# CHAPTER 5

# RAIL DAMAGE

## 5.1 Introduction

The background to rail damage has been described in Chapter 1. Rails experience a compressive rolling-sliding contact at maximum contact stresses up to 2 GPa[Sawley, 1989], i.e. higher than the tensile yield strengths of these steels. Rails must additionally resist bending stresses from deflections and thermal stresses from welding. Traction coefficients vary with local conditions, eg., near-dry; semi-dry with the usual fine mineral and biological surface layer amalgam; fully wet (rain), and on some track curve locations, full lubrication with grease applied to the gauge face. Although rails are considered in this work, many forms of wheel damage are similar, as are the types of steel.

Damage seen on heavy haul track tends to be similar, but more extreme, to the damage seen on the European and Japanese high speed rail networks. Forms of damage include:

* Gauge face wear and plastic deformation, particularly on bends.
* Wear and phase transformation# of the central running band. (# Generation of a hard, brittle white etching constituent, hereafter referrred to as "WEC".)
* Impact wear ("batter") of the sharp nose at a rail crossing/junction.
* Rolling contact fatigue (surface initiated) cracking leading to eventual spalling ("squat defects") and occasionally transverse fracture.
* Gauge face cracking, and eventual spalling, due to crack initiation beneath plastically deformed lip at gauge corner ("gauge corner shelling").
* Sub-surface initiated fatigue (on heavy-haul systems) leading to deep spalling ("shelling") and occasionally transverse fracture.
* Sub-surface initiated fatigue due to hydrogen; effects as above ("tache ovale").

* Regular plastic longitudinal deformations ("corrugations") of the rail contact surface, in different wavelength bands, giving noise and vibration annoyance to passengers ("roaring rails") and increased dynamic loads to vehicles and track.
* Thermal damage and abrasion, and sometimes phase transformation leading to surface spalling, due to excess rail-wheel longitudinal slippage (eg. wheel and rail burn, wheelflats).
* General weld defects and eventual weld fracture of the rail.
* Rail surface "batter" in the form of localised vertical deformation and wear in the heat affected zones of the rail weld.
* For bolted track, "star cracks" from the bolt holes.

Over the years, in different countries, different expressions have evolved which describe similar forms of damage, or conversely, singular expressions have often been used which describe different forms of damage (eg. "shelling"). Attempts have recently been made to try and standardise such descriptions. In this text, commonly used British Rail expressions will be given in parenthesis.

It must be added that on the British Rail network, railway lines are subject to inspection and sophisticated non-destructive testing (eddy current and ultrasonic) at least once yearly and defects are detected at a sub-critical stage with respect to safety.

### 5.2 Gauge face wear and plastic deformation.

The form of wear which occurs on the high (outer) rail of a curve, for a passenger based rail network, is shown in Figure 1.1 (Chapter 1). The more severe damage on rail curves experienced on heavy haul rail networks, is schematically shown in Figure 5.1. The rail profile can be altered by a combination of material loss as loose wear debris, material loss from fine surface fatigue spalling, profile collapse from plastic deformation and material flow out of the contact, sometimes forming a lip, and occasionally complete gauge face spalling ("shelling") due to crack growth beneath such a lip (Figure 5.2). However the last case is rare on the British network where most rails are repaced due to the combination of excess wear and plastic flow out of the contact, with high rails on curves being most frequently replaced. Once formed, gauge face lips are usually of minor importance as they rarely fracture and reform[Clayton et al, 1982]. Rails are expected to last 25 years plus, however on some curved track, high rail replacements have been required only after a few months of service[Clayton et al, 1982].

The contact mechanics of wheel on rail were described in Chapter 3; wheel-rail profiles and tractive forces generate longitudinal, transverse and spin creepages. It was shown (for steady state contact with new rail) that where marked lateral displacement of the wheel toward flange contact occurs (Figure 3.10), high contact stresses are generated due to profile changes, in combination with maximum levels of creepage; here the tranverse component is maximised.

The author has not been able to establish exactly what levels of creepage are attained with flange contact and sidecutting of the flange into the rail gauge face. At a certain level of yaw, the wheel will climb the rail. Beagley[1976] gave creepage values of between 1% and 8% for flange contact and "sidecutting". Bolton[1986] and others at British Rail indicated that, based on Elkins and Gostlings' quasi-static curving theory[1977], maximum composite creepage would be around 3% on the British network. However, Danks and Clayton[1987], have favourably matched wear damage from 30% creepage Amsler tests with that seen on the flanges of heavy haul rails tested on the F.A.S.T. test track (Phoenix, Az., USA) and they feel that severe flange contact and sidecutting is near to pure sliding.

Bower and Johnson[1990] have shown that initially, pearlitic rail steels have high increments of strain per stress cycle (cf. Figure 3.30). Standard rails rapidly "wear-in" thus initial high contact stresses are lowered, however increments of strain per cycle rapidly diminish (Figure 3.30) and even the lowered contact stresses will not only exceed the rail bulk yield stress on severe bends with high tractive force, but also the shakedown limit of the rail. At such locations around the rail gauge face, there will be accelerated ratchetting (incremental plasticity) of the immediate surface layer (cf. Figures 3.28 and 3.30) with bulk flow of surface layers to the side of the rail (as shown to the extreme in Figure 5.2). At the immediate surface there will be plasticity exhaustion with consequent surface microcracking and flaking. Flake tips will fracture off as wear debris on a scale ranging from sub-micron to flakes of several millimetres in diameter, additionally milder oxidative forms of wear will be accelerated. (Large flakes are always present beneath highly worn gauge faces, however, as the test results in the following chapters will indicate, such large debris only accounts for a minor proportion of the total material loss.)

Clayton et al[1982] have attempted to match observations of rail wear severity with that seen on air-cooled, dry Amsler tests at British Rail Research[Beagley, 1976; Bolton et al, 1982] plus work later reported in Bolton & Clayton, 1984]. Amsler results were described in the form of three wear regimes:

* Type I, "mild wear". Low wear rates associated with mainly oxidative wear plus some metallic wear in the form of small thin flakes around 2μm thick. These flakes were associated with flattened MnS stringers forming planes of weakness in a deformed near-surface layer.

* Type II, "severe wear". An order of magnitude increase in wear, visually all metallic, with a flaking surface and the generation of larger, thicker flakes.

* Type III, "catastrophic wear". A further order of magnitude increase in wear with larger flakes plus ploughing debris, with surface roughening and visible plastic flow.

Their typical worn high rail profile (taken from the British rail network) is shown in Figure 5.3. Wear of the gauge face side of the rail was divided into four zones. In region A B C there was a well defined zone of surface deformation, which increased from A to B, reaching a maximum of 2.5mm depth, and then decreased from B to C. Material flow was from A to C. The surface had some flaking but no ploughing and was thus associated with the type II severe wear regime on the Amsler. Within region C to D surface deformation was uneven. There were areas of heavy deformation with ploughing damage and material flow opposite to that of traffic; other areas were relatively unworn. This damage was associated with type III catastrophic wear on the Amsler. The lip formed between D and E was thought to be caused by material displaced downward by the base of the wheel flange; once initially formed this part of the amended profile remained relatively unchanged.

Ghonem and Kalousek[1984] formulated an approximate model which linked total wear on both the low and high rails of a curve (Figure 5.1) to the angle of attack ($\phi$), or yaw, of the wheel. They found good agreement with field data. Creepage determinations, as described in Chapter 3, were used and, in addition to normal loads, the different wheelset lateral forces on each rail were taken into account. Wear rates were determined from Archard's Laws as described in Chapter 4. Except under heavy acceleration or braking, the major component of creepage was both determined to be, and observed to be (from the direction of surface deformation), tranverse. With reference to the creep curve shown in Figure 3.17, it can be seen that creepage reaches a saturation value where the traction coefficient (Q/P) becomes equal to the coefficient of kinetic friction, $\mu$. Ghonem and Kalousek[1984] calculated that, for transverse creepage, this occurs at a critical yaw angle of 0.0058 radians (i.e. $0^o$ 20'of arc) for dry contact and less for any form of lubrication. Transverse creep force, $Q_t/\mu P$, was expressed as $Q_t/\mu P = C_{22}\phi$, where $C_{22}$ is the transverse creepage coefficient. They then described the total wear in this regime as,

$$W_t = K_1\phi + K_2C_{22}\phi^2 \qquad (\phi \leq 0.0058 \text{ rad}) \qquad (5.1)$$

where $K_1$ and $K_2$ are constants. With saturation and full slip, $Q_t/P = 1$, wear in this regime can be expressed,

$$W_t = (K_1 + K_2)\phi \qquad (\phi \geq 0.0058 \text{ rad}) \qquad (5.2)$$

These two equations show that wear is a non-linear function that increases rapidly with angle of attack until this angle reaches a critical value. Rail life L (expressed as weight of traffic in kg) was then described by the authors in a similar manner,

$$L = l(\phi - m)_2 + n \qquad (\phi \leq 0.0058 \text{ rad}) \qquad (5.3)$$

$$L = p\phi + q \qquad (\phi \geq 0.0058 \text{ rad}) \qquad (5.4)$$

where l, m, n, p and q were constants determined for a specific set of boundary conditions. These were determined by track measurements for particular rail steels and track curvatures (with an assumption of smooth vehicle curving).

Flange face friction and wear, with respect to the angle of attack for different configurations of vehicle wheelsets, has been considered by Fastenrath[1977]. Additionally, the force required for wheel climbing and derailment was considered.

To combat gauge face wear, rail networks use more expensive, higher grade steel rails at the critical locations. Additionally, flange face lubrication on critical curves is used, particularly on heavy haul networks. British Rail use BS11 Grades A and B, and sometimes a 1% Cr steel (cf. Table 1.2)[Sawley, 1989]. In the past two decades, use of head-hardened rails has become commonplace now that on-line mill hardening techniques have been perfected[Sawley, 1989; Hodgson et al, 1982, 1988; Yoshitake et al, 1988]. All have refined the pearlitic structure (i.e. small grain size with minimal mean ferrite path[Clayton, 1980]) with compositions giving near to 100% pearlite. It is thought that the practical limit of pearlite strength has now been reached for these steels, although futher improvements may be achieved through greater control of inclusions and/or micro-alloying[Sawley, 1989]. The purpose of the research described in this thesis was to assess the suitability of bainitic steels for this purpose, as when the research was initiated, these steels had advantageous welding characteristics over pearlitic steels. Recent work by Devanathan and Clayton[1991] has indicated that some bainitic steels may offer distinct advantages in combating type III catastrophic wear at the gauge face of heavy haul rails. This is further discussed in Chapter 10.

On heavy haul systems, damage to the inner rail of a curve is an additional problem. These suffer from incremental plastic deformation ("crushing") rather than wear (Figures 5.1b and c). This can only be remedied by stronger rail steels and optimised wheel-rail profiles.

## 5.3 Damage to the central running band.

This area is shown schematically in Figure 5.4. The depth of deformation varies across the central bright band, being at a maximum near the gauge side limit (typically 0.5mm)[Clayton et al, 1982]. Only within the limits of this bright band, on some rails, Clayton et al found that part of the deformed layer had transformed to WEC. [WEC is thought to be a highly refined, densely dislocated, hard (> 1000 HV), brittle form of martensite usually produced by accumulative thermo-mechanical treatment[Rowntree, 1982].] Near the gauge limit this layer was found to be up to 0.3mm deep. The ductility difference between WEC and (deformed) pearlite facilitates surface fatigue crack initiation, as can embedded WEC debris. WEC formation commonly occurs during pure sliding and un-cooled pin on disc laboratory wear tests, however reported results from cooled rolling-sliding wear tests have not mentioned WEC formation and therefore this damage mechanism has not been modelled. No WEC formed during the tests described in this thesis.

Since the decline of steam vehicles, measured wear rates for the central running band of straight rail track have been low, less than 0.2mm a year on mainline British track[Clayton et al, 1982a]. On lesser used track, corrosion can be a faster process of vertical "wear".

## 5.4 Impact wear ("batter") at rail crossings.

A section of a crossing is shown in Figure 5.5 with its "nose" marked N[from Callender, 1983]. This sharp point is subject high dynamic loads and consequent impact wear ("batter"). In contrast to their performance in resisting rolling-sliding wear, the standard pearlitic rail steels have poor batter resistance and are not suitable for high volume, high speed and heavy haul railway crossings. At severe locations, British Rail have used cast austenitic manganese steel (AMS) and they have been experimenting with a bainitic steel[Frederick & Jones, 1980; Sawley, 1989].

The disadvantages of AMS are that it cannot be welded to standard track and the consequent bolt holes are subject to fatigue. Also, it is difficult to fully eliminate casting defects and its thermal coefficient of linear expansion differs (eg. some coefficients {°C x $10^6$}: AMS, 17.0; BS11, 11.25; BS11 Grade B, 11.4, 1% Cr rail, 11.8; bainitic rail, 11.6[Frederick & Jones, 1980]).

The search for a batter resistant steel, with similar thermal and welding properties to standard pearlitic rails, stimulated research into bainites[Callender, 1983]. The result of Callender's research was a recommended bainite composition. This was adopted and bainitic steel crossings have been installed on the British Rail network. The composition and strength of one of the early bainitic crossing rails is given in Table 1.2. This composition has subsequently been slightly amended and the cast and normalised crossings now produced have compositions around (wt.%) 0.1 C, 0.7 Mn, 2.0 Cr, 3.0 Ni, 0.5 Mo and 0.0025 B, giving a 0.2% proof stress of 1000 MPa (compared to 684 MPa for the bainite in Table 1.2) and a toughnesses ($K_{Ic}$) of 60-100 $MNm^{-1.5}$ [Sawley, 1989]. Only the centre of the crossing need be bainite with balance of pearlite welded on. Such alloys have formed the basis for the development of bainite wheels and for the range of bainites used for this thesis. For moderately used track, an alternative solution has been to weld two rails such that the nose consists of higher strength weld metal and for BS11 crossings on lightly used track, weld repair to the nose is used[Sawley, 1989].

### 5.5 Rolling contact fatigue and the balance with wear.

Track and laboratory investigations have shown that the presence of a light lubricant is required for the propagation of rolling contact fatigue cracks, where the rail is subject to normal load and creepage contact conditions[Clayton et al. 1982a, 1982b; Kalousek, 1986; Clayton and Hill, 1986; Ichinose et al, 1978; Nishida et al, 1985; Garnham and Beynon, 1990; Beynon, Garnham and Sawley, 1994a and b].

The lubricant is normally water plus the usual track contaminants. Under such conditions, the traction coefficient is still high enough to produce considerable plastic deformation in the near surface layer, yet low enough to prevent clearance by wear of the freshly initiated surface fatigue cracks. On most track locations, fine surface flaking cracks are already present due to dry wear mechanisms; regions with short periodic wet-dry climates present the worst scenario.

Fatigue cracks will preferentially propagate on the "braking" surface, where the tangential force is in the same direction as rolling, opposite to the creepage/slippage direction. Except where a train is braking, the rail is the braking surface rather than the wheel with respect to longitudinal creepage, and it will always be the high rail with respect to transverse creepage opposing curving forces. This preferential propagation is caused by the crack mouth being closed by the moving load and the entrapped lubricant within the acutely angled crack being subsequently pressurised in a hydraulic manner. This applies a tensile stress to the crack tip and lubricates the crack walls[Bower, 1987]. Bold et al[1990] have shown, via rail analysis and laboratory tests, that initial crack growth is by a mixed mode, in the plane of maximum shear stress, consisting of a staggered cycle of mode II shear and mode I tensile stresses.

The fatigue cracks described above, based upon the sheared surface, will be concentrated at the same locations as wear, particularly around the high rail gauge corner in curved track. The sequence of damage, leading to gauge corner spalling, is shown in Figure 5.6. Fatigue cracks can also initiate in the central running band for a number of reasons. Where there is high shear, due to surface indentation from foreign objects (often embedded in the wheel tread leaving periodic indentations), material will shear over the depression forming a lip, from which a crack will form. The initial depression, plus subsequent deformation, leaves a dark impression on the track; this black mark plus the associate fatigue crack is known as a "squat defect". Such a defect and associate fatigue cracks are shown in Figure 5.7. Occasionally, this form of crack can be particularly worrying, as shown in Figure 5.7b, as one branch is tending toward a transverse defect whilst the other shallower branches have partially obscured the severe crack from ultrasonic detection[Clayton et al, 1982a]. The formation of corrugations on track (discussed below) can generate intense shear at the peaks and sometimes WEC formation, both of which facilitate fatigue crack initiation. WEC formation in this central band can initiate cracks by brittle fracture within itself, by cracks forming at its boundary and by indentation of brittle WEC debris[Dikshit et al, 1990].

Resistance to rolling contact fatigue (RCF), as with wear resistance, is achieved by using a material with increased proof stress, toughness and shakedown limit. The relationship with contact stress and creepage is not straightforward[Clayton et al, 1982a, Clayton and Hill, 1986, Beynon, Garnham and Sawley, 1994b], generally the lower both are, the better. However, to some degree wear and RCF balance out each other. Replacement rails of higher strength have sometimes developed RCF problems, because, on the old softer rail, initiating cracks were worn away whereas on the harder rail they slowly develop and remain thus allowing water based propagation. This can also occur where lubricant is applied to the rail; this was spectacularly shown on the F.A.S.T. test track (Phoenix, Ariz.) where the complete test train was derailed as a result[Steele & Reiff, 1982]! (A good example of the economic advantages of small, laboratory based tests!) Kalousek[1986] in particular has studied this wear and fatigue balance with respect to rail grinding practice; as a result, regular light grinding is now standard practice on sections of heavy haul track, where there has been both a wear and RCF problem. Additionally, modified track profile grinding has been proposed for problem curved track so as minimise contact stresses, whilst retaining vehicle steering characteristics[Smallwood, Sinclair & Sawley, 1990].

**5.6 Sub-surface initiated fatigue ("shelling" or "detail fracture").**

This results from the presence of sizeable brittle inclusion stringers, usually alumina based, which are at a sub-surface location where a tensile residual stress has developed to counter the surface compressive residual stress developed from work hardening; typically around 8mm beneath a gauge corner[Steele, 1990]. Severe wear at the gauge corner can accelerate failure by moving higher contact stresses nearer the inclusion. This location, and examples of fracture, are shown in Figure 5.8. Fatigue fracture can occur in two modes; longitudinal propagation with eventual, deep gauge corner spalling and, occasionally, such cracks become initiation sites for transverse fatigue failure through the complete rail. Shelling is a particular problem on heavy haul lines and is rare on the European and Japanese passenger networks. The latter use cleaner steels and are subject to lower axle loads. (Note; some authors have additionally termed gauge corner spalling, due to *surface* initiated contact fatigue, as "shelling".)

## 5.7 Sub-surface fatigue and transverse fracture due to hydrogen ("tache ovale").

This occurs in the centre of the rail head[Frederick and Jones, 1980]. This is possibly a problem with older rails made by acid bessemer or open hearth steel-making methods; for the past few decades British rail steels have been made by the basic oxygen process where cooling and de-gassing procedures have eliminated hydrogen problems.

## 5.8 Track surface longitudinal undulations ("corrugations").

These are found world wide on both straight and curved track, on railway networks ranging from light narrow gauge to heavy haul; an example is shown in Figure 5.9. They occur with different bands of wavelength. Academic debate on their formation has continued for over one hundred years; part of a recent conference was devoted to this subject[Grassie (ed.), 1990]. A complete cure for this form of damage has not been found and regular track grinding is required to remove them; on heavy haul lines this is linked to the grinding removal of freshly initiated fatigue cracks (cf. Section 5.5). Their formation accelerates wear and fatigue damage and gives noise and vibration problems.

Under certain conditions, similar undulations form on discs of laboratory rolling-sliding wear machines. This had occurred with the research described in this thesis (cf. Chapters 6 to 9 plus appended papers[Garnham & Beynon, 1988, 1992]). As with wear and fatigue, many researchers have carried out parallel research into corrugation formation on track and in the laboratory.

On British Rail, the most common form of corrugation is the "short wavelength" variety with a wavelength between 40 - 80mm and amplitudes of less than 0.2mm[Clayton et al, 1982a & b]. These often have a secondary periodicity as a sleeper is approached, with decreasing wavelength and increasing amplitude. Other wavelengths found on British Rail[Harrison and Johnson, 1978] are some around 500mm ("long wavelength") and some between 75 - 150mm ("medium wavelength"). Within the short wavelength range, the shortest wavelengths are associated with terminal stations, the longest wavelengths with tight curves and mid-range with straight track; the last giving the (high speed) noise problem known as "roaring rails".

Research on the German rail network[Fastenrath, 1977] showed that the introduction of welded track, together with smoother rails (via surface finish and their sleeper supports) and stronger rail steels greatly diminished the occurrence of short wavelength corrugations, however long wavelength corrugations were found to be attributable to certain vehicles and not affected by rail changes. Grinding of new rails was found to delay corrugation formation, both in Germany and Britain. Clayton et al[1982a] gave two possible explanations; removal of a decarburised layer and any as-manufactured surface roughness.

On the heavy haul F.A.S.T. test track, corrugations developed on the low rail of curves with wavelengths around 200mm[Kalousek, 1986]. Here, lubricating the rails, or just the (non-corrugated) high rail gauge face, eliminated their growth on the low rail. Surface depressions, due to fatigue cracks, or soft zones near welds, were found dynamically to excite wheelsets, which in turn generated corrugations.

Longitudinal sectioning through corrugated rail has revealed structural differences between peaks and troughs[Clayton & Allery, 1982b]. The matrix at the peaks was highly deformed by shear, sometimes with WEC at the surface and/or wear and fatigue cracks (Figure 5.10). Peak surfaces were visually bright. The trough surfaces appeared dull and oxidised; sectioning revealed far less matrix shear strain. The difference in shear strain was reflected in work-hardening (Figure 5.11).

A common sliding wear phenomenon is "stick-slip" oscillations (cf.Chapter 4). Ahlbeck et al[1990] have linked "stick-slip" to the generation of short wavelength corrugations, due to a certain combination of wheel and track parameters. They linked long wavelegth corrugations to differential plastic deformation from dynamic loads. Tassily and Vincent[1990], in a study on the Paris rail network, have formulated a linear model with wear rate as a function of corrugation frequency. The theory examines how small fluctuations in normal load affect both longitudinal and transverse traction force and creepage, with fluctuations being at a maximum on sharp curves where there is saturated transverse creepage. The model was backed with field tests and experimental changes to track stiffness greatly reduced corrugations. Hayes and Tucker[1990] examined how different sources of wheel rail excitation could excite torsional oscillations in wheelset axles, thus generating stick-slip.

Frederick[1986] has developed a rail corrugtion theory based on observations and careful measurements of short wavelength corrugations on British Rail high speed track. He showed how measured relationships, which quantify the dynamic response of wheel and rail, can be combined with formulae for rate of rail wear and wheel/rail creepage to predict whether a small undulation in the rail surface will be deepened or erased by subsequent wheel contacts. He observed that on British Rail there was only severe plastic deformation on the peaks, not in the troughs. WEC formed on the peaks as here vertical contact forces were at a maximum. Whilst the complete rail was wearing primarily due to lateral creepage, wear rate was slightly more in the troughs. He also observed that, once formed, the longitudinal location of each corrugation peak generally remains at its respective position along the rail and also that corrugations did not form on rail with continuous support (i.e. on concrete), except on sharp curves. If such rails were transfered to periodic support (i.e. on sleepers), corrugations developed. This indicated the significance of the track dynamic response. It was also noted that grinding new rails to a superior surface finish delayed the onset of corrugations. This initial theory of Frederick did not explain why harder rails had shorter corrugation wavelengths; he subsequently amended his theory to include increments of plastic strain in addition to wear increments[Frederick, 1987]; this partially solved the anomaly.

Suda has developed a system (Figure 5.12) of corrugation development, based upon track and twin-disc laboratory studies. This has two sub-systems. The vibration - deformation system which describes the phenomena in the contact patch; input being surface profiles and outputs being vibrations and rail deformations (i.e. wear and plastic deformation). The other sub-system is based on the change of profiles; inputs being profiles of the *n*th contact and inelastic deformations and outputs are profiles of the (n+1)th contact modified by these deformations. Corrugation development is expressed by the feedback loop. Whether corrugations developed or not was determined by using the above concept as a self-exciting system. Favourable conditions for corrugation formation are determined by the amplitude and phase angle relationship between two functions, i.e. surface wave and periodic surface deformations.

Suda qualified the correlation of his theory and laboratory experiments, stating that their application mainly concerned a type of corrugation which forms on heavy haul railway tangent track, where growth was mainly due to plastic deformation from high axle loads with low creepage, rather than wear. This differs from the wear-related theories of some other researchers.

**5.9 Thermal damage.**

Wheelburns form on rail due to uncontrolled slippage of the wheel during acceleration or braking; these can be at a singular location due to wheel spin or extend along a length of running surface[Frederick & Jones, 1980]. The frictional temperature rise is sufficient to transform pearlitic rail steel into forms of brittle martensite, including WEC. Subsequent cracking and spalling of the transformed microstructures cause surface discontinuities leading to high dynamic stresses and fatigue initiation. Modern track vehicles have traction control on their powertrains, both to prevent this and to maximise traction efficiency.

Tanvir[1980] developed an analytical solution to quantify the temperature rise from wheel slippage, which predicted temperatures in excess of 1000°C would be generated by braking slip rates in excess of 7m/s for slow forward speeds and 17m/s for high forward speeds and, for accelerating wheel traction slippage, for respective slip rates of 10m/s and 19m/s. It also predicted that, for normal running with no slippage, longitudinal tractive creepage could generate temperatures up to 100°C in the contact. This would affect the lubricant properties of rail head contaminants.

**5.10 Rail welds.**

Starting in the 1950's, rail welding has developed as the standard method for joining track, offering safety (i.e. elimination of bolt hole crack risk), passenger comfort and annual cost savings of £millions for high speed rail networks[Fastenrath, 1977]. To overcome thermal expansion buckling, rails are welded under tension. The higher than average temperature, at which thermal expansion eliminates this tension, is known as the "force free temperature". With service, rails can "roll out" and become fractionally longer; this turn can reduce the force free temperature by 6°C in a year for new rails before stabilisation[Frederick & Jones, 1980]. Initial installation tensions have to account for this.

Damage problems with welded rails include the usual range of possible weld defects and detrimental microstructures in the heat-affected zones (HAZ's). Preferential wear of HAZ's (called rail end "batter" on heavy haul track[Steele & Rieff, 1982]) can generate high dynamic load problems, as with corrugations.

Three weld procedures are used on British Rail, flash butt, thermit and "build-up repair" with metal arc weld deposit[Frederick & Jones, 1980]. Most failures (eg. lack of fusion, hot tears, porosity) have been associated with thermit welds with 80% due to operator errors. Most flash butt weld failures have attributable to welding machine deficiences and post weld treatments. For both, controlled weld cooling normally produces a satisfactory weld with the pearlitic structure retained. Steele and Rieff[1982] found that flash butt and thermit welding developed similar batter problems on heavy haul track, with much dependent on operator skill.

Higher strength, fine pearlite rails, particularly head-hardened rails, require even more care so as to avoid softening in the HAZ, or hard phase development from manganese segregation. Easier welding with less rigorous cooling control was one of the major reasons for investigating the suitability of bainitic rails, particularly for crossings.

### 5.11 Testing for rail damage.

Most rail networks use a combination of tests (Figure 5.13), ranging from the installation and monitoring of test rails on service track, experimentation on test tracks (eg. F.A.S.T. in Arizona) and, in research laboratories, simulated wheel-rail contact with large experimental machines, modelled contact and material behaviour with bench mounted tribo-test machines, such as the twin-disc (LEROS, Amsler, Nishihara) and pin on disc machines, plus the standard mechanical tests for metals. Compared with field trials, experimentation on tribo-test machines is highly controllable and extremely rapid at a fraction of the cost. However, results must be carefully correlated with field experimentation, as complete modelling is not possible. Field tests involve observing and recording track surface features, careful measurement of transverse railhead profiles (and longitudinal profiles for corrugations), collection and analysis of debris and finally rail removal for metallurgical analysis. Test rails are usually placed at accelerated damage locations and interspersed amongst standard rails for comparative reference. Standard wheel steel has been used as the counter reference material for nearly all laboratory rail wear and fatigue tests.

With field tests, on networks and with F.A.S.T., it is difficult to assess one factor in isolation; for example, wear, fatigue (cf. Section 5.5) and corrugation formation can all inter-relate and be affected by track support variability and environmental changes. Some success has been achieved by some contact simulations, particularly the 1:10 scale machine developed by Kalousek et al[1982], where two rails are represented by profiled discs (Figure 5.14). The effect of yaw on rail wear and fatigue can be examined on this machine. (Their wear formulae were given in Section 5.2.)

A machine developed by British Rail Research[McEwen & Harvey, 1983] involved the repeated motion of a full size wheel over a short length of track, into which experimental materials blocks could be inserted at flange locations; again the wheel could be yawed. However, track correlations showed that Amsler twin disc machine trials were just as effective in predicting rail steel performance, at greater speed and less cost.

Most reported work on the wear and fatigue of rail steels has been carried out on twin disc machines of the Amsler type, where a fixed geared drive gives a fixed initial creep rate for equally sized discs. Some results will be compared with this work in the Discussion (Chapter 10). Some of the extensive British Rail work with the Amsler machine was mentioned in Section 5.2[Beagley, 1976; Bolton et al, 1982, 1984].

The twin disc machines used for this work, the modified Amsler machine and the in-house twin disc machine (LEROS), are described in the next two chapters, respectively.

**5.12 Summary**

Various types of rail damage have been described together with respective material and contact mechanics aspects. Safety and economic considerations have generated research into minimising rail damage. This research involves timely and expensive trials on track together with numerous, (relatively) rapid and inexpensive tests in laboratories which are aimed at specific aspects of rail damage. Although perfect correlation with track trials can never be achieved with laboratory tests, the clear indications such tests can give greatly assist in efficiently programming track trials.

The purpose of the laboratory tests described in this thesis has been the examination of the comparative suitability of a different type of rail steel microstructure for reducing rolling-sliding wear damage, as this form of microstructure had been successfully used in addressing other forms of rail damage, including problems associated with welding.

**5.13 References.**

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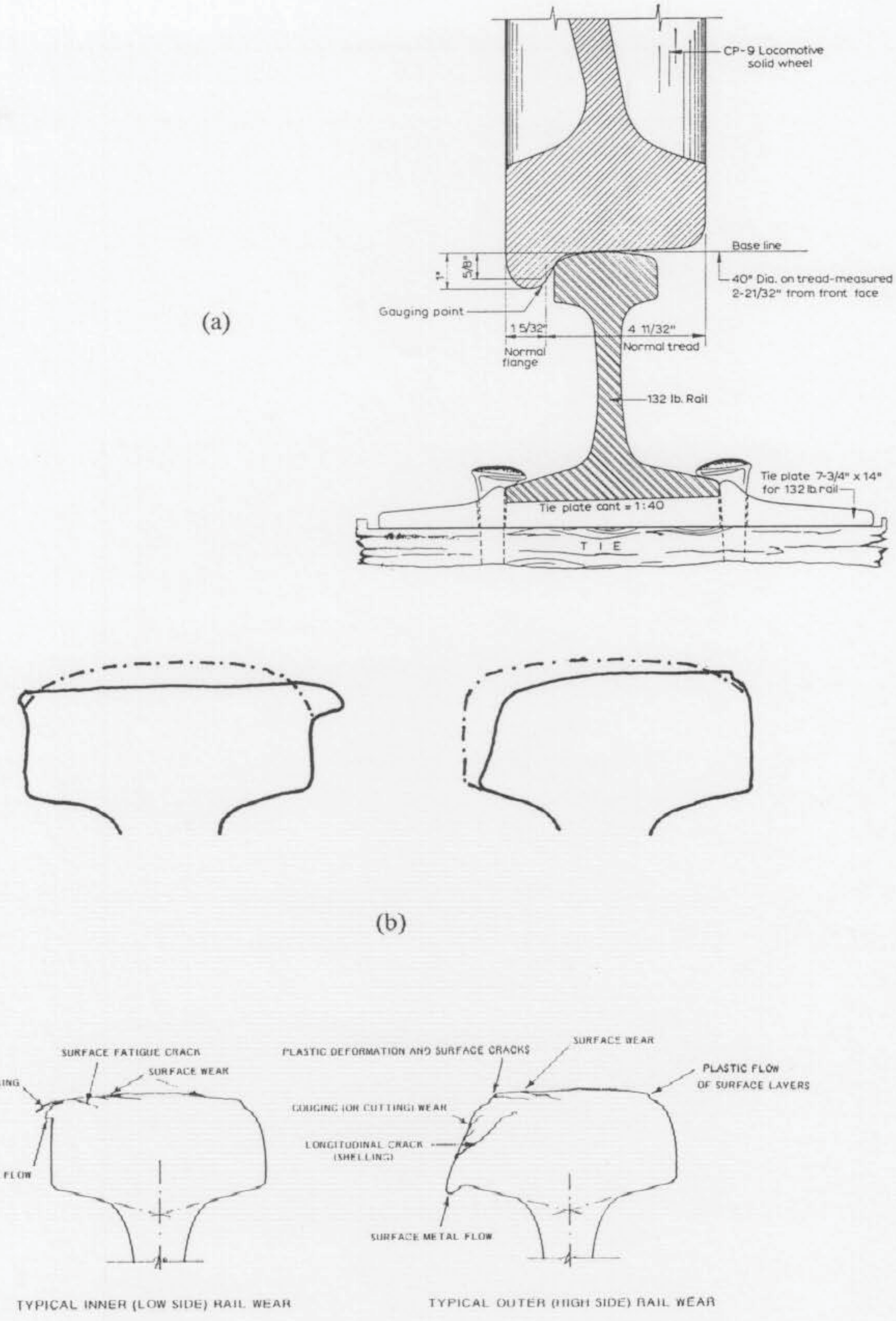



**Figure 5.1** Heavy haul rail damage.

(a) Wheel-rail contact[from Kilburn, 1963].

(b) Rail profile changes with wear on curved track[from Kilburn, 1963].

(c) Damage modes of low and high rail on curved track[from Ghonem, 1984].

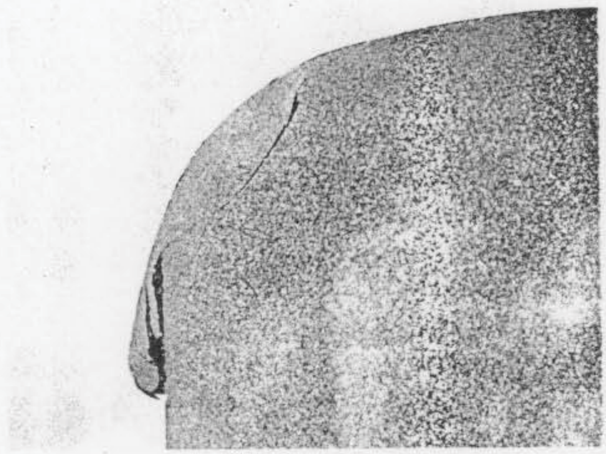


**Figure 5.2** Gauge corner spalling crack from plastic deformation lip[from Clayton et al, 1982a].

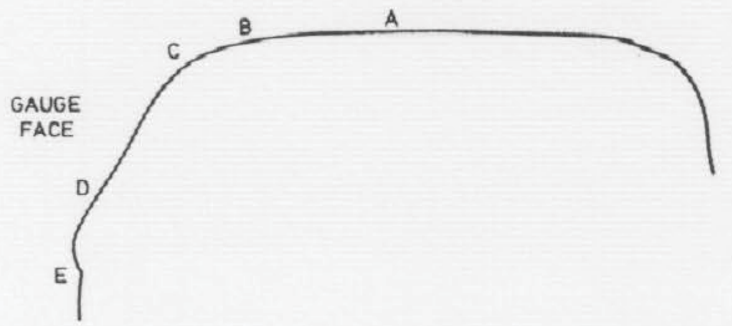
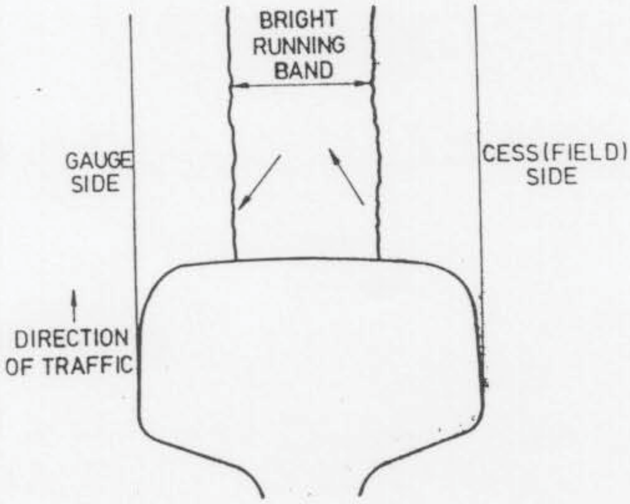



**Figure 5.3** Transverse profile of worn rail head[from Clayton et al, 1982a].




(a)

(b)

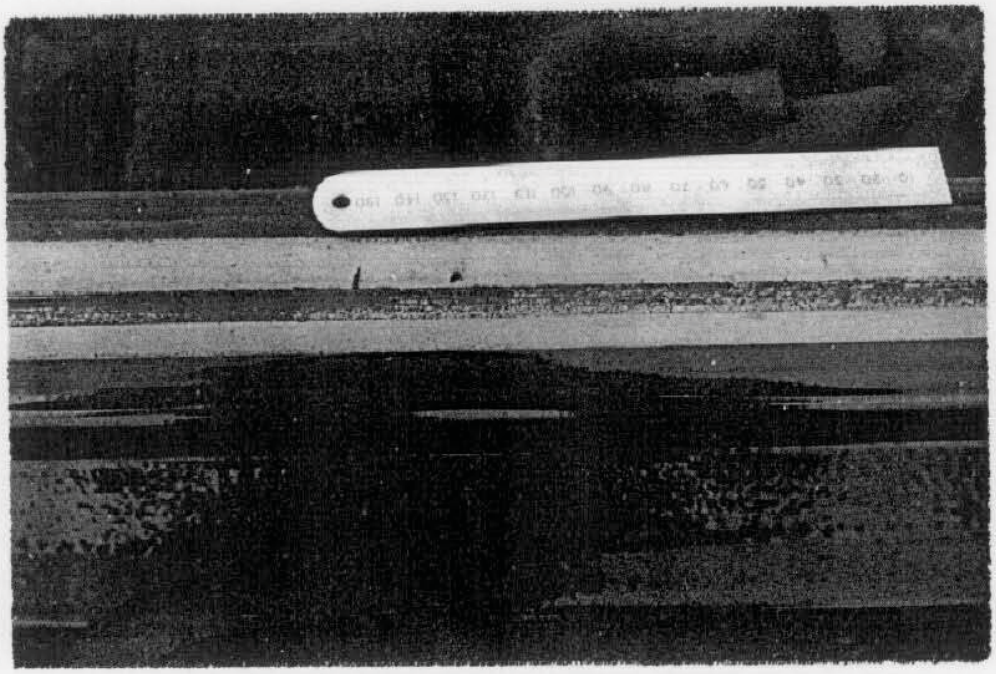


**Figure 5.4** The rail central running band.

(a) Surface shear directions[from Clayton et al, 1982a].

(b) Etching of rail surface to reveal of bands of WEC[from Clayton et al, 1982b].

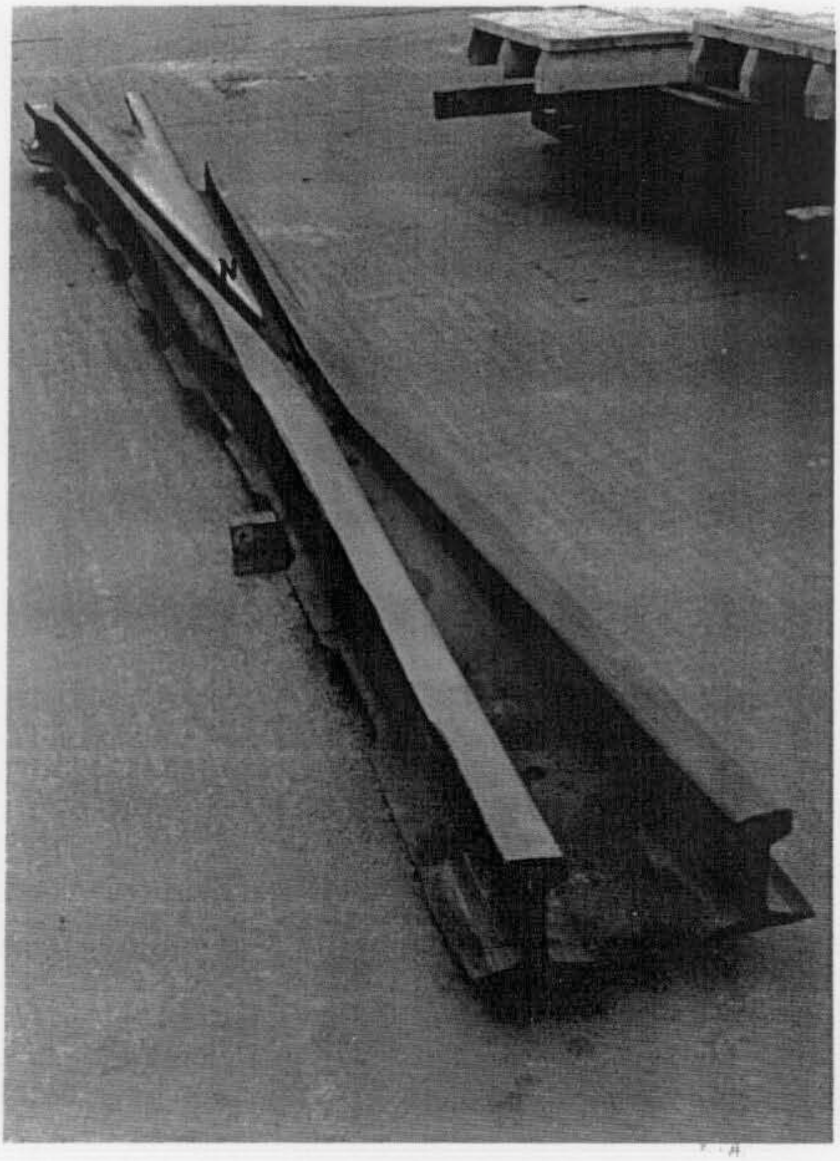


**Figure 5.5** Part of a railway crossing; the nose is marked "N"[from Callender, 1983].

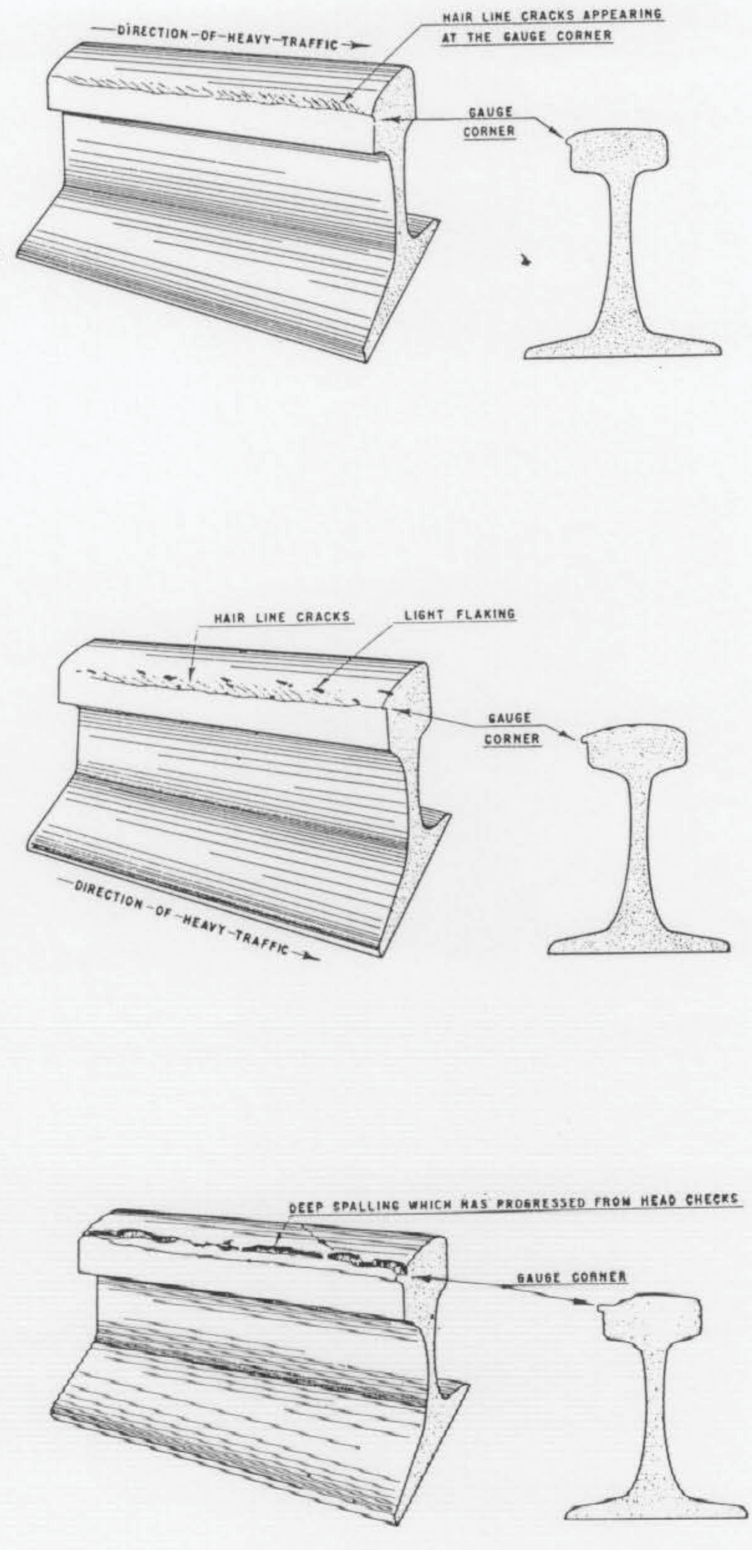
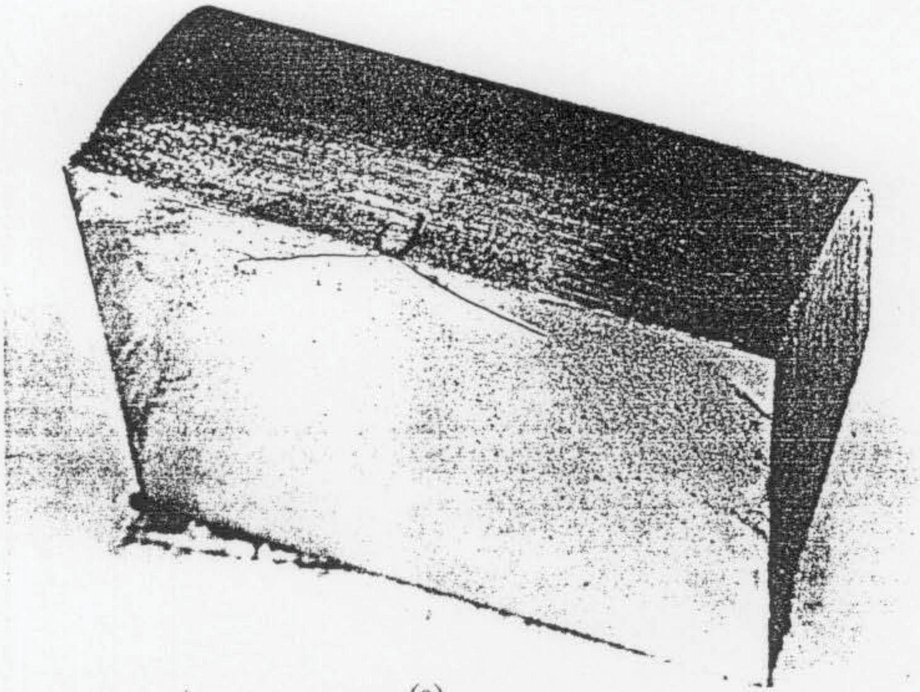
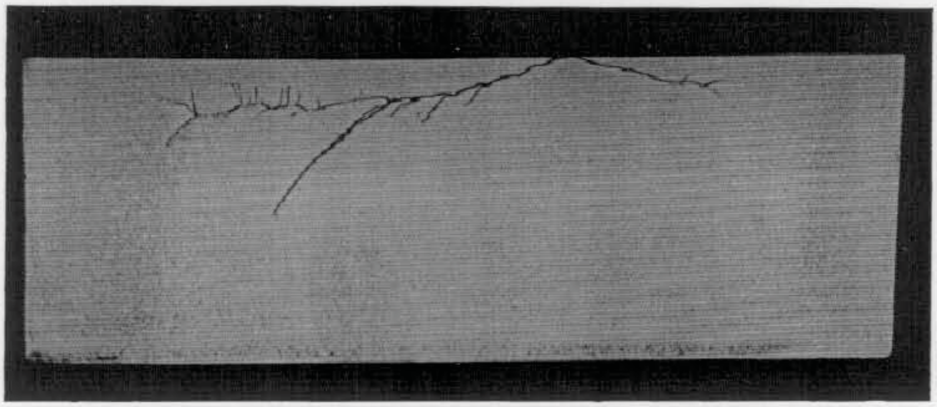



**Figure 5.6** Sequence of rolling contact fatigue damage at a gauge corner leading to spalling[from Kilburn, 1964].



(a)

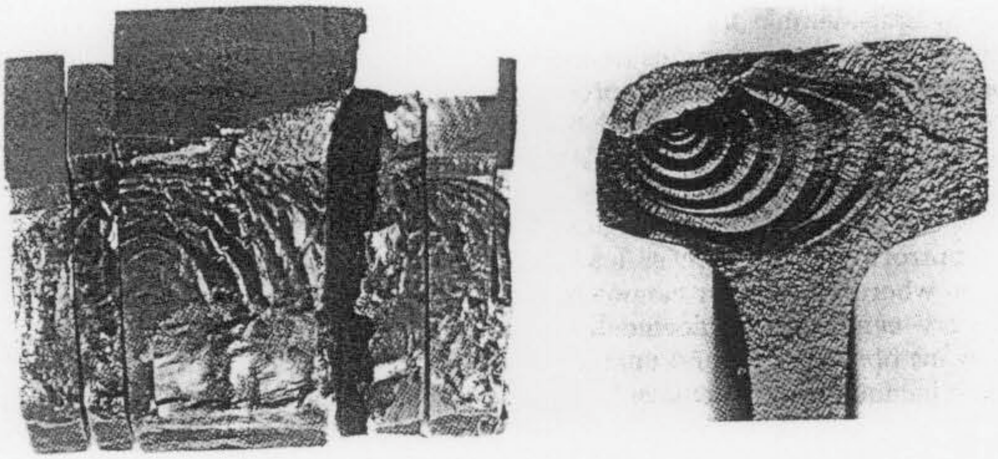


13 mm (b)

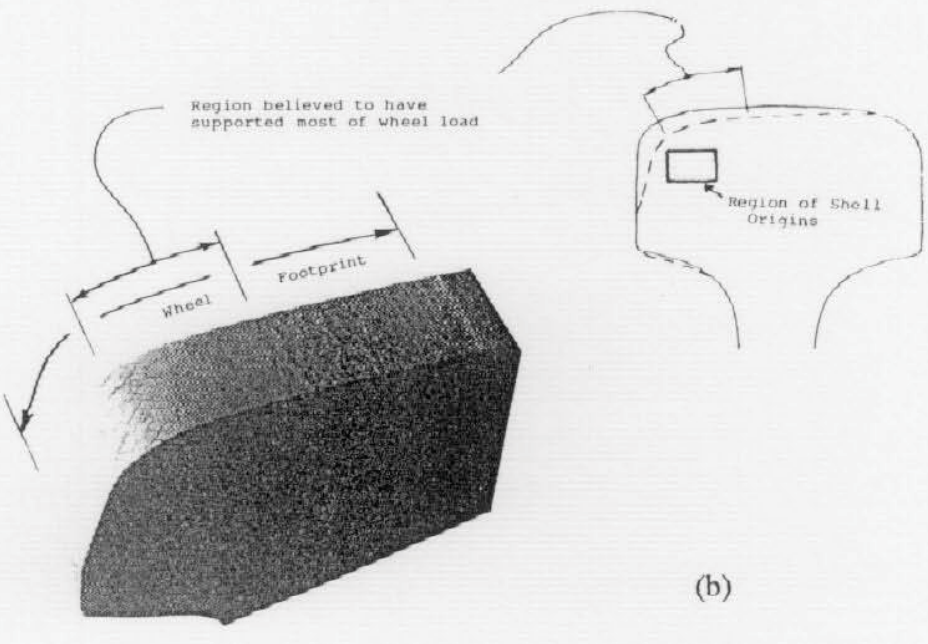
**Figure 5.7** Rolling contact fatigue cracks.

(a) Axial section through a typical squat defect[from Frederick and Jones, 1980].

(b) Fatigue crack with steeply angled branch[from Beynon, Garnham and Sawley, 1994].



(a)

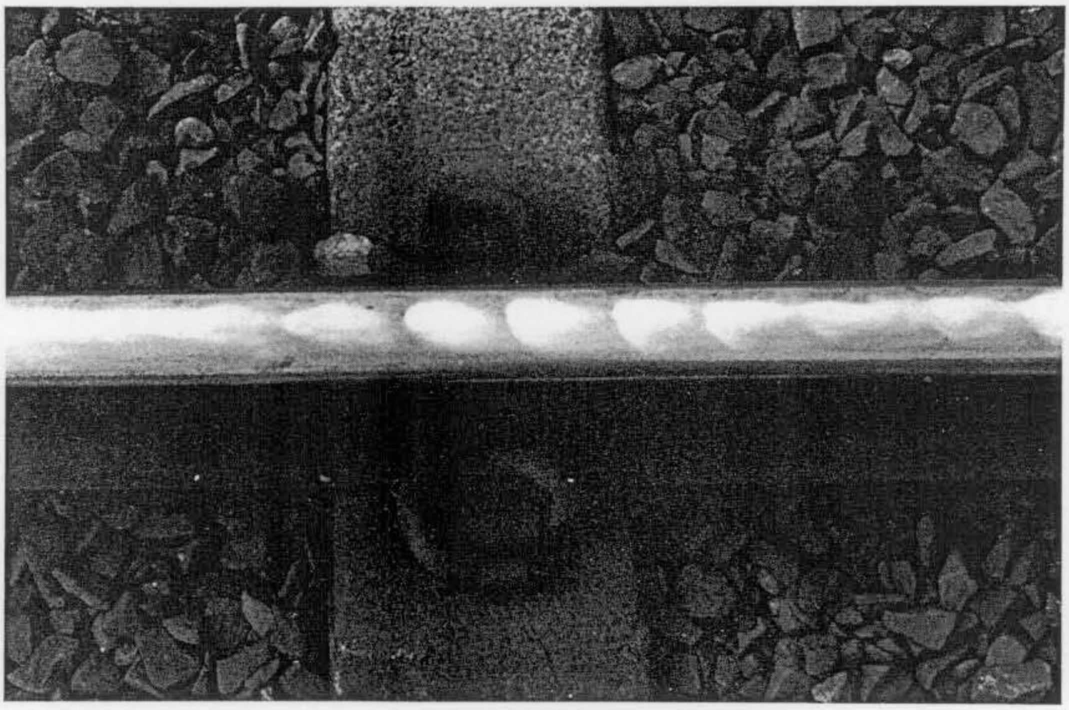



(b)

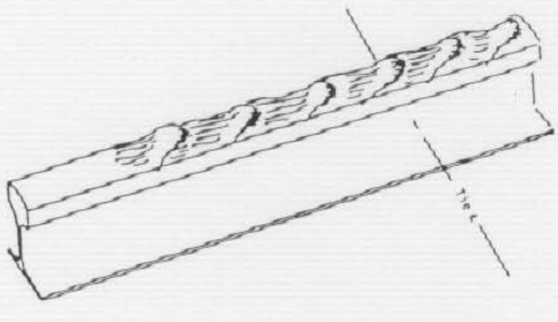
**Figure 5.8** Sub-surface initiated rail fatigue; "shelling".

(a) Longitudinal and transverse shelling failures[from Steele, 1990].

(b) Location of shelling failures[from Steele, 1990].



(a)

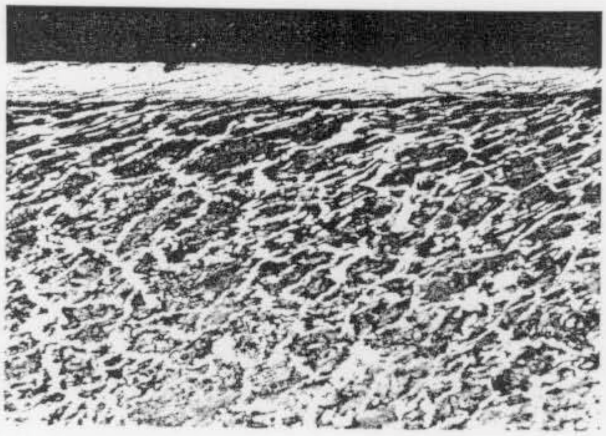


(b)

**Figure 5.9** Rail head corrugations.

(a) Typical corrugated rail from the British network[from Clayton & Allery, 1982b].

(b) Sketch of Baltimore Metro rail corrugations[from Ahlbech & Daniels, 1990].

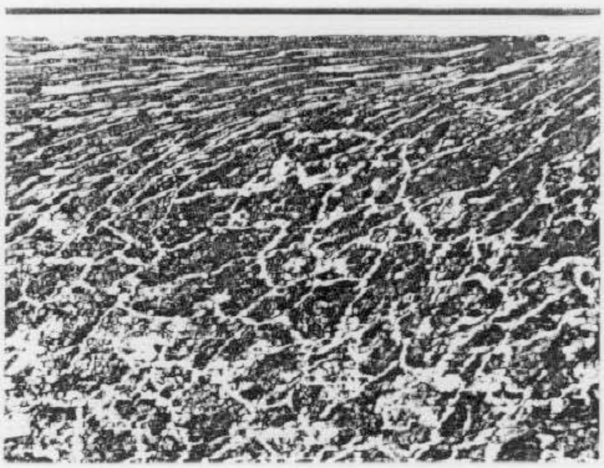


← W.E.C. (not nickel plate)

(a)

← nickel plate on microsection

(b)



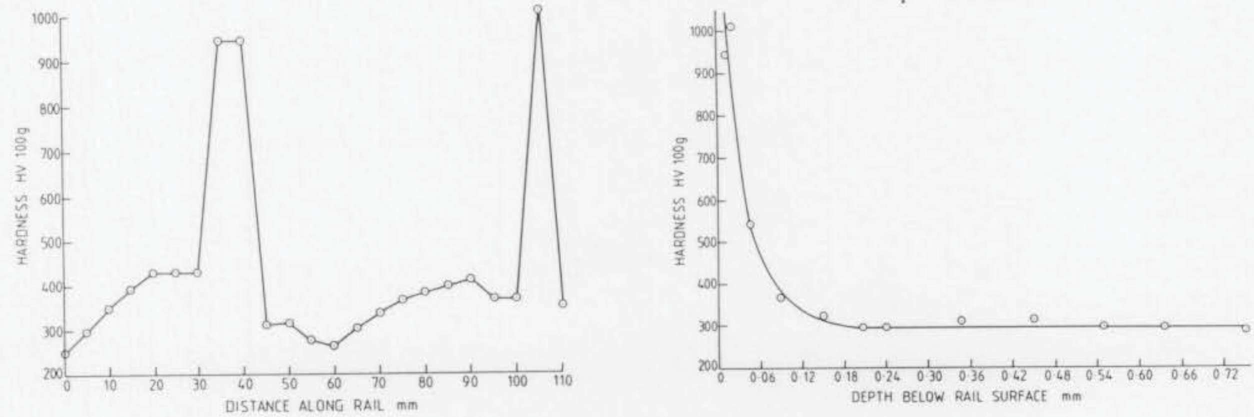
← nickel plate on microsection

(c)

**Figure 5.10** Longitudinal sections through corrugation peaks[from Clayton and Allery, 1982b].

(a) Sheared pearlite and WEC.

(b & c) Sheared pearlite with aligned cracks.




(a) (b)

(c) (d)

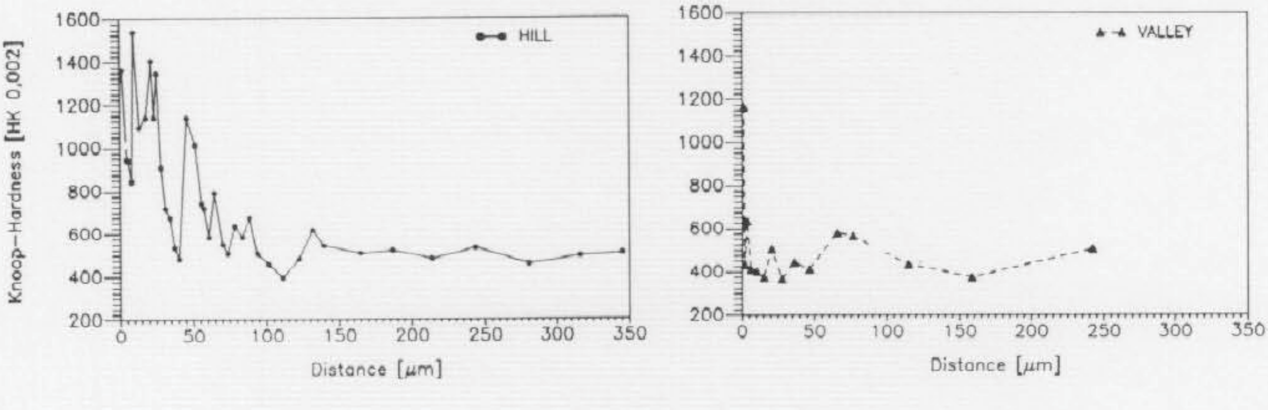



**Figure 5.11** Micro-hardness profiles of corrugated rail.

(a) Longitudinal traverse 0.02mm sub-surface across two BS11 rail corrugation peaks[from Clayton & Allery, 1982b].

(b) Surface hardening at a BS11 rail corrugation peak[from Clayton & Allery, 1982b].

(c & d) Surface hardening at a UIC60 rail corrugation peak (c) and trough (d)[from Feller & Walf, 1990].

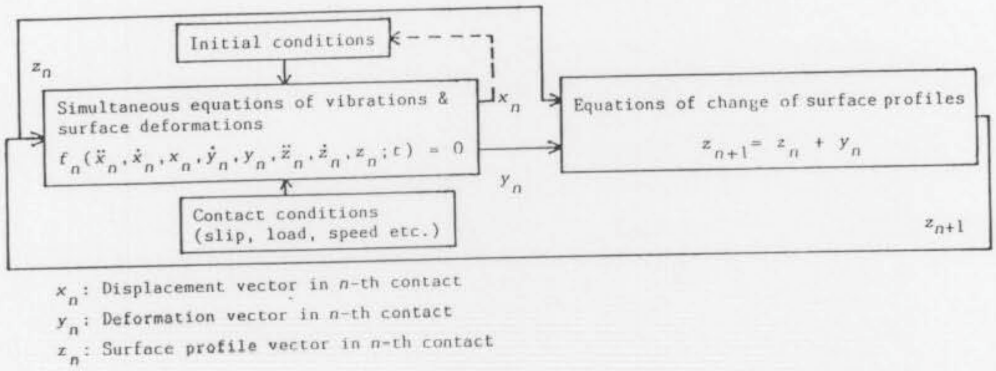



**Figure 5.12** A system for corrugation development[from Suda, 1990].

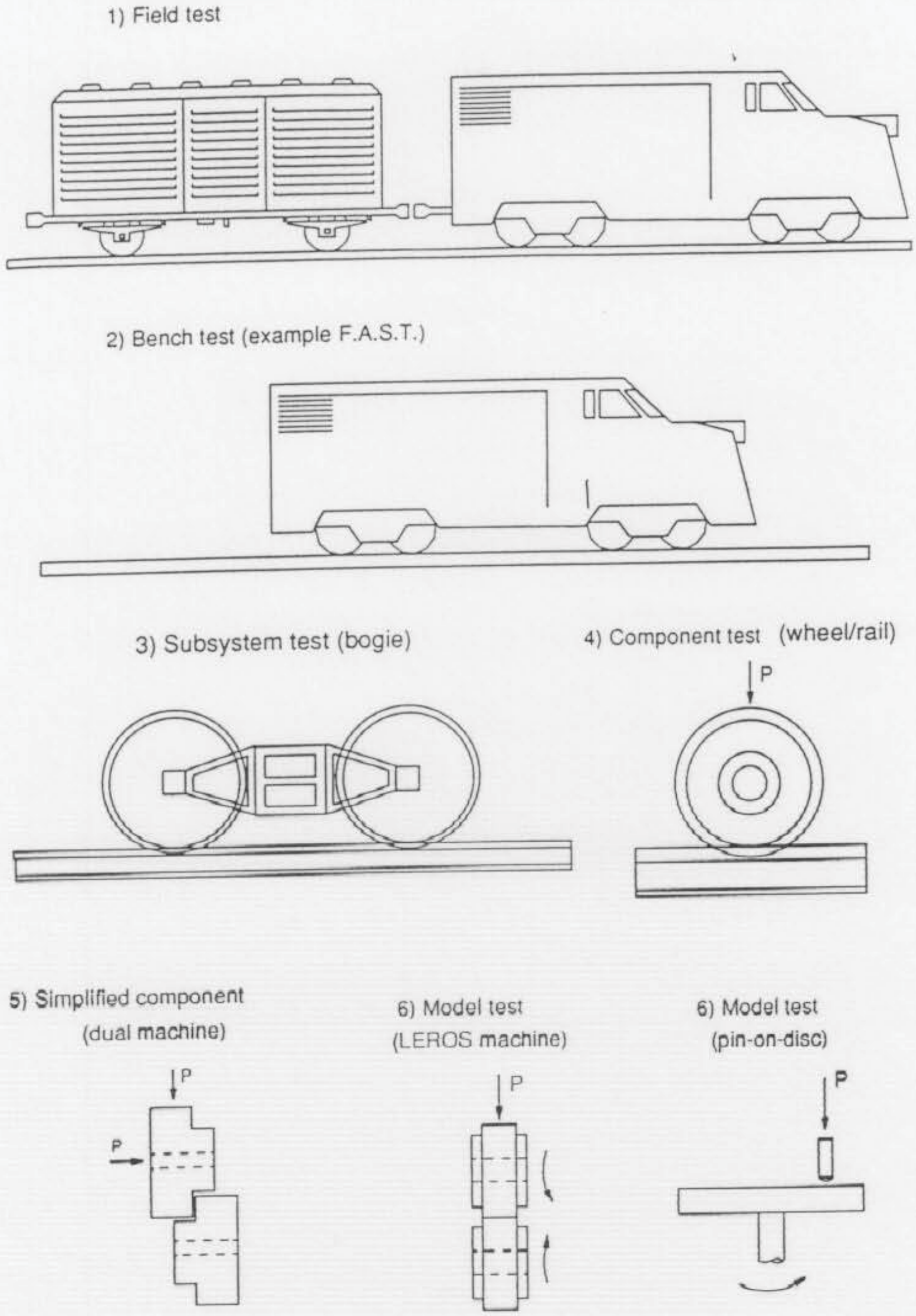



**Figure 5.13** Types of rail material test[from Perez, 1992, after Zum Gahr, 1987].

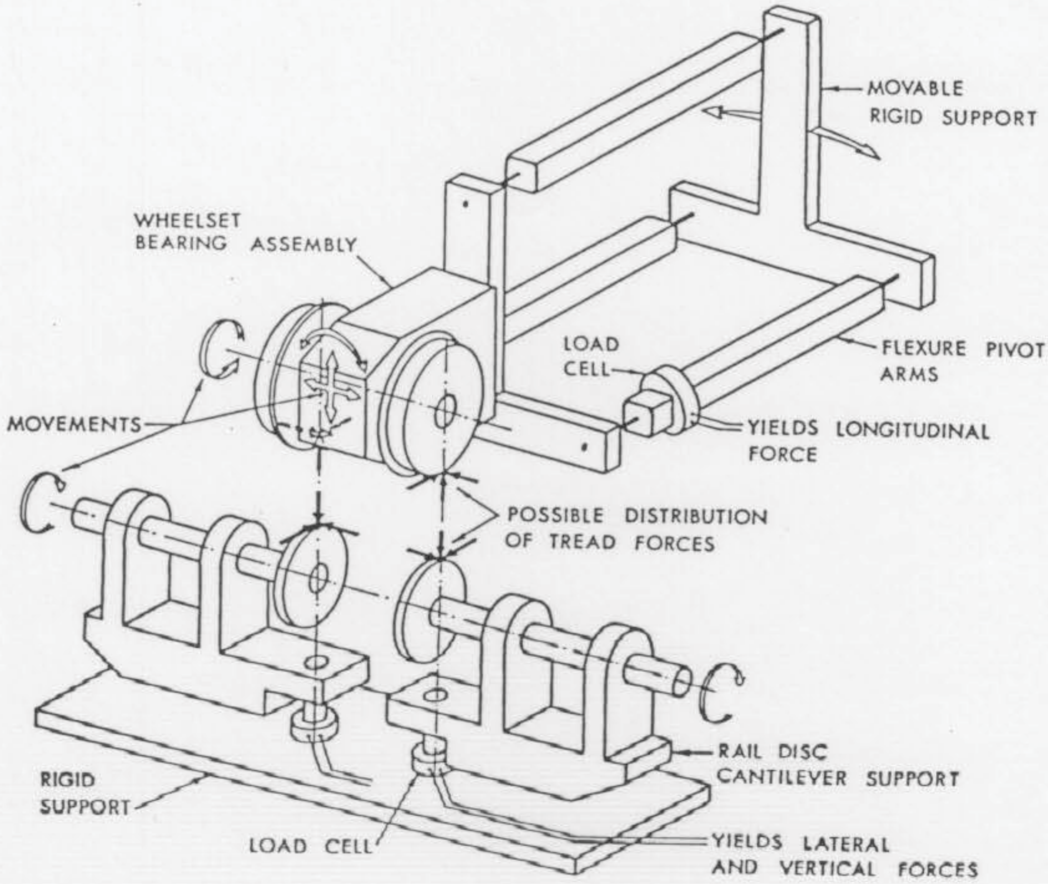



**Figure 5.14** Tenth scale rail-wheel contact, yawing test machine[from Kalousek, 1986].