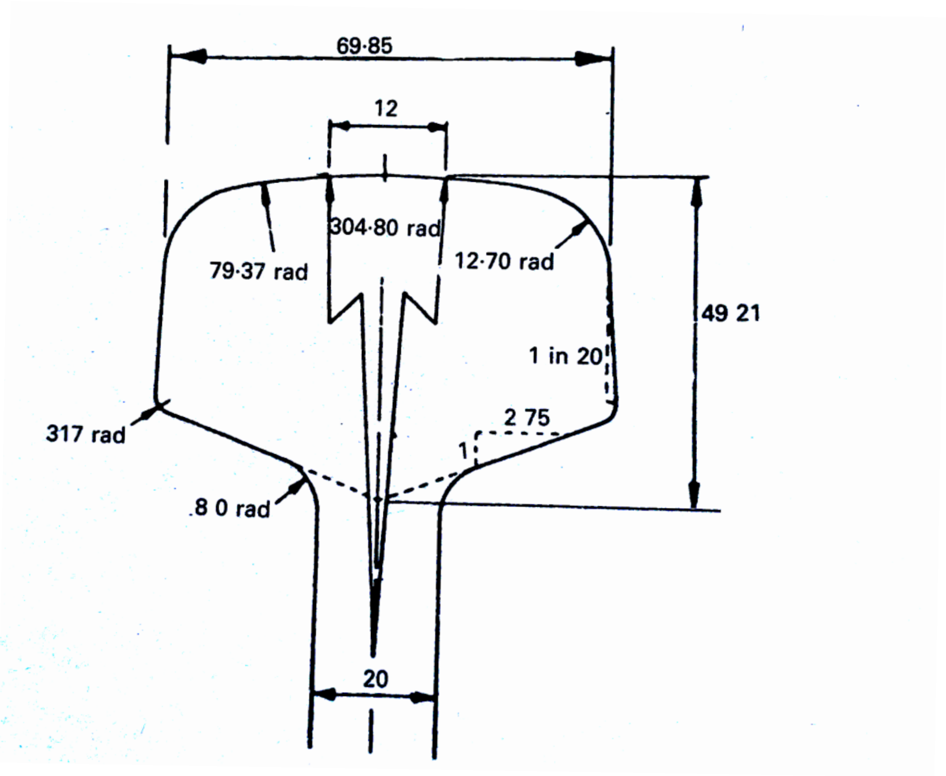


Figure 3.3: 56E1 Rail Section (BS113A) with 12mm wide crown (as modified from 1993)

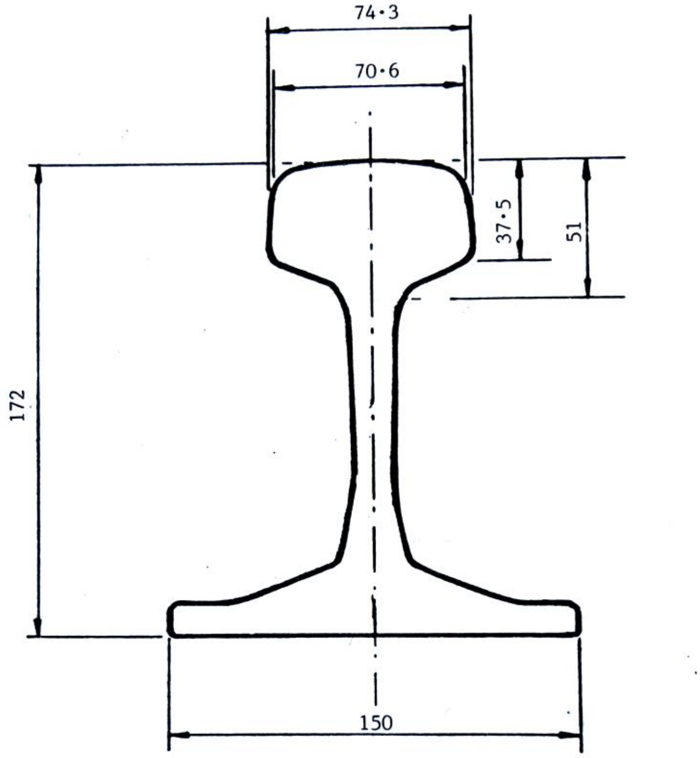


Figure 3.4: 60E1 (60kg/m) Rail Section

39E1 rail, previously described as BS80A (80lb/yd), is still used in several UK light rail systems and, notably, was the section used on the initial lines of the Hong Kong Mass Transit Railway (MTR). In track renewal work MTR has replaced 39E1 rail by 60E1 section and some UK light rail systems have used 56E1 section in more recent system expansions.

3.6.2 Switch Crossings and Rail

For switch and crossing work certain variants of the basic FB rail are available and described in EN 13674-2. The main features of these rails are that they have a much thicker web than is customary and are much shallower and squatter in section. They come in both a symmetrical form, where the foot of the rail is the same width on both sides of the web, and asymmetrical, where the foot on one side is virtually absent. Examples of these rails are illustrated in Figures 3.5 and 3.6.

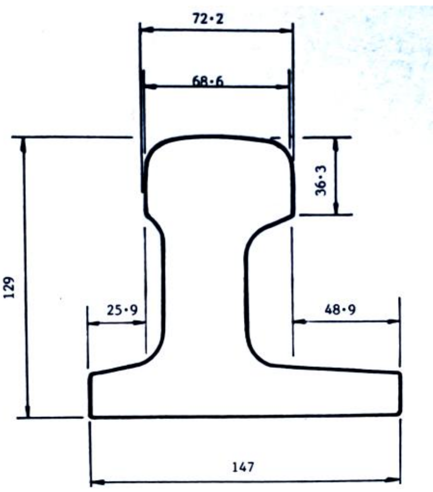


Figure 3.5 54E1A1 Asymmetrical Shallow Depth Rail Section for use with 54E1 or 56E1 Rail

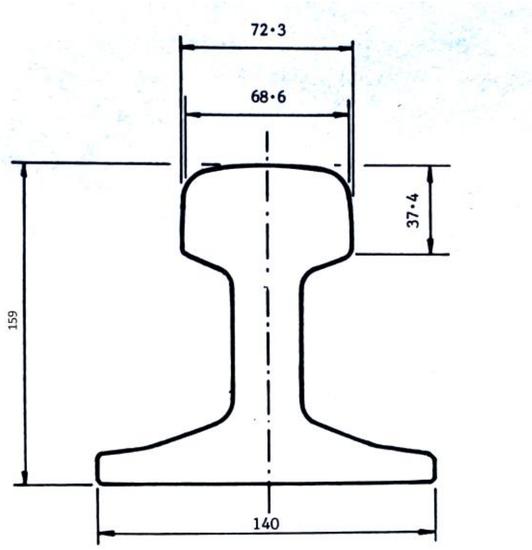


Figure 3.6 54E1T1 Symmetrical Shallow Depth Rail Section for use with 54E1 or 56E1 Rail

EN 13674-3 describes special rail sections used for making check rails. 33C1 rail is often used for this purpose in UK main line and heavy metro systems and it is illustrated in Figure 3.7.

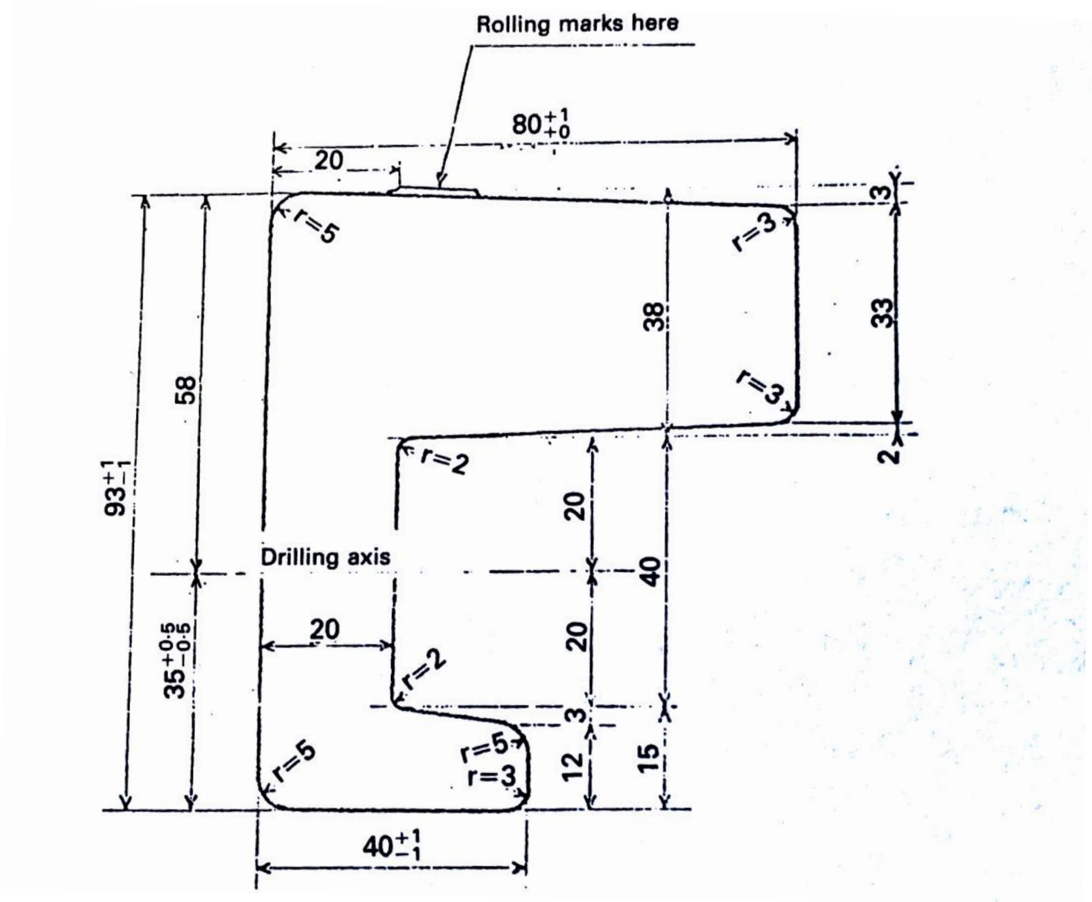
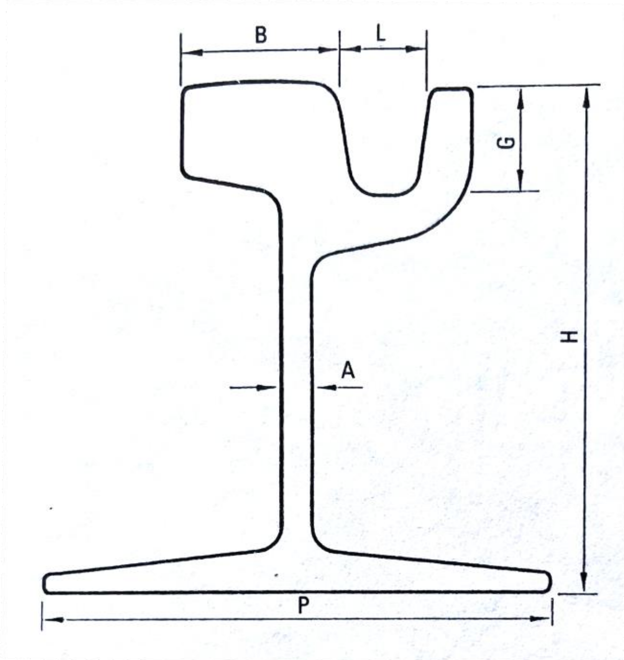


Figure 3.7 33C1 Check Rail Section Mass 32.3kg/m

3.6.3 Tram Rails

In tram systems for street running grooved rail is essential. Standard modern tramway rail sections are described in EN 14811. Ri 60 and Ri 59 (Ri stands for Rillenschiene, the German word for grooved rails) are shown in Figure 3.8. It should be noted that the "Ri" rails have a groove which is much too narrow to take a standard railway wheel tyre flange. This is because a groove wide enough for a standard vehicle would endanger cyclists, and so where street running is anticipated, the vehicles must have an appropriately designed tyre profile with a narrower flange. This in turn creates problems with switch and crossing work when it is desired to run Light Rapid Transit (LRT) vehicles over the same metals as standard vehicles. A common solution to this problem, which arises in many "Tram-Train" schemes, is to make the wheel disc wider inside the tread circumference and use raised check rails on the main line S&C where trams are permitted to operate. The raised check rail thus "sees" a wheel of standard main line thickness while the narrower wheel flange is compatible with grooved rail.



Rail Designation	Weight	H	P	B	A	L	G
	Kg/m	mm	mm	mm	mm	mm	mm
Ri59	58.96	180	180	56	12	42	47
Ri60	60.48	180	180	56	12	38	47

Figure 3.8 Tram Rails Section properties

3.7 WEARING RESISTANCE

3.7.1 Abrasive wear

Abrasive wear occurs when there is contact between the side of the flange of a wheel and the gauge face of the rail. Such contact usually takes place between the leading outer wheel of a vehicle or bogie, and the outer rail of a curve. In this case the wheel is directed towards the outside of the curve, so that as that part of the flange which is forward of the area of contact between the tyre and the rail head moves downwards, it attacks the side of the rail head (the angle which the wheel makes with the line of the rail is called “the Angle of Attack”). It is to be noted that this orientation of the wheel is caused, not by centrifugal force, or the momentum of the vehicle, but rather it is associated with the requirement that the longitudinal axis of the vehicle must change direction as the curve is traversed, and hence the outer rail must be continually pushing the outer leading wheel inwards towards the centre of the curve. These effects (known as “guidance forces”) are discussed in more detail in Chapters 4 and 15. The effect of the wheel flange rotating ever downwards in contact with the side of the rail head is akin to that of a grinding wheel and the result is the same, namely loss of metal from the side of the rail head by abrasion.

3.7.2 Plastic Flow

When a wheel rolls along a rail, with its flange clear of the gauge corner of the rail, the area of contact between the two is extremely small. In theory contact between the conical wheel flange, and the rounded rail head is only possible at a point, but this implies an infinitely large pressure at the point of contact, and in practice, both surfaces deform slightly with the result that a contact patch forms. The shape of this contact patch varies but its maximum area is typically about 100 mm^2. Consequently, the contact pressure is very great. Under the wheels of Heavy Axle Load (HAL) wagons, pressures will average around $1200N/mm^2$ across the whole patch. Such a stress is much greater than the yield point of the steel and causes the metal in and near the contact patch to become plastic, so that if it were not for the restraining effect of the main bulk of the metal in the rail head, the material under the wheel would squeeze out sideways like toothpaste. Indeed, the metal on the surface of the rail head does in fact flow under the combination of the contact stress and tangential forces between the wheel and the rail. A frequently observed example of this effect is the flow of steel on the head of the low rail in curves, from the gauge side towards the field side of the rail. This effect is particularly marked on sharp curves where trains move slowly, and it is caused by the gauge spreading force which is a by-product of the frictional forces involved in curving, rather than by cant excess (see Chapter 4 for further discussion of the forces resulting from curving).

A further effect, not observable with the naked eye, is that even on straight track the longitudinal forces between the wheel and rail cause the surface metal to flow along the rail. After some time in service, examination under the microscope of a section taken along the rail reveals changes in the shape of the crystals of steel and, in some circumstances, cracking can eventually occur, leading to the development of the defect known as a “squat”.

3.7.3 Limits on Wear

As a result of both plastic flow and abrasion, metal is lost from the rail head and over time 10% or more of the area of the rail head may get worn away. Eventually the loss of section becomes such that the rail must be removed from service, either because its strength as a beam is no longer sufficient or because the head has become so misshapen that the conditions for satisfactory (or even sometimes, safe) running can no longer be guaranteed.

3.7.4 Headwear

Loss of depth of the rail due to wear of the crown is a slow process which ultimately reduces the bending stiffness of the rail and increases the likelihood of a tall flange hitting track fittings in the flangeway. There is, consequently, a headwear limit which is expressed as a remaining rail depth.

3.7.5 Sidewear in Plain Line

Sidewear, as its name indicates, is caused by wear between the wheel flange and the gauge face and gauge corner of the rail. Sidewear has been regularly monitored at many locations over many years and it is observed that the maximum flange contact angle remains virtually constant as the sidewear progresses across the rail head. The shape of the head, however, tends to become increasingly concave as more of the flange overlaps the original rail outline.

All railway administrations set limits on consistent sidewear, often in combination with headwear, to maintain a minimum rail strength. A further limit dictating that the wear scar should not cut the bottom corner of the gauge face serves to keep worn wheels (tall flanges) clear of fishplates and other track components. Limits may also be set for intermittent sidewear on curves and cyclic sidewear on straight track.

3.7.6 Side and Headwear Gauges for Plain Line

A wide range of gauges continues to be developed to measure rail headwear and sidewear. An example of such a gauge, used to measure sidewear, is shown in Figure 3.9. To use this gauge, it is placed on the railhead and the straight jaw lined up with the outer face of the rail as shown. A stepped wedge is inserted into the slot in the centre of the gauge face jaw. This wedge will enter the slot by a varying amount depending on the amount of sidewear. The numbers engraved on the wedge indicate the “lift-off” measured in millimetres. The rate of sidewear can be ascertained from the change in ‘lift-off’ measured over time.

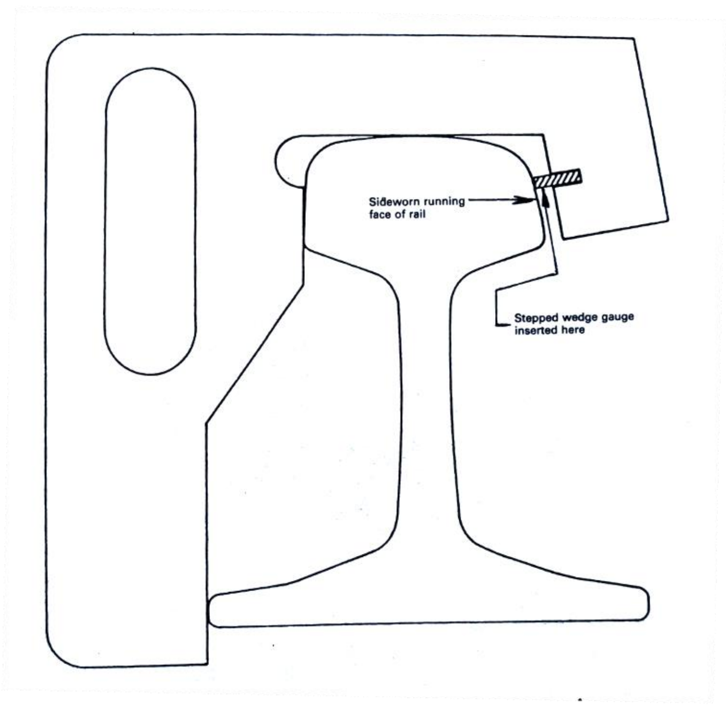


Figure 3.9 Example sidewear gauge in use

3.7.7 Switch and Crossing Wear

Wear and damage to switches, particularly in the critical load transfer area, has the potential to create significant derailment risk and most railway administrations have detailed requirements for the management of switch wear and switch profile to mitigate such risks. Commonly, five specific hazards are recognised:

i. Sideworn stock rail in combination with an unworn (little-used) switch rail;

ii. Stock rail and switch rail both sideworn;

iii. Stock rail head wear associated with a less head-worn switch rail;

iv. Switch rail damage;

v. Switch rail with a sharp gauge corner profile.

It is critical that these risks are properly understood and managed, and suites of rail profile gauges have been developed to identify emerging hazards and to confirm that corrective work has eliminated the potential for derailment.

Rail wear in the crossing area can significantly reduce a crossing's working life and, if not corrected, can create serious derailment hazards. Again, a range of gauges have been, and continue to be developed to accurately measure crossing and check rail wear, allowing potential hazards to be identified and corrected before they become critical.

In all cases it is critically important that the measurement and hazard management regimes laid down by the railway administration are competently and conscientiously applied.

3.7.8 Obtaining Wear Resistant Rail

Much research and practical experimentation has been devoted to the complex problems involved in understanding the mechanisms by which wear takes place, and of selecting the proportions of alloying elements which will give the best possible wear resistance without making the rails less serviceable in other ways.

Since it is abrasion (side wear) which can cause the most rapid loss of metal from the head, the first priority has been seen as producing an abrasion resistant steel. After much experimentation it has been established that for pearlitic steel there is a correlation between abrasion resistance and hardness (measured as Brinell hardness number), so that the greater the hardness, the greater the abrasion resistance. It happens also that there is a similar positive proportional link between hardness and ultimate tensile strength (UTS). This latter property is the key parameter by which steel quality is measured, and to obtain high UTS it is necessary to ensure that the finished steel has as fine a grain structure as possible. This fine grain structure can be obtained by:

- modifying the chemical composition of the steel, or
- careful heat treatment, or
- a combination of both.

The first method is used to produce what are termed "naturally hard" steels, of R260 grade. The HBW (Brinell Hardness) values of such rails is about 270-290 compared with 230-250 for R220 rail.

Still finer grained metallurgical structures are obtained by using an alloy containing up to 1.20% of chromium (Cr). The resulting steel has a UTS some 30% higher than R260, and correspondingly enhanced hardness (HBW around 330-350) and abrasion resistance.

Rails are manufactured from this steel and have been used for many years in industrial railway tracks, under combinations of very high axle loads (45-60 tonnes) and severe curvature. More recently such rails have been used on heavy haul railways, and very selectively on more conventional railways and metros, where service conditions are extremely harsh. Rails made from 1.2% Cr steel, are however very difficult to weld, and tend to be subject to mechanical damage during handling. They are not therefore normally recommended for use on public railway networks.

The part of the rail which it is most important should be wear resistant is the head, and if a method could be devised whereby in an otherwise normal rail, the wear resistance of the head could be greatly enhanced, the result would probably be economic by comparison with a rail made entirely of wear resistant material. The first method of doing this consists of reheating the head of the rail until it is austenitic, by electromagnetic induction (this method of heating involves placing electrically conducting, water cooled coils close to the rail head; when a high frequency alternating current is passed through the coils the constantly changing magnetic field in the rail causes it to heat up), and then passing the rail under a series of hoods through which a mixture of water and cold air is blown. By controlling the force of this blast, it is possible to obtain an austenitic/pearlitic transformation temperature low enough to develop the required degree of hardness in the rail head.

A similar effect can be achieved by subjecting the rail head to a computer-controlled air/water quenching system as it emerges, hot, from the final shaping rolls. The cooling is controlled so that a very fine pearlitic structure is produced, and hardness levels between 300 and 390 HBW can be achieved.

From what has been written about the effects of flash butt and thermit welding on the crystalline structure of rail steel it will be clear that the thermal cycle induced during welding (i.e., the heating up and subsequent cooling of the rail ends making the welded joint) will modify the metallurgical structures developed by these accelerated cooling treatments. To avoid the retention of softened areas produced in the weld heat affected zones (HAZ) which could lead to excessive wear at these positions, special cooling treatments need to be applied to the weld to induce hardness levels similar to those in the unaffected parts of the rails making the joint. Chapter 6 provides an outline of the process involved.

Some indication of the economic value of the increases in hardness discussed above may be gained from the fact that the rate of wear per million gross tonnes (MGT) of traffic if rail of 370 HBW is used is about one fifth of that experienced when rail of 260 HBW is used. However, nothing is entirely unalloyed advantage, and it must be noted that as the rate of surface wear is reduced, so the tendency towards rolling contact fatigue increases.

3.8 RAIL SPECIFICATION

3.8.1 EN13674

The main features of this standard specification are:

a) it applies to rail with a mass of 46kg/m or more.

b) the purchaser's obligations to supply information to the supplier in his enquiry and order are defined.

c) it includes tables of dimensions, areas, properties, and mass per unit length, with which rails ordered by rail section number must comply.

d) the manufacturer is responsible for deciding the source of the steel and the steelmaking process employed, although if the purchaser asks to be told the process to be used, this cannot be changed without informing the purchaser.

e) EN13674 recognises seven grades of steel for the manufacture of rails: for each of these grades the specification quotes a permitted range of chemical compositions (see Section 3.4 above) and lays down how the required tests shall be carried out to confirm the chemical analysis.

f) The toughness of the rail steel is required to be checked by a Falling Weight test, which is described in detail.

g) The strength of the steel is required to be checked by tensile testing. The required ultimate tensile strengths (UTS) and minimum elongations at rupture for each of the three grades of steel are specified.

h) Standard brand markings to be rolled in relief on the side of the rail to enable the origin of the rail and its grade of steel to be permanently recorded are laid down. Provision is also made for the identification of the purchaser. In addition, each rail is required to be identified on its web in such a way that the complete manufacturing history of the rail can be traced.

i) The manufacturer is required to supply master-templates and a set of plus and minus limit acceptance gauges to the purchaser (subject to certain limitations): facilities for the purchaser to observe the manufacturing process and inspect the finished product must also be provided.

j) Dimensional tolerances and requirements for freedom from surface and internal defects are laid down.

3.8.2 Other Types of Rail Steel

Rails made from steels not described in EN13674 are available. Perhaps the best known of these, as it has been available for very many years, is the rolled Austenitic Manganese Steel (AMS) rail. The process for making AMS is described in Section 3.4.7 above, from which it will be seen that in order to obtain the desired austenitic crystal structure, it is necessary, after the rail has been rolled, to quench it in cold water.

With the development of low carbon austenite manganese steel (LCAMS) it is possible to produce AMS rails without the quenching into water necessary with the higher carbon original Hadfield composition. AMS rail tends not to be of the same high geometrical quality as rails to EN13674. Nevertheless, the rail is useful in localities where sharp curves and very heavy traffic are combined.

Other alloys sometimes used for making rails are those including small percentages of chromium (Cr).

3.9 FRACTURE TOUGHNESS AND FATIGUE

The most common cause of failure of structures and components made from metals is that of fatigue, and rails are no exception. Failure by fatigue almost always occurs in three stages:

(i) the initiation of a crack,

(ii) the growth of the crack,

(iii) final fracture or collapse of the structure.

Stages (i) and (ii) of the fatigue process are caused by repeated loading of the structure which, in rails, is primarily due to the passage of wheels. (In rare cases, stage (i) of the process may not occur, or be very short, if the structure contains a crack-like defect which is created by some other mechanism). Stage (iii) is caused by one loading event which may be abnormally severe or as is more likely, the final occurrence of a normal load.

The initiation of a crack (stage (i)) may require millions of repeated loadings and during this time there is no way of detecting the forthcoming crack. The growth of the crack, particularly in its early stages, may also require the application of millions more loading cycles. Stages (i) and (ii) therefore take place over a period of time, often years, and during this period there will be no perceptible change in the shape or dimensions of the rail. The final stage of fatigue failure in the common types of rail steel described in this chapter will be sudden brittle fracture during a period of increasing load. It is the lack of warning of fatigue failure that has caused so many notorious incidents involving, for example, aeroplanes, ships, road vehicles, power generation equipment, pressure vessels, pipelines, offshore platforms, and trains. The time required to develop fatigue cracks does, however, at least offer the opportunity of applying ultrasonic testing methods in an attempt to find them before final fracture occurs.

With the exception of wheel/rail contact stresses, which are a special case, the stresses in rails are only a fraction of the Ultimate Tensile Strength (UTS) (see Chapter 2). However, fatigue failures occur at stress levels well below the UTS. This is caused by the gradual accumulation of fatigue damage with each stress cycle. As the range of stress (i.e., the difference between the maximum and the minimum stress levels in the cycles) decreases, more stress cycles are required before failure occurs.

This phenomenon continues until a stress range is reached when, for all practical purposes, fatigue no longer occurs. This stress range is sometimes referred to as the material’s fatigue strength and for new, as-rolled normal quality rail steels, its value is about 300 MPa. The fatigue strength of rail steels, in common with many other steels, is established at about 2 million stress cycles and for this stress range, and all lower ones, the fatigue life of the rail steel may be considered to be infinite. The fatigue strength may appear to be high compared to, say, nominal bending stresses in the rail; however, the rail presents many localised areas (stress concentrations) where these nominal stresses are substantially increased.

These stress concentrations are caused by many features that disturb the smooth flow of stress contours. Some are caused by the design of the rail itself such as:

- fish bolt hole
- radii between the head and web, and foot and web

Other stress concentrations may be unintentionally caused by the manufacturing process:

- hydrogen shatter cracks
- non-metallic inclusions
- roller guide marks
- scores and scratches
- pits caused by indented mill scale

Some stress concentrations are caused intentionally by the user:

- drilled holes for cables and other attachments
- stamp marks

Stress concentrations are also caused unintentionally during use of the rail:

- damaged hole surfaces caused by poor drilling or using crow bars or badly fitting bolts
- rail surface damage caused by hitting the rail with unsuitable tools
- wheelburn cracks
- plastic flow of the rail head
- foot galling
- corrosion pitting

Apart from stress concentrations, other features occur in track which raise nominal stresses. These include:

- track irregularities such as bolted and welded joints
- wheelburn depressions
- poor support conditions
- rail head depressions caused by dripping water in wet tunnels
- transitions, off and onto bridges

Residual, or locked in stresses, which are originally produced during rail manufacture (roller straightening) and subsequently modified by service loadings, also play a role in determining the fatigue performance of the rail and possibly add to the stress causing final fracture of the rail. Thermal stresses in CWR play a similar role to residual stresses but they, of course, vary according to weather conditions and time.

The final fracture of the rail will occur when the fatigue crack length and applied, residual and possibly thermal tensile stresses combine to cause a critical, unstable condition and as mentioned above, in common rail steels this results in an instantaneous brittle fracture of the rail. This unstable condition is determined by the fracture toughness of the material, sometimes described as its resistance to fracture in the presence of a sharp fatigue or fatigue like crack.

Fracture toughness is measured in tests based upon the principles of fracture mechanics, and it is found that it decreases with decreasing temperature and, in general, decreases with increasing loading rate. Consequently, fracture will occur in a fatigue cracked rail more readily at low temperatures and with impact loads (caused for example by wheel flats and badly dipped joints).

As noted above the only practical way of controlling rail fatigue failure in service is by ultrasonic inspection. Any periodic ultrasonic testing policy should include that:

(i) detection techniques will detect cracks which are less than the critical size,

(ii) the time periods between inspection should not allow a crack to grow to its critical size,

(ii) sizing of cracks should be accurate enough to allow logical withdrawal criteria to be determined.

Developments in steel technology have reduced, and in some cases eliminated, some traditional fatigue failure types, whilst improved ultrasonic test methods and a better understanding of fatigue mechanisms and fatigue life prediction, are helping to contain the problem in service. A better understanding of wheel rail interaction has also led to vehicle and rail design improvements. Nonetheless the constant drive for higher speeds and heavier axle loads will demand that a continued effort be maintained to keep rail fatigue failures under control.

3.10 CORRUGATIONS

Rail corrugations are more or less periodic undulations which form under traffic on the running table of a rail. They vary in wavelength from 50 mm or so up to 300 mm or even longer. In the case of the shorter wavelength corrugations the phenomenon becomes troublesome at amplitudes from peak to trough of 0.1 mm or less, and amplitudes of 1 mm or more occur on the longer wavelengths. The interaction between the wheel and the rail, when passing over short wave corrugations particularly, produces a very high noise level, audible both in the train and at the lineside, the latter leading to complaints of noise nuisance. As well as these environmental problems, very high frequency vibrations of the rail on its support occur. These are liable to damage the fastenings, pads, and sleepers. Particularly severe damage may be caused to concrete sleepers which may render the sleepers unserviceable in a very short space of time.

The ideal solution to this problem would be to prevent the corrugations forming in the first place, but to achieve this it is necessary to know what causes the phenomenon.

3.10.1 Causes of Corrugations

Despite much research, there are still gaps in our knowledge of the origins of rail corrugations, and the design of corrugation proof track forms remains problematic. The present state of knowledge is broadly outlined below.

The wheelset, and the rail, are parts of two independent mass-spring-damper systems. The two systems are connected by the contact patch, and it seems that corrugations form when the complex dynamic interactions between the two independent mass-spring-damper systems affect the adhesion conditions across the contact patch (i.e., whether at anyone instant there is relative movement across the patch, and whether the movement, if any, is creepage or sliding) in an unfavourable manner. Some researchers have built mathematical models which express the relationships involved and have even been able to explain why corrugations have formed at certain locations and not at others.

In closely controlled conditions (e.g., on non-ballasted track) it appears possible to design a relatively corrugation proof track, but on ballasted track the variability of the stiffness and damping of the ballast is such that occasional corrugation appears almost inevitable, and the only remedy is correction by grinding (see Chapter 14).

3.10.2 Reprofiling of worn and damaged rails

Rail reprofiling is now carried out routinely on many railway systems throughout the world. Whilst this activity has been carried out since the 1960s to remove rail corrugation, reprofiling is now also carried out to:

- maintain the wheel-rail interface profile close to design and thus maintain good vehicle curving performance while minimising rail wear, and;
- remove microcracking in the rail surface caused by rolling contact fatigue and thus eliminate nascent rail defects before they become otherwise actionable.

Two basic types of powered rail mounted machine are commonly employed for this work: rail grinders and rail millers.

Rail grinders remove metal by employing a series of powered grinding stones. Each stone grinds a flat strip, also known as a “facet”, along the rail head. A series of grinding stones are angled to grind overlapping facets which create the desired rail head profile. Typically grinding machine heads are mounted on rollers which run along the rail head. Pinch rollers locating on the sides of the rail head determined the lateral position of the grinding heads relative to the rail. The machine profiles both rails (simultaneously if required) by making several passes with the grinding stones set at predetermined angles to regenerate the rail head profile. The number of passes required depends on the extent of reprofiling required and the number of grinding heads on the plant deployed.

Rail millers typically use one or more cutting wheels on which numerous hardened cutting blades are positioned such that as the cutter wheel rotates, the blades cut away the rail surface to create the desired head profile. Generally, rail millers produce a target rail profile in a single pass.

Rail grinder heads can generally be adjusted so that the output rail profile may be varied as work progresses however, the output profile of a rail miller is determined by the way the individual cutting blades are set on the cutter wheel and it is generally not possible to adjust the blades while the machine is working.

Grinders are normally used to remove smaller depths of metal: anything from 0 mm to 0.5 mm of metal from the crown of the rail in one pass. Milling machines cannot reliably remove *less than* 0.1 or 0.2 mm of material but in some cases are able to remove up to 6 mm from the rail crown in one pass. For both types of machine, output varies significantly with the size of machine (for example some small grinders are equipped with only 4 stones, larger machines may carry 64 stones or more).

It is the case that, size for size, a milling machine is capable of removing more metal per pass than a grinding machine, but a grinding machine can be used to make fine adjustments to rail profile, not removing any metal from certain facets. The type of machine deployed is thus generally selected based on the maximum depth of metal requiring to be removed. The milling machine’s capability to remove up to 6 mm of material is particularly useful in removing microcracking in the rail surface caused by rolling contact fatigue.

Grinding machines produce a dust comprising small stone and steel particles. A high proportion of this dust can, where necessary, be captured via suction systems mounted on the machine. Milling machines produce metallic swarf which has the potential to interfere with the operation of railway traction and signalling equipment. Rail millers are thus generally equipped with magnetic swarf collection systems which deposit the swarf into a large container mounted on the machine.

3.10.3 Modifying the head profile of new rail

A principal reason for high rates of rail wear in curves is the aggressive attitude adopted by the leading outer wheel of a bogie. It can be predicted from advanced curving analysis, carried out using computer models such as VAMPIRE, that if a means can be found of increasing the effective conicity of the wheel-rail interface, then for any given lateral displacement of the wheel the restoring force able to be exerted across the interface will also be increased. It also follows that for a given forcing level, the lateral displacement experienced by the wheel will be reduced and consequently the likelihood of flange contact will be decreased.

In curves with differing profiles on the high and low rail the point of zero rolling radius difference can also be offset radially to reduce to some extent steady state curving forces. This effect is most significant in shallow curves (say of radius greater than about 900 m) and decreases with reducing radius.

The theoretical development of the concept was originally undertaken on behalf of certain heavy haul railways in Australia, and differing preferred profiles were developed for the high and low rails of curves. A series of practical tests were carried out with the rails strain gauged to measure lateral and vertical forces. It was found that by adjusting the rail profiles the forces involved in steady state curving could be reduced by up to 90% in curves of a 900 m radius and greater, and by about 50% in curves down to 550 m radius. The dynamic components of the wheel-rail interaction forces were also reduced, and also the effect was to redistribute the lateral forces so that lateral forces at the leading outer wheel were reduced and those at the outer trailing wheel increased.

These force reductions when applied to actual railway conditions were found to lead to significant reductions in rail side wear.

The reprofiling process requires the removal of about 1 mm of metal from the rail head in the vicinity of the 79.4 mm transitional radius and has the effect of making the average crown radius less than normal. Removal of this thickness of metal with earlier generations of grinding train was a very slow process and this work was the impetus towards the development of the so-called aggressive grinding which is possible with modern grinding trains. Such methods are now widely applied.

3.11 THERMAL EXPANSION AND ITS EFFECTS - RAIL END GAPS AND RAIL ADJUSTING

Most materials expand as they get warmer and contract again on cooling, and railway rails are no exception. The extension of a bar of material, expressed as a proportion of its original length, which occurs when the temperature of the bar is raised by one degree, is called the Coefficient of Linear Expansion. The “dimensions” of this coefficient (see Chapter 2 for a definition of the term “dimension”) are:

$$\frac{change\ in\ length}{length}.\frac{1}{degree} = \frac{1}{degree}$$

Hence values of the Coefficient of Linear Expansion are always expressed as a figure per Degree C. The Coefficient of Linear Expansion of rail steel is usually taken as 0.0000115 per °C.

If a rail which is nominally 18.3 m long is laid into the track at a temperature of 0°C, then on a warm sunny day when the rail temperature has reached 30°C its length will have increased by:

0.0000115 x 18300 x 30 = 6.31 mm

The rail, even in UK, may get a good deal hotter than this, say as hot as 45°C, by which time its length will have increased by around 9mm.

3.11.1 Rail expansion and the stressing of CWR

If the rail is constrained so that it cannot expand, then in order that it shall remain at its original length, the rail must undergo a compressive strain which is equal and opposite to the thermal strain, and according to Hooke’s Law, is subject to a compressive force determined by the expression:

Force = (Strain) x (Cross sectional area) x (Modulus of Elasticity)

In the above expression, let:

Cross sectional area be A. (A =7184.5 mm^2 for 56E1 rail)

Modulus of Elasticity be E. (E =200000 N mm^2 for rail steel)

Coefficient of Linear Expansion be C.

Temperature rise be t°C.

The thermal strain is equal to the Coefficient of Linear Expansion multiplied by the temperature rise, so that can write:

Thermal Force = C . t . A . E

= 0.0000115 x t x 7184.5 x 200000

= 16524 N/°C

= 1.7 Tonnes/°C (approximately)

= 76.5 Tonnes for 45°C temperature rise.

A compressive force in each rail of this magnitude is sufficient to cause the track to buckle and it is essential for safety that it is prevented from developing such a force. This is done in CWR by artificially extending the rail at the time of laying and fixing it down when in tension. By this means the rail does not go into compression until the temperature exceeds some predetermined value (this value is called the neutral or “stress-free” temperature and it is 27°C in the UK), thus reducing the thermal force on the hottest day to less than half what it would otherwise be. The rail may be artificially extended either by warming it, or as is universally done nowadays, by stretching it with a tensor. In either case the amount by which the rail must be extended is calculated by multiplying together the difference between the actual rail temperature and the required neutral temperature, the length of rail being treated, and the coefficient of linear expansion, and the track engineer must check that the calculated extension is obtained, that it is evenly distributed down the whole length of rail, and finally that the rail at either end does not move.

The neutral temperature takes into account the average climatic conditions prevailing in UK. It should not be blindly applied elsewhere. If called upon to design CWR working instructions in a “green field” situation, the engineer should first study the climate, so as to form an estimate of the likely maximum and minimum rail temperatures and fix a neutral temperature about midway between these values. Ideally records should be kept over as long a period as possible to validate any preliminary estimate made. The possibility of the temperature range influencing the choice of rail section is discussed in Chapter 2.

3.11.2 Rail end gaps in jointed track

In jointed track the build-up of compressive force is prevented by building in expansion gaps at the rail joints when the track is laid. The size of gap varies according to the rail temperature at the time of laying. In the UK these should be:

Below 10°C	10mm
10-24°C	6mm
34-38°C	3mm
Over 38°C	zero

Special shims of the thicknesses prescribed in the table above (usually referred to as "Expansion Irons") are available and must always be used when laying jointed track. They are slipped over the ends of the rails as they are laid in, and the rails are pulled up tight against them before the fishplates are assembled and bolted up. Care must be taken to see that the irons are all collected up when the work is completed.

A rail thermometer should be used to determine the rail temperature.

3.12 CONDUCTOR RAILS

There are two main types of system:

a) The Third Rail System, where the power (positive) rail which supplies the traction current is located to one side of the running rails, and either one or both of the running rails is used to return the (negative) traction current to the substation. The conductor rail may have the contact surface at the top, under or inside.

b) The Fourth Rail System, where two top contact conductor rails of similar properties are provided, the power (positive) rail located to one side of the running rails and the return (negative) rail located between the running rails on the track centreline. This latter is the system installed on the lines of London Underground Limited.

On the majority of electrified railways where conductor rail is installed, it is supported by the track structure. A selection of typical conductor rail installations are shown in Figure 3.12.

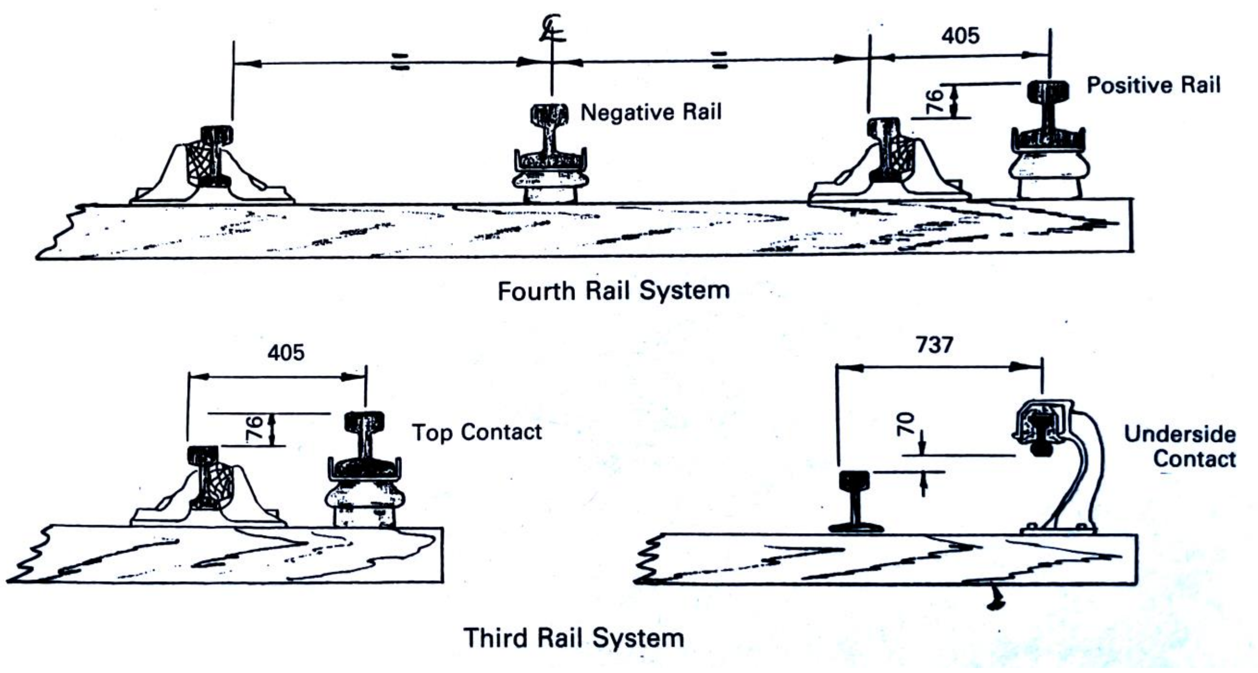


Figure 3.12 Typical Conductor Rail Systems

The following notes reflect the practice in the Southeast England 660/750 volt direct current (DC) electrified lines, which is the world's largest conductor rail installation. It is a third rail system with top contact conductor rails. The term "conductor rail" should in this section be understood to refer to the positive conductor rail which supplies the traction current.

3.12.1 Materials and Sections

Steel conductor rails

Conductor rails are made of steel containing 0.04% carbon and chromium respectively, 0.36% manganese, and a trace of silicon. Such steel is designed to be of high electrical conductivity but containing as it does only a tenth of the carbon of normal rail steel, it is also extremely soft, and of low strength. Apart from this metallurgical difference, conductor rails are made to the same standards of straightness and dimensional accuracy as the running rails. Whilst such low carbon steel is not so brittle and notch sensitive as rail steel, its softness and low strength imply that it also needs to be handled with care. Conductor rails for use on the UK's national network are rolled to weights of 52.6 and 74.4 kg/m. The dimensions of the sections of these rails are shown in Figure 3.13.

Conductor rails can be joined by fishplates of special design to fit in the space between the fishing surfaces, which are much closer together than those on running rails. Where fishplated joints are used it is necessary to fit laminated or stranded copper bonds to ensure good electrical continuity across the joint. In the pressed or riveted type of bond connection the terminals are pressed hydraulically into holes drilled through the bottom flange of the rail. Alternatively welded bonds can be used. These are placed under the rail; the terminal being welded to the underside of the rail foot. Ideally the use of conductor rail fishplates is to be avoided, the rails being welded into as long lengths as practicable. Conductor rail runs are anchored at their midpoints and allowed to expand freely towards the ramped ends. The maximum length of a run is determined by the friction forces generated between the rail and its insulated mountings and transferred into the rail as compressive (buckling) forces. Permissible maximum lengths generally reduce as curve radius tightens.

Aluminium - Stainless Steel Composite (ASC) conductor rails

Steel conductor rail was the most economical and effective material for heavy traction current railways despite its relatively high electrical resistance (14 milliohms/km when fully worn) compared to other components of the traction current supply system. The lower resistance of aluminium and the wear resistance of stainless steel are combined in Aluminium- Stainless Steel (ASC) composite conductor rail. This is lighter and smaller in cross-section than conventional steel conductor rail, yet it is robust enough to resist mechanical and electrical damage during a service life estimated to be in excess of 45 years.

Two sizes of ASC conductor rail are used on the UK national network:

a) Standard conductivity (resistance 14 milliohms/km) - a rail with a resistance similar to steel conductor rail for installation as a replacement on existing systems.

b) High conductivity (resistance 7 milliohms/km) - a rail with a lower resistance which enables an improved electrification system design, and a reduction in the substations required for the power supply.

A section of the ASC conductor is shown in Figure 3.14.

The rails are supplied in 15 metre lengths and connected on site by aluminium fishplates secured by four pre-tensioned multi-groove locking (MGL) pins. The fishplates are sized to provide both the mechanical and electrical connection. The high conductivity section shown in Figure 3.14 weighs 16.5 kg/m, the light weight by comparison to steel making handling and installation easier and enabling the lengths of rail to be transported to site by light weight self-propelled rail vehicles. The ease with which ASC conductor rail may be removed and reinstated in association with track maintenance and renewal work is seen as making a long-term contribution to reducing track costs.

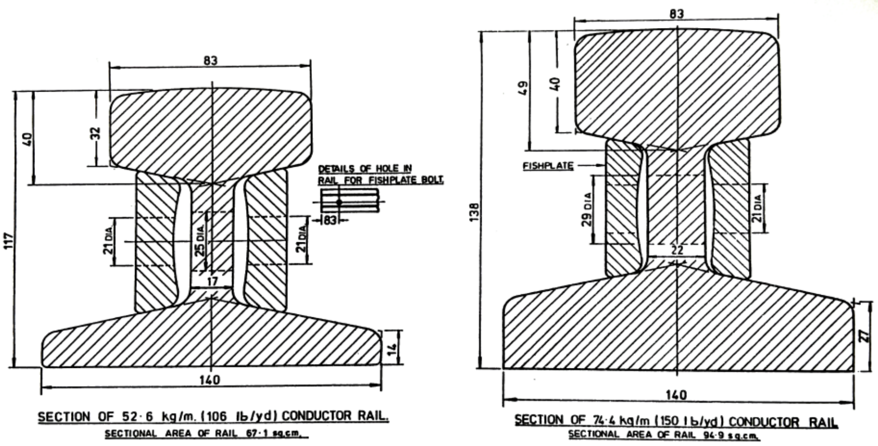
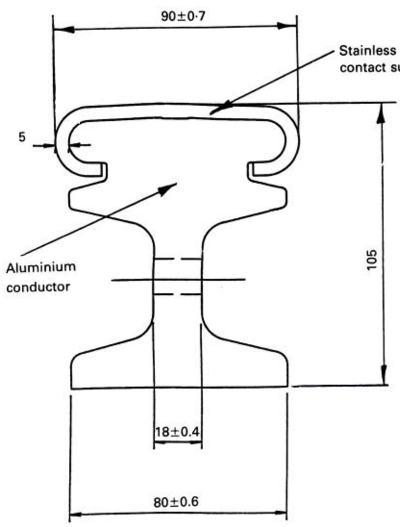


Figure 3.13 Steel Conductor Rails



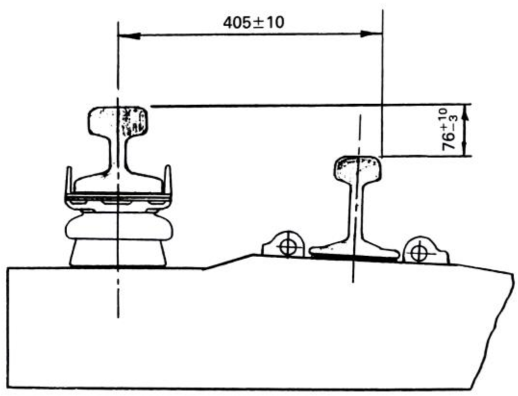


Figure 3.14 Composite Conductor Rail **Figure 3.15 Position of Conductor Rail**

3.12.2 Supports

For steel conductor rails

The conductor rail is supported by insulator assemblies spaced at every eighth, sixth or fourth sleeper depending on the track curvature, location, and type of fixing. The traditional insulator assembly consists of a cast malleable iron cap, the underside of which is in the form of a lug which is cemented into a porcelain pot. The purpose of the cap (sometimes termed the ears) is to locate the conductor rail transversely relative to the running rails, without restraining it longitudinally. The insulators lie on top of the sleeper and are restrained by a pair of cast malleable iron wrap-round base clips which are fixed to the sleeper. Where timber sleepers are used the clips are fixed by coachscrews, but when concrete sleepers are used, fixing is either by coachscrew into plastic insert, or by special fixing bolts, the sockets for which are inserted into holes preformed in the sleeper during manufacture. For this reason, and also because a level space must be formed at the sleeper end to support the insulator, concrete sleepers for third and fourth rail electrified track are manufactured to a special design.

The rates of head wear of conductor rail and running rail are not as a rule the same, and therefore provision must be made in the supports for adjustment of the height of the conductor rail above the sleeper. This is done at two locations: between the rail and the ears, and between the insulator and the sleeper. The adjustment between the rail and the ears takes the form of a number of steel or plastic shims which are inserted when the rail is first laid and can be removed if the rail has to be lowered. That between the insulator and the sleeper consists of timber or composite material packings which are added if it is required to lift the conductor rail.

More recently dough moulded resin compound (DMC) insulators have been used to support conductor rail, the insulators having an inbuilt height adjustment mechanism.

For ASC conductor rails

ASC conductor rail is similarly supported by porcelain or DMC insulators and is free to move longitudinally. However, because the rail is so light it has to be restrained vertically as well as laterally to avoid displacement. The top cap of the insulators has ears which are curved over the bottom flange for this purpose. The insulator is mounted on timber or concrete sleepers by a malleable iron baseplate, which has a square spigot which projects up the centre of the insulator to permit easy removal, whilst preventing the insulator from turning. The baseplate is secured to the sleeper by coachscrews or expanding bolts like the fastenings for steel conductor rail. The insulator is held down in position on the base spigot by the weight of the rail. The rail can be removed by raising the insulator clear of the baseplate spigot and turning the insulator through 45 degrees.

Anchorages

To prevent longitudinal movement or creep of the conductor rail, which arises due to variation in the neutral point from which expansion and contraction occurs as the rail temperature changes, “anchor insulator assemblies” are installed at the midpoint of all conductor rail lengths. The number of assemblies required depends on the length of conductor rail to be anchored.

3.12.3 Detailing Conductor Rail Layouts

The location of the conductor rail relative to the running rail is shown in Figure 3.15. The conductor rail may be placed on either side of the track. In modem twin track installations, it is usually placed between the two tracks, where it is out of the way of personnel walking along the cess. In stations it is positioned, if practicable, away from the platform edge, and through switch and crossing work it will be so arranged as to minimise loss of contact between shoe and rail.

Wherever possible, steel conductor rails are laid in long continuously welded lengths up to a maximum of 550 metres on straight track, the length being reduced in proportion to the increased friction forces generated on track curved below 600 metres radius. Similar arrangements apply to ASC conductor rails, the maximum fishplated length for the high conductivity section being 310 metres.

Gaps are required at level crossings, and at substations and track paralleling huts (TP huts) where the traction feed cables are attached to the conductor rails.

Whenever the conductor rail ends, ramps must be provided to ease the collector shoe on and off the rail with minimum impact. In the early days of electrification these were made by bending a section of plain conductor rail downwards with “crow” (a type of rail bending machine) in two places. As train speeds increased this arrangement was found to be unsatisfactory, and the present practice on the national network is to use a single bend ramp, the extreme end of which is supported on a shallow insulator as shown in Figure 3.17. Prefabricated horizontal base ramps as shown in Figure 3.17 are installed at locations where the clearance to ground is inadequate with the standard ramp formation. Ramp gradients should be quite closely controlled, to minimise the impact caused when the collector shoe strikes the ramp. London Underground makes extensive use of specially fabricated ramps with gradients designed for specific speed ranges. More steeply graded “low speed ramps” are installed in depots and the low speed tracks of crossover roads on both national and LUL networks.

To provide a clear passage for the collector shoes at turnouts and junctions, the conductor rails are terminated as shown in Figure 3.18. Where this arrangement creates unacceptable “gapping” (i.e., where it is possible for all the collector shoes on a train to be out of contact with a conductor rail at the same time), consideration may be given to installing a continuous length of conductor rail on the higher speed track. The collector shoes of trains approaching from the low speed track are then raised on to the top contact surface of the conductor rail as they pass towards the switch and vice versa by the use of a ‘side entry ramp’ which is bolted to the inside of the conductor rail. The principle and construction of side entry ramps is shown in Figure 3.16. It is important that the conductor rail to which the side entry ramp is attached is installed and maintained to a high standard, to ensure that the position of the ramp does not change, and that the top is level with the contact surface of the conductor rail. Side entry ramps are not used on the LUL network and should be avoided wherever possible, because the impact between shoe and side ramp can cause very heavy wear, both on the ramp and on the collector shoe. The speed at which trains approach the ramp from the side must not exceed 20 mph (32km/h).

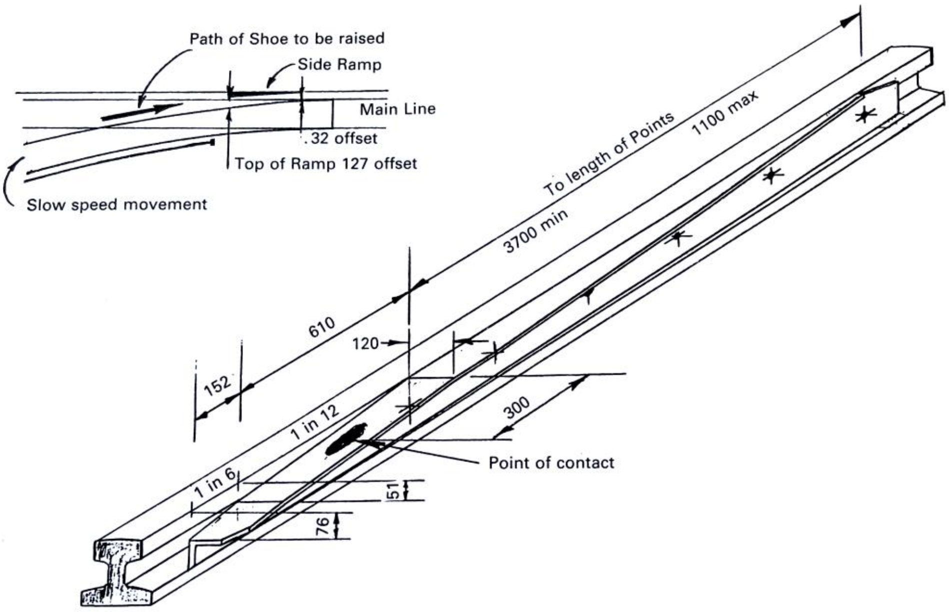


Figure 3.16 Side Entry Ramp

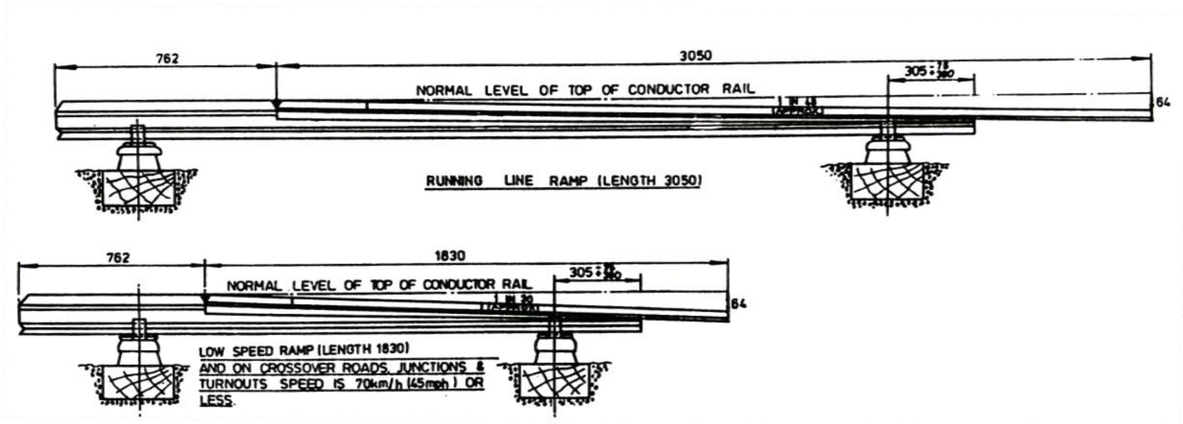


Figure 3.17 Conductor Ramp Ends (Prefabricated-Horizontal Base). Note the shallow insulator at the ramp end in the top figure

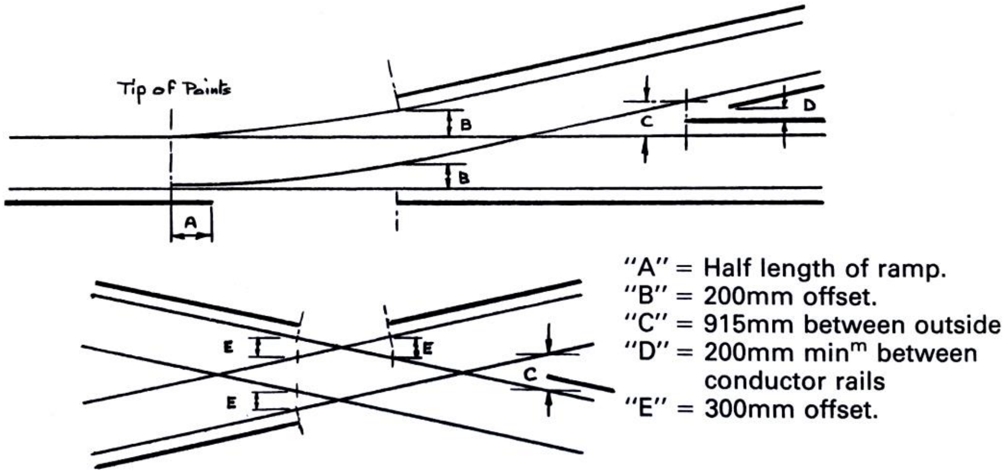


Figure 3.18 Termination of Conductor Rail at Points and Crossings

3.13 DEFECTIVE AND BROKEN RAILS: THEIR SIGNIFICANCE, CAUSES, DETECTION AND REMEDIAL ACTIONS

Rail steel has a considerably higher carbon content than mild steel, and hence in the non-heat-treated state (pearlitic) is more brittle. Consequently, as described in Section 3.9 a variety of stress concentrating defects in rails, combined with the alternating loads from the passage of traffic, can produce a slowly propagating fatigue crack. On attaining a critical size, this results in an almost instantaneous brittle fracture. Broken rails are an obvious hazard to the safe passage of traffic and therefore need to be minimized as far as practically possible. The significance of broken rails is emphasised by the fact that the UK has a statutory obligation on network operators to report certain types of rail fractures.

Most wear resistant rail steels have similar fracture properties to the normal grade steel. However, austenitic manganese steel is very much tougher than normal grade rail steel and does not produce a brittle fracture provided it has been correctly heat treated. Despite this, any slow growing fatigue crack in this material could still result in a complete, although ductile, fracture of the rail, or even collapse of the rail.

3.13.1 Causes

Initiation of fatigue cracks comes from a variety of causes, such as the passage of traffic where vehicle wheels can damage the running surface. The historic steel manufacturing process left inherent defects in the rail such as hydrogen shatter cracks, piping, and non-metallic inclusions. Welds used to join lengths of rail or for build-up repair can also contain defects which eventually result in a rail failure. Corrosion and mechanical damage can produce a sufficient stress concentration to initiate fatigue crack growth. Thermal damage in the form of accidental heating can produce a very brittle structure which easily forms cracks that can propagate further by fatigue.

3.13.2 Classification

As well as having a statutory obligation to report certain rail fractures there is also a need to make a continuous assessment of the rail defect situation, both for safety and financial reasons. In order to do this, it is necessary to classify the types of defects so that trends can be detected. The original classification scheme was produced in conjunction with the International Union of Railways (UIC). The classification scheme deals with all defects, cracks and fractures found in rails, most of which require removal from track soon after discovery. Permanent way engineers also need to monitor defects and cracks which have been detected in track but are not sufficiently serious at that point in time to warrant removal. In order to manage these, a database is needed with the key features of monitoring minimum actions. Rail authorities now have quality systems for classifying and recording rail failures.

There are approximately 50 different types of defect in plain rails (switches and crossings are dealt with separately). However, when rail failure statistics are examined, it is found that about 75% of these defects are accounted for by just six or seven types. These are squats, taches ovales, alumino-thermic welds, bolt holes, vertical splits of the head and web, rolling contact fatigue and wheel burns.

The following sections give a brief description of these major types of rail defects.

Squats

These are fatigue cracks initiated at the running surface by wheel/rail contact forces. They are visible on the running surface as cracks, usually with a black central area, where the wheel loses contact with the rail. The crack propagates at a shallow angle to the horizontal until it reaches 3 to 5 mm below the surface. At this depth, it usually branches downwards to form a defect which is very similar in appearance to a Tache Ovale (see below). If left in track, this would eventually produce a brittle fracture and a complete transverse break of the rail.

There are two types, random and periodic. The former can occur anywhere on the rail with multiple defects common at spacings from a few millimetres upwards. The high rails in high speed curves are particularly susceptible to this form of the defect. This common occurrence of multiple defects increases the possibility of the loss of a section of running rail thereby representing a considerable safety hazard.

The periodic type occurs at spacings of about 2.9 m, resulting from some hard object becoming embedded in a vehicle tyre and indenting the rail. As the rail wears down, the indentation forms a crack, which propagates as described above. In a similar manner to the random type, the fracture of two adjacent defects could result in the loss of a section of running rail.

Another form of rolling contact fatigue defect is the shell and detail fracture. These usually result from large non-metallic oxide inclusions just below the running surface at the gauge corner. This form of the defect is very rare mainly because of the use of rail steel which has been killed with silicon rather than aluminium.

Figure 3.19 Squat failure (courtesy Jay Jaiswal)

Taches ovales

This defect name comes from the French meaning an oval spot, which describes the shape of the fatigue crack in the rail head, (Figure 3.20). In ingot produced rail steel (pre-1974), these defects initiated from shatter cracks, which result from excessive hydrogen in the metal during or soon after the production stage. It was hoped that with the changeover to continuous casting the annual number of these defects would decline. To date, the rail failure statistics show little evidence of this. The main problem with this type of defect is that it is only rarely visible on the rail surface before it produces a brittle fracture. The only satisfactory method of detecting it is by ultrasonics. The other important aspect is that when it results from hydrogen embrittlement in ingot produced steel, the whole rail and possibly all other rails from the same cast are likely to contain multiple defects increasing the potential hazard to safety.

Figure 3.20 Tache Oval Failure (courtesy Jay Jaiswal)

Defective Alumino-thermic welds

Alumino-thermic welds are used to join lengths of rails together in track. Therefore, they are made under more adverse conditions than the depot produced flash welds and as a result are subject to more defects, see Chapter 4. In addition, the process itself is more prone to produce defects than flash welding. The most common of these are lack of fusion, where the weld metal has not completely bonded to the ends of the rail; slag or sand (from the mould) inclusions; gas porosity; and hot tears resulting from the hydraulic tensioners being removed too soon or slipping. Although some of these defects manifest themselves on the surface, most are internal and therefore are only detectable using ultrasonics. Since the complex geometry of an alumino-thermic weld makes a full ultrasonic examination very time consuming and expensive, the avoidance of failures relies mainly on improvements to the welding consumables and practice. Whilst radiography has been used to test rail welds the process itself can lead to embrittlement and is no longer generally applied.

Cracks radiating from Bolt Holes (at Rail Joints).

These are often referred to as star cracks because of the characteristic way the fractures occur at 45° to the vertical, (Figure 3.21). In this case, the stress concentration is due to the bolt hole itself, which under higher than normal service stresses can initiate a fatigue crack. In this situation, the critical fatigue crack size to initiate brittle fracture is only a few millimetres. The actual size at fracture is determined by the magnitude of the impact forces, which are a function of the traffic speed and dip angle in the running table at the joint. The likelihood of this type of defect developing is increased by damage to the bolt hole such as the use of a crowbar to turn the rail, or bad drilling (or reaming) producing a burr. Due to the small size of the initiating fatigue cracks and the fact that most bolt holes are covered by fishplates, the only satisfactory method of detecting them is by ultrasonics.

The current method of inhibiting crack initiation is Cold Bolt Hole Expansion, often referred to as CBX. Pulling a mandrel through the hole fitted with a split stainless steel sleeve produces compressive residual stresses in the surrounding material. This resists the formation and propagation of fatigue cracks.

Figure 3.21 Bolt Hole Failure (courtesy AREMA)

Vertical splits of head and web.

These defects, (See figure 3.22), are mainly a problem in old rails produced by the ingot process. Insufficient cropping of the ingot leads to fissures or bands of non-metallic inclusions in the rail, which act as fatigue crack initiators. Although splits in the rail head can exist for several metres, they fortunately have little tendency to form transverse fractures.

These types of defect can be detected visually as a black line or crack on the running surface, or cracking in the upper fishing radius in the case of head splits. Visual detection of web splits is usually by observation of the bulging effect. Both types of defect can be confirmed by the use of callipers to determine the existence of head or web bulging. However, the most common method of detection is by ultrasonics using a recently developed procedure. As older rails in track are gradually being replaced by rails made from continuously cast steel, these types of defects are decreasing in number.

Figure 3.22 Vertical Split Failure (courtesy Jay Jaiswal)

Wheel burns

Wheel burns result from spinning of a driving wheel on the rail. The resulting heat input from friction is often sufficient to produce a metallurgical transformation in the steel to an extremely hard and brittle structure, which easily breaks up under traffic. Fortunately, most of these defects simply shell out and rarely form a transverse fracture.

They are found in two forms, isolated and continuous. The former are produced by a stationary vehicle and often show the bogie wheelbase pattern on the track. The latter are formed when the vehicle is moving slowly whilst the wheels are spinning. These defects are easily detected visually and are dealt with either by replacing the rail or weld repair depending on the economics of the situation.

Rolling Contact Fatigue

The phenomenon known as rolling contact fatigue or “gauge corner cracking” has been around for many years and was often to some extent ignored. This was because the small cracks (See figure 3.23) did appear to get worn away by varying profiles of wheels. The cause is related to creep and plastic flow due to rolling stresses that eventually cause fatigue failure. Two key processes govern RCF - crack initiation and crack propagation. These processes are governed by a number of factors including environmental conditions, rail and wheel profiles, track curvatures, grades, lubrication practices, rail metallurgy, vehicle characteristics, track geometry errors, and rail grinding practices. They all play a role in the formation of RCF and – universally – can be used to control and minimize RCF.

The amplitude and position of the crack initiating stresses varies depending on the contact geometry, load, and friction conditions. Under high friction conditions shear stresses are large but very shallow. Under low friction conditions, the peak shear stress decreases but extends deeper into the railhead. (See figure 3.22). The result is that some RCF defects are initiated at the surface and others below the surface.

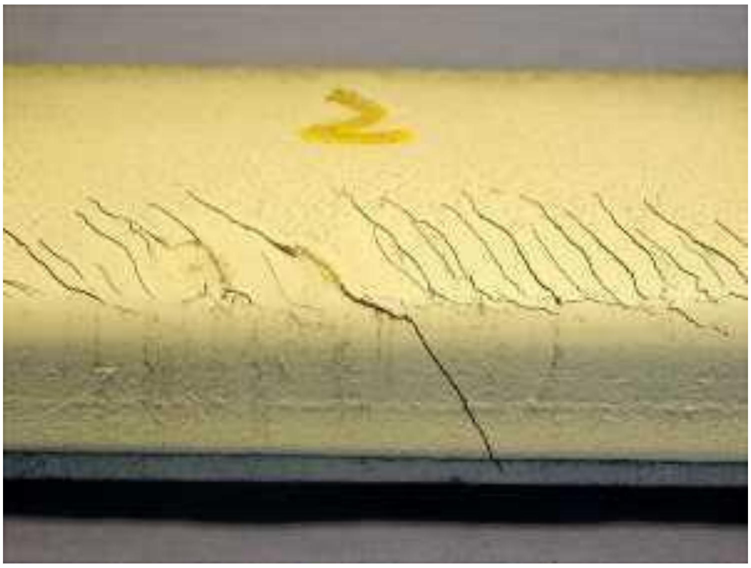


Figure 3.23 Rolling Contact Fatigue Crack Propagation (courtesy Jay Jaiswal)

Figure 3.24 Rolling Contact Fatigue Cracking leading to Failure (courtesy Jay Jaiswal)

3.14 DETECTION

The first source of defects likely to cause rail failures is the manufacturing process. However, over the years, the manufacturers have made considerable improvements to reduce the number of defects or make their detection much easier. In 1974 rail production by British Steel was changed from the use of ingots to continuous casting, reducing the likelihood of piping and related defects. On-line non-destructive testing using visual inspection and a variety of ultrasonic probes on the head, web, and foot, guards against most of the surface and embedded defects commonly associated with the manufacturing process. After production, the rails are inspected by appointed quality assurance personnel, but this is mainly aimed at geometrical tolerances.

Once the rails are in track, they are subject to regular and frequent (depending on track category) visual inspection for gross defects. However, most defects are hidden and therefore not detectable by visual inspection. Hence various types of non-destructive testing techniques such as ultrasonic inspection are employed, as described below.

3.14.1 Ultrasonic Detection

The ultrasonic (sound at a frequency higher than that detectable by the human ear) examination of rails for internal defects is carried out on a regular basis by rail borne ultrasonic testing unit or by pedestrian operators.

The principles of operation of ultrasonic testing are similar for both these methods and are as follows. The flaw detector equipment produces a short electrical pulse which is applied to a piezo-electric transducer (the ultrasonic probe). The piezo-electric transducer has the ability of converting an electrical pulse into an acoustic pulse and conversely of converting an acoustic pulse into an electrical signal. The probes are manufactured to produce a beam of ultrasound which propagates into the rail at a given angle. The commonly used angles (measured from a perpendicular line to the rail head) are 0°, 40° and 70°.

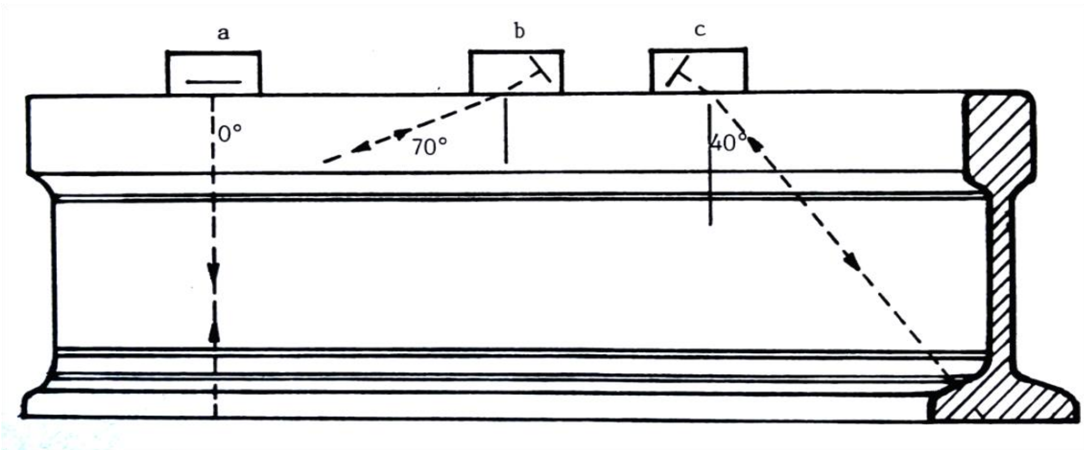


Fig. 3.25 Probe Arrangements

Figure 3.25 shows the typical probe arrangement. On the left it shows how, when a 0° probe is placed on a rail head with a coupling medium of water or oil, the pulses of sound will pass from the probe down through the rail section to the rail foot, where they will be reflected back (like the way in which light is reflected from a mirror) to the rail head. At the rail head some of the sound passes back to the probe and the remainder is reflected back to the rail foot as a repeat echo but at a lower amplitude. The sound pulse that returns to the probe is reconverted to an electrical signal. The time difference between the two pulses indicates the distance the pulse of sound has travelled, and the amplitude of the signal represents the strength of the returned pulse. If there is a discontinuity, such as a bolt hole or a defect, the pulse will return at a shorter time, and hence at a shorter range than that from the rail foot. Figure 3.25 shows the 70° probe which scans the rail head for taches ovales. And shows the 40° probe which scans the web of the rail for bolt holes and associated defects.

The 40° probe will locate either a bolt hole or a bolt-hole crack. The detection of the crack rests on the fact that a sound bolt hole will produce one reflection, whereas a bolt hole with a crack will produce either two or three reflections, and the time intervals between sending and receiving pulses or echoes will be different.

Two tests are required to detect cracks in the “S.W.- N.E. direction” and the “N.W.-S.E. direction”.

3.14.2 Pedestrian Operators

The pedestrian operator’s equipment, (Figure 3.26) is portable and the pulse echo display is presented on a cathode ray tube which allows the operator to interpret the signals to find any abnormalities within the rail. The operator has two methods of testing, the first is with a small trolley which is pushed along the rail head and the second is with handheld probes for bolt hole testing or assessing defects such as squats. The trolley is fitted with a 0° probe for the detection of horizontal defects and a 70° probe for the detection of tache ovale defects. Handheld probes are provided at angles of 0°, 40° and 70°.

The main limitation of using pedestrian operators to detect defects is the limited amount of track they can cover in a given time. However, they are able to test awkward areas such as points and crossings and assess the severity of a defect more comprehensively than vehicle borne equipment.

Figure 3.26 Sperry Walking stick in use. (Courtesy of Nexus)

3.14.3 Ultrasonic Test Unit

Ultrasonic test units, (example at Figure 3.27), enable the rails to be tested at speeds of typically 70 km/h on continuously welded track and good quality jointed track. The units consist of self-propelled or hauled vehicles providing power, and accommodation, and housing instrumentation. The instrumentation vehicle has a rail-mounted stable platform to which the ultrasonic probes and associated control gear are fitted. This vehicle uses a number of small wheels with ultrasonic transducers fitted to their axles which are enclosed by polypropylene tyres. The tyres are filled with a water-glycerol mixture and a water couplant is used between the tyre and rail. The ultrasound travels from the transducers through the internal fluid, the tyre, tyre/water couplant and into the rail to the rail foot and then returns back to the transducer. The probe is guided down the centre line of the rail head by means of a servo system and maintains contact with the rail head by its own weight. At fishplated joints the resilience of the tyre allows contact with the rail to be maintained. However, if the rail joint is in poor condition with an excessive amount of movement between the rail ends then probe rail contact could be lost, and the testing speed must be reduced to allow the rail to be tested satisfactorily. The wheel probes on each side of the vehicle contain transducers which produce signals, each of which is processed by the onboard computers. Such processing allows a defect or anomaly to be identified in real time, so that its position can be immediately marked on the rail. The type of defect is printed out with a record of the mileage and route being tested. The pattern of the signals in the vicinity of the defect is stored for further processing and confirmation of the defect. Non- contacting eddy current probes are also employed for the detection of surface defects. These allow squats and wheel burns to be detected.

Figure 3.27 Ultrasonic equipment on UTU 2 (Courtesy of Network Rail)

3.14.4 Other Methods

There are several methods of non-destructive testing, other than ultrasonics, which may be employed to detect defects in rail. Those in current use are: visual examination; magnetic particle inspection; dye penetrant testing, and; eddy current testing.

A brief description of each method and its application to rail testing follows.

(a) *Visual inspection*

This is the primary and most easily applied method for detecting and evaluating defects. However, there are cases where other methods of testing are required to show the severity of the visual defect. An example is the squat defect where ultrasonic testing is required to indicate the severity of the sub-surface defect. Conversely, there are cases where visual indications can lead to an incorrect conclusion, such as interpreting the fusion lines at a weld boundary as a defect. In cases of doubt other methods of non-destructive testing must be used as a means of confirmation.

(b) *Magnetic particle inspection*

This technique can only be applied to ferro-magnetic materials and therefore cannot be used on austenitic manganese steel (AMS) rails, which are non-magnetic. When a magnet, either a permanent or electromagnet, is applied to a ferro-magnetic material magnetic lines of force flow through the material. If a surface defect, or one very close to the surface, is present within the magnetic field, the lines of force are interrupted, and a leakage field occurs at the defect. If iron particles are applied in the vicinity of this leakage field, they will be concentrated at the point of leakage and the crack will be indicated by the presence of the particles. The particles are highlighted by first coating the component to be tested with a white background paint.

(c) *Dye penetrant testing*

This method can only be used on surface breaking cracks and should only be used on non-ferro-magnetic materials, such as AMS rails, as it is considered to be a less sensitive test than magnetic particle inspection. This technique relies on a dye which has the properties of being highly mobile. The component under test must be clean so that when the dye is applied it will penetrate into any defects open at the surface. Surplus dye must be removed from the surface and a developer, consisting of a white powder, sprayed on the surface. Any defect will be filled with dye and the developer acts as a blotter which will soak up the dye showing the position and extent of the defect.

(d) *Eddy current testing*

This technique is used for the detection of surface breaking defects in both ferrous and non-ferrous metals. This is an electro-magnetic method of detecting defects that uses eddy currents induced into the component being tested by means of a small coil which is fed with an alternating current. The currents in the component interact with the current in the coil and change its characteristics depending upon the nature of the material being tested. When the component contains a surface breaking defect, the eddy currents around the defect are altered to the extent that they can be detected by the coil. This allows an instrument to be calibrated to detect these changes in the coil which can measure the presence, and under certain circumstances the depth of a defect.

Other possible sources of detection of broken and defective rails are visual and ride observations by train crew, and signallers reporting loss of track circuit continuity.

3.15 CAST CROSSINGS

The majority of the methods of detecting defects in rolled rails listed above are applicable to cast crossings. However, there are a few exceptions. The magnetic particle method cannot be applied to non-magnetic materials such as AMS or stainless steel. Due to its large grain size, it is difficult to inspect cast AMS using ultrasonic equipment, though some progress has been made in this area using “phased array” ultrasonic test equipment.

3.16 REMEDIAL AND PREVENTATIVE ACTIONS

Visual and ultrasonic (manual and vehicular) testing of track for defects are carried out at specified frequencies broadly related to the volume of traffic passing. On London Underground frequencies are defined in terms of traffic tonnes passing while on the national network a system of track classification is used. When a defect is detected, it is reported and entered into a computer-based work management system. From the details entered, such systems are designed to immediately indicate the minimum action which must be taken to deal with the defect. These minimum actions, which depend on network operator and the type and severity of the defect, range from imposing a temporary speed restriction (typically 5, 10, or 20 mph), fitting emergency clamped fishplates, and removing the section of rail within a tightly defined time period (typically 24 or 36 hours), to simply retesting at the specified frequency. In between these two extremes, defects can either be subject to removal of the rail within a longer set time period or repaired by welding.

More recently routine periodic rail grinding (using a grinding train) has been successfully deployed by London Underground to remove fine running surface cracking, preventing crack growth and the subsequent formation of squats and other serious rail head defects. The technique is also being adopted by other network operators.