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Grassie, Stuart L, Fletcher, David I, Gallardo Hernandez, Ezequiel Alberto et al. (1 more author) (2011) "Studs": a squat-type defect in rails. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit , 226 (3). pp. 243-256. ISSN 0954-4097

https://doi.org/10.1177/0954409711421462

"STUDS": A SQUAT-TYPE DEFECT IN RAILS

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ABSTRACT

In the mid-2000s a rail defect that was classified as a "squat" became increasingly common on London Underground's track. By 2006 there were about 600 of these and they had become the Underground's single most common rail defect. This defect occurred almost exclusively on lines carrying relatively new rolling stock. The work reported here was undertaken initially to characterize this defect, advise as to whether it was indeed a squat and propose a hypothesis that explained its mechanism of formation. The paper includes observations and measurements from track and initial results of metallurgical analysis. The hypothesis for formation of the defects is presented, and both similarities and differences are discussed between these defects and the classical "squat". The defect on London Underground appears to be the same as that described by Marich and his colleagues in Australia and by Li and his colleagues in the Netherlands. It is evidently not a rolling contact fatigue defect. In order to avoid confusion arising from simple misuse of an established term, it is proposed that these defects be given a different name, for which "stud" is proposed. Evidence to date is that the "stud" is a significantly more benign defect than a "squat".

Keywords: Squat, stud, rolling contact fatigue, rail, pearlitic steel

1 Introduction

A squat is a rolling contact fatigue (RCF) defect in rails whose characteristics are well understood as a result of more than two decades of research from the mid-1970s, primarily in Europe and Japan e.g. [1,2]. Squats are particularly dangerous defects because if they are allowed to remain in track, the commonly develop into rail breaks. For this reason railway systems are concerned about the presence of squats and ensure either that rails are ground routinely to prevent small surface breaking cracks propagating and to manage rail-wheel contact stresses, or that rails containing cracks which have developed too deeply to be ground out are removed. The fact that squats to date have been associated primarily with passenger and mixed traffic railways has heightened an awareness of this hazard.

There is evidence that in the last 10-15 years a defect that shares many characteristics with the classical squat has become more prevalent. The literature on this defect is very much less mature than that on squats: Marich and his colleagues in Australia e.g. [3,4] and Li et al in the Netherlands e.g. [5] are responsible for most if not all of the published work to date. In order to provide relevant background to the present paper, a companion paper [6] summarises the current understanding of the classical squat, the very much more limited material on those more recent defects that have been classified as squats, and draws attention to a couple of earlier references where the current problem may have been discussed without this having been realised at the time.

The original work described here arose primarily in an attempt to understand and assist with these defects, which beset London Underground (LU) in the mid-2000s. These defects, of which there were about 600 on LU's 840 track km in 2006, were classified by the ultrasonic operators as squats. They appeared as squats to the naked eye and also the signal on their ultrasonic equipment (the conventional and widely used "walking stick") indicated that there was a sub-surface defect of substantially the same character as a squat. The vast majority of these defects occurred on the Jubilee, Northern and Central Lines, which had the newest rolling stock on the Underground. It was noted also that the defects were almost absent in tunnels, which was consistent with what was known of classical squats.

Although Tubelines had received advice from several sources that these defects were indeed squats, it was proposed that this was not in fact the case. An initial hypothesis to explain their development was proposed and used as a basis for the further investigations presented here. This paper contains initial measurements and observations from track in London and elsewhere and also the results of metallurgical investigations, which were essential to reveal critical characteristics of the defects. Similarities and differences between these defects and squats are tabulated and discussed, and a more complete hypothesis is proposed for their development that is consistent with research undertaken to date. It is difficult to be certain that these defects are identical to those studied elsewhere [3-5], but the critical characteristics appear to be identical insofar as these can be determined from the published literature and otherwise.

The defects studied here are certainly not squats, insofar as the term was introduced and used by Clayton, Allery and others [1,2]. However, the defects share superficial characteristics. To reduce confusion not only in the text but more importantly amongst railway engineers, it is proposed that these defects be referred to by another name, for which "stud" is proposed. If these defects are indeed recognised as a different phenomenon with a different cause, this is a first step to devoting resources to solving the correct problem. The potential for confusion is exemplified by the recent publication of two "best practice" handbooks on the wheel/rail interface. In one of these the conventional explanation is given of squats as an RCF defect [7] whereas in the other, squats are treated as a different type of defect whose characteristics are less well defined [8]. This paper suggests that one way of resolving this undesirable state of affairs is to consider that there are two significantly different defects. It is proposed that one of these defects (the classical squat) is relatively well understood as a result of decades of fruitful research. On the other hand, research into and understanding of the other type of defect (a "stud") is in its infancy.

2 Contribution of the current work

2.1 Observations and characteristics

The majority of work described here was sponsored by Tubelines Ltd who maintained about half of London Underground's infrastructure in a Public-Private Partnership initiative that came to an end in 2010. In 2006-2007 528 defects were classified by

Tubelines staff as "squats" on the 330 track km that they maintained. Almost 500 of these defects were on the Jubilee and Northern Lines, which had new rolling stock. Elsewhere on London Underground (LU) these defects had been found only on the Central line, which was maintained at that time by Metronet Ltd and which also had relatively new rolling stock. This type of defect existed previously and some metallurgical analysis and prior investigations had been undertaken, but by 2006 they had become LU's single most common rail defect problem. The cost of their removal, primarily by rerailing the affected sites, was then about £6 million p.a.. Localised weld repair, which is used also elsewhere for this problem, has subsequently been developed as a less expensive treatment of studs.

Examples are shown of studs from the Northern Line and from two other metro lines (Figures 1(a)-(c) respectively). In the first two cases there were several dozen defects within a few hundred metres of track. Defects were observed in curves and also in straight track, and in almost all cases had the characteristic appearance of the defects shown in Figures 1(a) and (b), with a V-shaped surface-breaking crack whose apex pointed to the field side of the rail. In all cases the stud is more or less in the centre of the running band. In some cases, as in Figure 1 (a), corrugation was present and had been exacerbated by the irregularity of the stud. The stud shown in Figure 1(b) was in the high rail of a curve. This had some gauge-corner cracking (GCC), but there was no sign of the stud being associated with surface cracks on the gauge corner. There has been some spalling from the defect in Figure 1(c), probably as a result of relatively recent grinding.

Defects on LU were concentrated not only on specific lines but also in so-called “hot spots” on those lines: 10 sites on the Jubilee and Northern Lines were responsible for 45% of Tubelines’ defects. Defects occurred almost exclusively in open rather than covered/tunnel sections: this has also been observed by Marich and his colleagues e.g. [4]. Both characteristics are apparent from the “map” of defects shown in Figure 2 (for the Central Line). Stations are shown along the middle of the map. Left and right rails on the eastbound and westbound tracks are shown above and below the stations respectively. There are clear concentrations of defects e.g. around 28km on both lines and also a gap from about 32km to 48km with very few defects. The line is underground in this area. Several “hot spots” are on the approach to signals, where many trains would first be braking and then under traction. This characteristic has also been observed by the first author on other railway systems. Marich and his colleagues claim to have found no correspondence between defects and signals on RailCorp track in Australia [4]. Some hot spots on London Underground are not where a train would be expected to stand awaiting signal clearance, but on the straight approaching a signal, where drivers may coast at low speed for a signal check then apply traction when the signal turns to green. Other hot spots on the Northern Line and on other metro systems are found on the grade rising out of the underground section, where trains would be under consistently high traction. Some particularly severe areas of studs are associated with a combination of the two conditions i.e. signals at the top of the incline from an underground section.

It had been suggested from previous metallurgical analysis that the defects initiated at a depth of about 3-5mm and then propagated in both directions i.e. along (and slightly down) into the rail, and up to the rail surface. No initiation mechanism was proposed. A typical cross section from a defect that was removed from the Jubilee Line in 2006 and classified as a squat is shown in Figure 3.

In some "hot spots" defects developed in about 3 months from laying of new rail (on lines carrying barely 20MGT of traffic per annum), which is an order of magnitude faster than a classical squat (see e.g. Figure 4 of ref [6]). Although many defects had been detected, these appeared to be relatively benign: few if any rail breaks had been directly attributed to these defects. In 2006, only one broken rail on Tubelines' system occurred in which the crack had initiated at the railhead. This had all the appearance of a classical RCF defect with a crack developing through a highly sheared surface layer, then turning down into the rail and resulting in a transverse defect. This apparently more benign characteristic of studs as compared to squats has also been noted by Marich et al [4,5]. Nevertheless because cracks exist only a few millimetres below the surface (Fig 3), rails are regarded as "ultrasonically untestable". If operators had more sophisticated equipment that enabled the rail to be tested from the side as well as from the running surface, it would be possible to test the defects in detail and determine the depth of cracks, their rate of development and whether other defects were hidden by cracks close to the surface. However, a conventional (and certainly also a safe) approach is to consider that a crack that has developed sufficiently deeply in the rail is a potential hazard and to schedule this for renewal or repair.

2.2 Inspection and measurement in track

An initial hypothesis was proposed that the defects observed on London Underground were the product of wheelslip, and that it may accordingly be possible to observe and measure features on both left and right rails even if an "ultrasonic defect" had been noted on only one rail. Both rails would be affected by wheelslip since they are linked by a common axle, although effects may differ because of friction, torsion of the axle etc. To test whether this was the case, observations were made in track and later supplemented by more detailed metallurgical investigation (Section 2.3).
Measurements and photographs are shown in Figure 4 from a known "hot spot" on the Northern Line where sub-surface cracking had been observed ultrasonically at about 3.55m and 7.4m on the left and right rails respectively (on the scale in Figure 4) and the defects classified as "squats". Measurements of irregularities on the rails were made with the CAT (Corrugation Analysis Trolley) [9], which is not designed for this purpose

but appears nevertheless to have worked satisfactorily. It is not proposed here that the defects arose from wheels slipping at the same time on the same bogie (although this could occur). Spacing of these pairs of defects along the track is therefore irrelevant.

At the larger defect, on the right hand rail at 7.4m, irregularities were visible almost directly opposite one another on both rails. Their depth was about 0.4mm and 0.1mm on right and left rails respectively. At 3.55m, an irregularity was visible on the left hand rail, and was barely 0.1mm deep. No irregularity was measurable on the right rail, and although no defect was visible the surface appeared heavily scuffed. The surface of both rails was relatively smooth, whereas a rail with surface-initiated RCF (such as a squat) is rough to the touch in one direction and smooth in the other. This roughness is attributable to the uni-directional accumulation of strain at the rail surface typical of RCF initiation. At the site shown in Figure 4 there were locations with quite distinct "blobs" of white phase directly opposite one another on the two rails, but no ultrasonic defect had been noted. Quasi-periodic white phase of this nature is a feature of stud sites more generally, and may (for example) occur because of torsional oscillation of axles when starting from standstill. This is discussed further in Section 2.3.4. It was also noted, and is to some extent visible in the photographs, that there was lubrication on the gauge face of the rail opposite the defect i.e. the right rail at 3.55m and left rail at 7.4m. Evidence of an obvious difference in friction on opposite rails has been noted at other sites where studs are present.

2.3 Metallurgical examination

Several defects were removed from an open section the Northern Line, on ballasted track, for detailed metallurgical examination. Results are given here from a rail removed from one of the sites examined (designated site A) at which samples were taken close to two visible defects. One defect was at 370-470mm within the rail section removed, and is referred to as being nominally at 430mm, whereas the other was at 1360-1480mm and is referred to as being nominally at 1450mm. The rail from site A was removed from 65m before a signal. In view of the hypothesis that studs may be a consequence of wheelslip, samples were removed from both rails opposite one another. These were aligned in the laboratory using the marks that had been made by the sleepers on the railfoot (Figure 5 shows the defect at 430mm aligned with the opposite rail). The ultrasonic defects, which were the reason for removing the rail section, were in the right rail (where right and left are defined looking in the direction of traffic). The defect from location 430mm is shown in greater detail in Figure 6 and has the characteristic appearance of an inverted V, with the apex towards the field side of the rail. The right rail defect at 1450mm was in fact a series of defects similar to Figure 1(b). In both cases there was visible damage on the opposite (left) rail.

2.3.1 Surface profile examination

The surface profile of both left and right rails was measured at the defect location and compared to the profile of a section of rail at which there were no visible defects or surface irregularities (Figure 7). For defect location 430mm the depth of the dip in the defective rail is about 400μm, which is similar to that of the defect measured elsewhere in track (Figure 4). The depression spans about 60mm (390mm to 450mm, where the scale is that shown by the tape in Figures 5 and 6). The ridge in the middle of the depression (between the two "lobes" of the defect) is barely an inflection in the height of the dip, at about 425mm. On the opposite rail there is a very much shallower irregularity with a length of about 30mm (435mm to 465mm) and surface scratches of 20-50μm depth at about 427mm and 442mm, which are apparent also in Figure 5. This irregularity on the 'opposite' rail is not greatly different from the background level of surface irregularity measured well away from any visible defects.

For the defect at 1450mm the undulations reflect the multiple defects present. There are also undulations on the opposite rail. On the right rail the peak to trough surface height difference is about 100μm, a quarter of the defect depth at the 430mm location. The large spike in the right rail profile at 1425mm was caused by a crack mouth in the main depression of the series of defects. The spike at 1460mm was caused by a crack mouth in the adjacent depression. The small spikes on the opposite rail (1380 and 1460mm) are similar to those on the left rail of the 430mm sample. Inspection of the rail surface showed the most likely cause in both cases was damage sustained in removing the rail from track. At the 1450mm location damage to the right rail (large visible defect) consists of two depressions of 80-100μm depth, while on the opposite rail there is a trough of approximately 50μm depth over a length of about 120mm.

At both defect locations, the length of surface profile recorded should adequately cover the location for both wheels on a single wheelset. Site A was on tangent track, so there would be little yaw of the wheelset, and both wheels would be running at approximately the same longitudinal location on the rail. Any effect on the surface profile at the left and right wheel should have been captured if it had progressed sufficiently to affect the surface profile of the rails. The different degree of damage on the 'opposite' rail was explored further by taking cross-sections and hardness readings as reported below.

2.3.2 Cross-sections through major defects

Samples were removed from both rails at both defect locations by cutting vertically in the longitudinal rail direction along the centre of the running band and through the centre of the visible defects. Specimens were etched to show the grain structure and extent of plastic deformation, and micrographs were stitched together to show detail of the cracks in the defective rail. Figure 8 shows that the defect at 430mm was surface-breaking on the sectioning plane selected whereas the defect at 1450mm was sub-surface on this sectioning plane. The defect at 1450mm broke the surface elsewhere as shown by the spike in the surface profile in Figure 7(b). Figure 8(b) is therefore not an indication of completely sub-surface growth, just that the crack was entirely below the surface on this sectioning plane through the rail. Both defects had developed more extensively from their shallowest point in the direction of traffic, but also had branches running in the opposite direction to traffic.

Although there is superficial similarity between the cracks in Figure 8 and a conventional RCF crack, closer inspection reveals that there are also significant differences. Close to the surface there is almost no accumulated plastic flow in the rail except just above the crack mouth. Minor distortion of the microstructure to a maximum depth of about 130μm is present across the sample. This is far below the 'ductility exhaustion' level typically seen in RCF crack initiation for which plastic flow accumulates in a heavily sheared layer throughout the rail (see e.g. Figure 3 of ref [6]). RCF cracks initiate when the ductility of this layer has been exhausted. The only location of greater plastic flow (to a depth of 450μm) is in the poorly supported material just above the crack. However, even here the well supported material below the crack remains undeformed below 130μm. This localisation of plastic flow indicates that flow is a consequence of the crack rather than its cause: the material has become poorly restrained due to the crack and has then undergone plastic deformation. The 'ductility exhaustion' level of plastic flow at the surface needed for crack initiation is not present.

At depths below 450μm the cracks follow an erratic path crossing grains of pearlite. They are not restricted to the softer inter-granular ferrite. There is also no evidence in the individual micrographs which make up the composite pictures in Figure 8 of corrosion of the crack faces. It is therefore unlikely that water contributed to crack growth. This strongly suggests that fluid entrapment, which is a commonly accepted mechanism for propagation of surface-initiated RCF cracks was not active for these cracks. There is also no evidence from the meandering crack faces of the smoothing that would have taken place if significant shear displacement with rubbing of the crack faces had been responsible for crack growth.

It is improbable that these cracks appeared 'fully formed' or spontaneously. However, the metallurgical evidence presented here does not support either of the commonly accepted mechanisms of crack growth.

The two cracks that are apparent in the cross section (Figure 8(a), forward and reverse of the surface breaking location) correspond to the two surface depressions in the rail. The crack mouth coincides roughly with the ridge at about 420mm in Figure 6(a).

2.3.3 Cross-sections to reveal white etching layer

Examination of rail cross-sections at just below the running surface revealed patches of white etching layer (WEL) on both right (visibly cracked) and left (opposite) rails. Figure 9 illustrates the white etching layers found very close to the main defects on the right rail, and in the ‘opposite’ left rail at the same location. The WEL in most cases is well attached to the rail surface. In some locations there were small voids below patches of WEL, although these were not observed close to the major defects. Figure 9 also shows the absence of all but minor plastic flow at the rail surface.

At location 430mm the WEL thickness was greater on the right rail (70μm depth) than on the left rail (18μm depth). On both rails it was found in patches rather than as a continuous layer. From Figure 9(b) it is clear that the pro-eutectoid ferrite has persisted within the WEL, and this emphasizes how little plastic damage is present. This strongly supports formation of this layer by a thermal mechanism rather than by the plastic work mechanism proposed in ref [3] and by Ivanisenko et al [11].

The WEL on the left rail at location 1450mm was different from that observed elsewhere in that it was much thicker. The boundary between WEL and the underlying pearlite was also much less distinct. The patchy nature of the WEL is revealed in this sample, with a separation of about 2mm between the centres of WEL patches. Although the bottom of the WEL layer is indistinct, the layer is nevertheless more than 125μm thick. In track this sample was opposite the site of the undulating surface (Figure 7(b)). Such a thick layer of WEL strongly suggests that the rail steel was exposed to very high ‘flash’ temperatures. Formation of martensite, which gives the white etching appearance, requires that the rail steel reaches a temperature in excess of 727°C followed by rapid cooling [12]. Sufficiently rapid cooling occurs because of the high thermal inertia of the rail, with heat at the surface rapidly dissipated into the surrounding steel [13].

2.3.4 Rail surface hardness

Core hardness readings were taken at 23mm and 28mm depth on the defective and non-defective rails respectively. The difference was dictated by the size of the samples. In both cases the measurements were made well below the contact surface and any accumulated plastic flow. The core hardness (HV, 10kg, average of 5 readings) was 232HV on the right (visibly defective) rail and 290HV on the non-defective left rail. Since both sets of readings were taken well away from any plastic flow produced by the passage of trains, the hardness readings demonstrate a difference in rail microstructure. The production year of the right rail was determined from its rolling mark as 1984, but unfortunately the left rail section did not have a visible rolling mark. (In view of the history of defects at this site, this rail may well have replaced one with defects.)

Surface hardness (HV with a 1kg indenter) was measured along the running band on both left and right rails (Figure 10). There is some periodicity in the hardness on both rails and at both sites with a similar wavelength of about 20-30mm. At location

430mm, where there is a single defect, the peaks in right rail hardness at 390mm, 420mm and 440mm correspond roughly to the running-off end of that defect, the centre and the running-on end respectively (Figures 5,6). At location 1450mm the correlation of hardness and features of the multiple defects is less clear.

The hardness variations are the result of patchy, quasi-periodic white etching layer (WEL) on the rail crown. One possible cause of the quasi-periodic WEL is that it was established by some periodic behaviour of the wheelset. A second possible cause is short-wavelength rail corrugation associated with the track's pinned-pinned resonance [10]. This is commonly at about 460Hz on London Underground as a result of the small rail section and wide sleeper spacing, so a 20-30mm wavelength would correspond to a speed of 33-48km/h. However, in view of the slightly different wavelength of the variation in railhead profile (Figure 7), particularly on the undamaged rail, it would be desirable to examine other samples to resolve the interdependence of periodicity of WEL and corrugation, and to what extent (if any) their periodicity is associated with the stud. In the work of Li et al e.g. [5] it appears that the periodicity of corrugation is closely related to the spacing of the two "lobes" of defect, although it is unclear whether this is a necessary condition for either the defect or corrugation to exist. It is quite possible that WEL is established in a quasi-periodic manner at some locations whereas at others it is initially more continuous and then worn away (or detached) quasi-periodically by traffic.

2.4 Similarities and differences between squats and studs

Similarities and differences between squats and studs are summarised in Table 1.

Table 1 Similarities and differences between squats and studs

Squats	**Studs**
Not found in tunnels: cracks propagate as a result of hydraulic entrapment	Not found in tunnels: no evidence that hydraulic entrapment is required for crack propagation
Apparent as two depressions in rail surface, resulting from leading and trailing sub-surface cracks	Apparent as two depressions in rail surface, resulting from leading and trailing sub-surface cracks
Found in straights and gentle curves	Found in straights and on high and low rails in curves (not just gentle)
Found in locations with high driving traction	Found in locations with high driving and braking traction e.g. approach to signals
Associated primarily with passenger and mixed traffic railways i.e. not heavy haul	Associated with several types of railways: metros, heavy haul, passenger and mixed

or freight lines.	traffic
Not associated with a specific type of traction.	Apparently more prevalent with AC traction.
Plastic deformation ("ratchetting") of surface layer from driving traction is the cause of crack initiation. Unidirectional flow of the surface can be detected by "stroking the rail", as is common with surface-initiated RCF.	Studs exist where there is minimal sub-surface plastic deformation i.e. "ratchetting" is not the cause of crack initiation. Unidirectional surface flow may be present but is not an essential feature.
WEL is found at sites with squats, but no evidence that WEL is a necessary condition for squats.	WEL exists over the crack in all locations where studs have been found. Some detachment of WEL was observed, but no evidence that detachment is required for a stud to initiate.
Initiates at the gauge corner side of the running band.	Initiates in (or below) the middle of the running band.
40MGT of traffic required for "seed" of	Stud can develop within 10MGT of laying

squat to develop; about 100MGT required for squat to become a defect of concern.	new rails.
Crack initiation is consistently at about 20° to the rail surface.	Some cracks are at about 20° but there is no consistency. It is unclear whether cracks initiate at the surface and propagate down or initiate sub-surface and propagate both into the rail and up to the rail surface.
Cracks propagate along the heavily sheared inter-granular ferrite.	Studs develop even where pearlite is not heavily sheared: cracks wander around and through pearlitic grains.
Major crack develops in the direction of traffic, primarily as a result of hydraulic entrapment or shear mode crack growth.	Major crack develops in the direction of traffic but there is no evidence of hydraulic entrapment. Propagation mechanism is currently an open question.
Squat develops under influence of hydraulic entrapment to the edge of the layer of compressive residual stress (about 5mm depth), then usually "branches"	Studs develop in rails in which there is no significant plastic work and accordingly no significant depth of compressive residual stress. Significant crack is at 3-

down to form a transverse defect.	6mm depth in rail. No evidence to date that studs form transverse defects.
No relationship noted between defects on one rail and those on the opposite rail.	Studs on one rail are sometimes associated with an irregularity on the opposite rail but may also appear on only one rail.
Squats are a risk because they can form transverse defects, and also because the rail underneath the squat cannot be tested ultrasonically from the running surface except using specialist equipment.	Studs are a risk primarily because the rail underneath the stud cannot be tested ultrasonically from the running surface except using specialist equipment.

2.5 Hypothesis

The following hypothesis is proposed to explain the features of studs that have been observed to date and the circumstantial evidence regarding their appearance. This is substantially the same as that which was advanced in early work with Tubelines in 2007.

1. Studs are initiated by thermal damage of the rail.

2. Thermal damage results from limited wheelslip, possibly associated with localised areas of poor adhesion. Where studs appear on one rail, there is circumstantial evidence that this results from different friction conditions on the two rails. These would cause one wheel to slip preferentially and the other to slip as a result of the two wheels being interconnected. In such circumstances, thermal damage would be greater on the rail with greater friction, so the stud would initiate on this rail.

3. Studs are associated with vehicles having AC traction or thyristor-controlled DC traction because wheelslip is better controlled than with conventional DC traction. Severe wheelburns are a consequence of gross wheelslip, which may be more common on older forms of DC traction because of more basic wheelslip control. More modern traction systems commonly have higher limiting values of "traction coefficient" i.e. the ratio of traction : normal load. This is particularly the case with so-called "high traction" locomotives that are widely used on the heavy haul systems examined by Marich and his colleagues [3,4].

4. Studs appear on open track and not in tunnels because wheel/rail friction is lower in open track and conditions exist for wheelslip to occur. In tunnels, limiting friction is commonly (but not always) sufficiently high to sustain high traction ratios.

5. The mechanism by which studs propagate is unclear, but may be a low cycle fatigue mechanism associated with contact stresses, of a similar form to that which causes shells to propagate initially parallel to the rail surface [14,15].

3 Conclusions

A type of rail defect has been observed increasingly in the last 10-15 years that bears superficial similarities to the so-called “squat”, which is a surface-initiated rolling contact fatigue defect that was first identified in the 1970s. The more recent defect which is christened here as a “stud”, appears to those who undertake ultrasonic testing of rails to be sufficiently similar to the classical squat for them to classify it as such. Although there is no evidence to date that studs break rails, whereas breaks commonly develop from squats, the fact that there is a sub-surface crack makes the rail “ultrasonically untestable” (at least by conventional means). The defect must therefore be removed or an alternative treatment or inspection method developed. Studs can be extremely common and concentrated within short sections of track: they appear to be particularly prolific on the approach to signals and on the incline up from underground sections of metro systems, where dozens may exist within a few hundred metres. Studs also develop within about 10MGT, which is almost an order of magnitude more quickly than squats.

Examinations have been made of studs in the field and a detailed metallurgical examination has been made of studs removed from a metro line. From this work it is clear that studs are not a conventional RCF phenomenon, and indeed that they can develop (as in the sample considered here) in the absence of significant plastic deformation of the rail surface. White-etching layer (WEL) is closely associated here and in some previous work with studs, and it is proposed here that the white-etching layer is a fundamental component of the mechanism of thermal damage as a result of controlled wheelslip that initiates a stud. Different forms of damage, such as irregularity of the running surface and patches of WEL, have been noted on pairs of opposite (left and right) rails in the field and in the laboratory, which is consistent with the proposed initiation mechanism by controlled wheelslip.

Studs appear to be associated with more modern traction control systems, in particular AC traction, in which wheelslip is better controlled to permit operation at higher traction ratios. It may correspondingly be the case that wheelburns are less common with such traction packages.

Work is in hand to test the proposed hypothesis more fully and, if it is found to be viable, to develop a way of obtaining the benefits of modern traction control systems at less cost in rail (and possibly also wheel) damage.

4 Acknowledgements

The authors are grateful to Tubelines Ltd for supporting the initial work and the metallurgical analysis contained in this paper and to Tubelines and Transport for London for permission to publish the paper. They are also grateful to the reviewers for their constructive suggestions on the initial paper, and to other railway systems and suppliers whose support has made it possible to collate the material presented here. Parts of this work were presented at the 8th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems in Florence in September 2009.

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Figure captions

1 "Studs" from three railways (arrows on the rails in (a) and (b) point in direction of traffic and towards gauge face; arrows superposed on photos point to the apex of the "V" shaped crack)

2 Defect "map", showing position of defects on the Central Line

3 Cross section of defect, showing depth of a few millimetres below rail surface and length of about 30mm

4 Observations and measurements from opposite rails at defect locations (classified as "squats" on left rail at 3.55m and on right rail at 7.4m)

5 Overview of rails at site A 430mm defect

6 Detail of defect on right rail

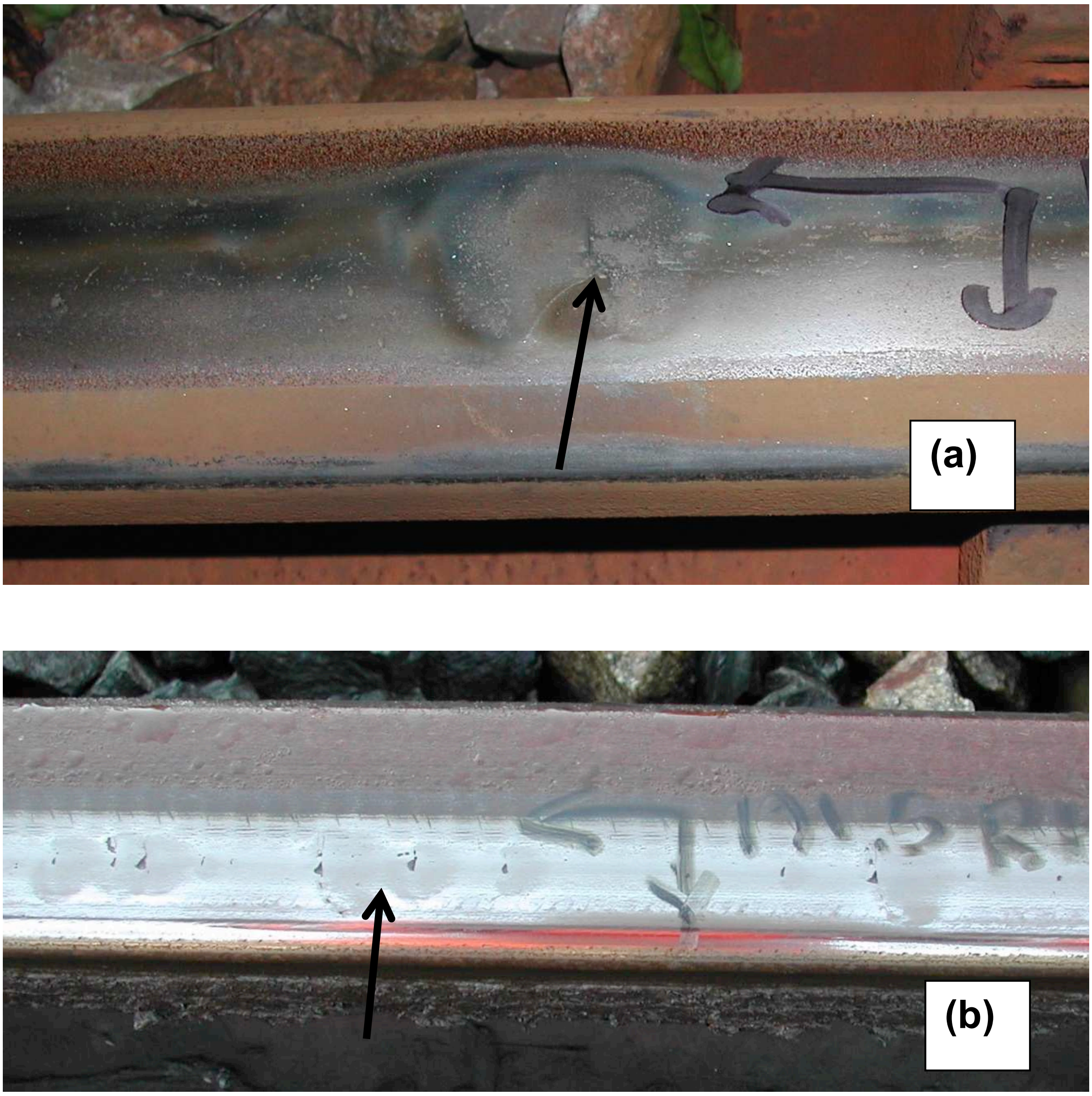
7 Irregularities on defective rail, opposite rail and a reference section of rail. The reference data is vertically offset for clarity. (a) Defect location 430mm. (b) Defect location 1450mm.

8 Detail of crack in defective rail, formed using multiple micrographs. (a) Location 430mm. (b) Location 1450mm.

9 White etching layer on the rail running surface. (a) Location 430mm, left rail. (b) Location 430mm, right rail. (c) Location 1450mm, left rail. (d) Location 1450mm, right rail. All sections are in the rail longitudinal direction, except (b) which is from a transverse section.

10 Variation in surface hardness on defective rail and opposite rail (aligned) for locations (a) 430mm and (b) 1450mm. Average of two readings at each position.

Figure 1



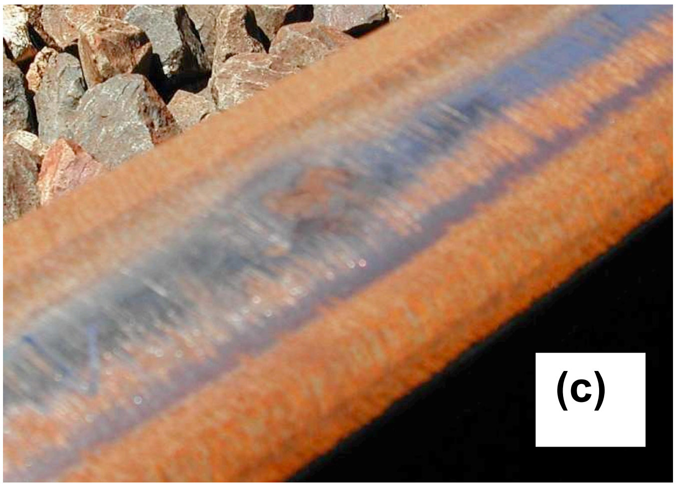
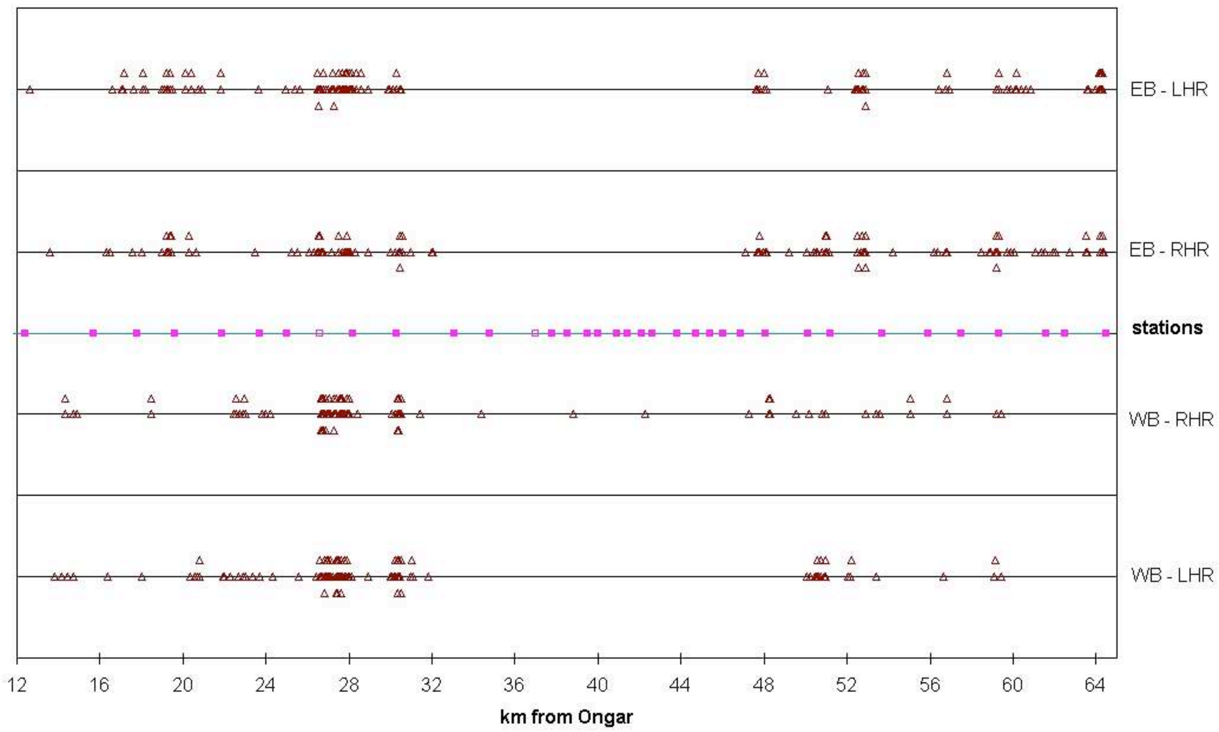


Figure 2



EB - LHR
EB - RHR
stations
WB - RHR
WB - LHR
12
16
20
24
28
32
36
40
44
48
52
56
60
64
km from Ongar

Figure 3

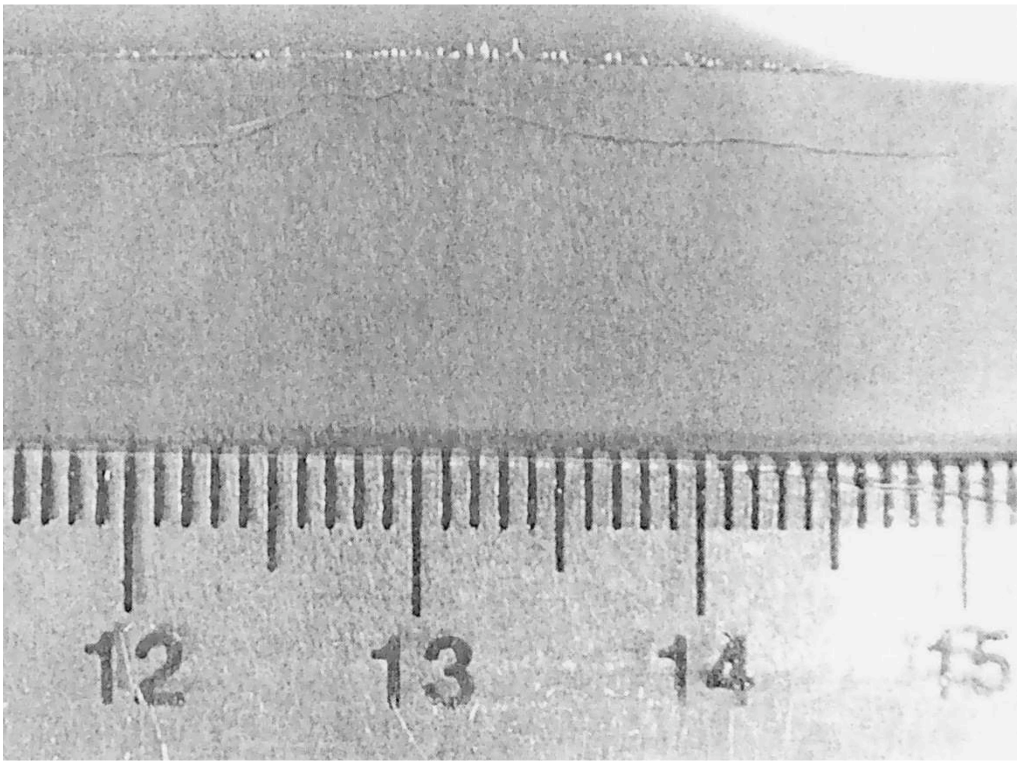


Figure 4

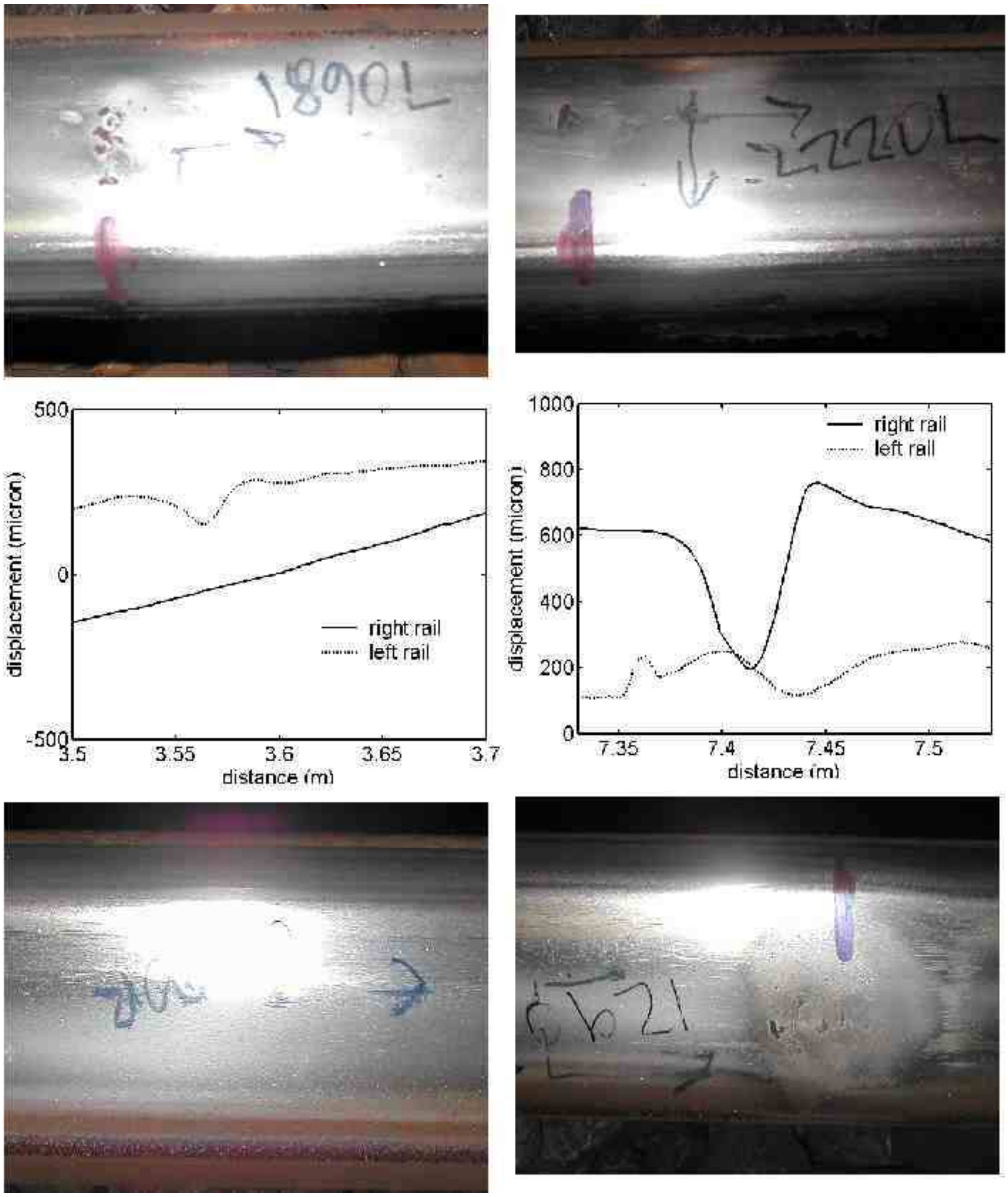
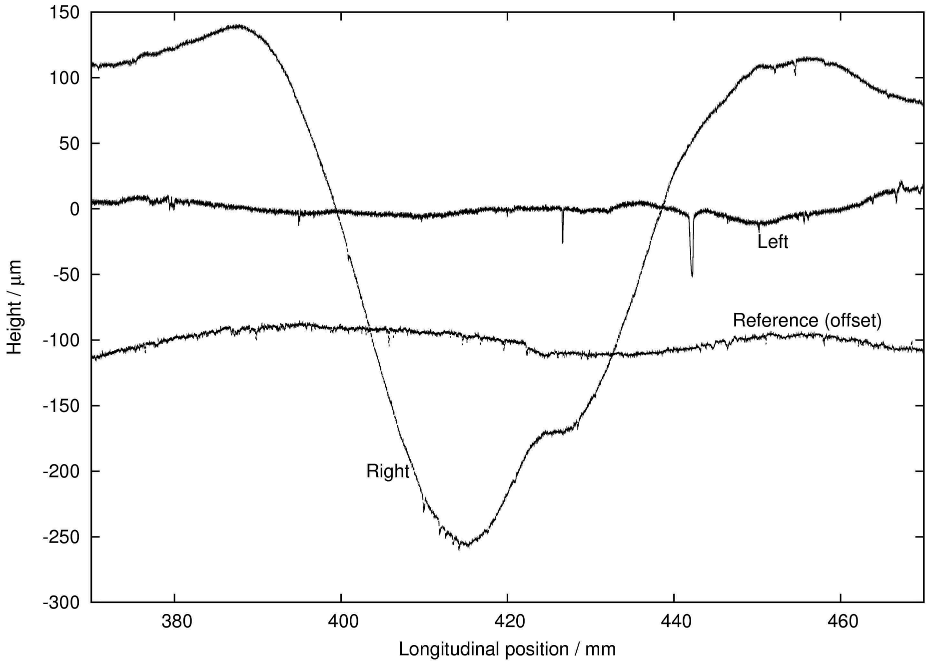

1890L
2220L
displacement (micron)
distance (m)
right rail
left rail
500
0
-500
3.5
3.55
3.6
3.65
3.7
1000
800
600
400
200
0
7.35
7.4
7.45
7.5

Figure 5

Figure 6

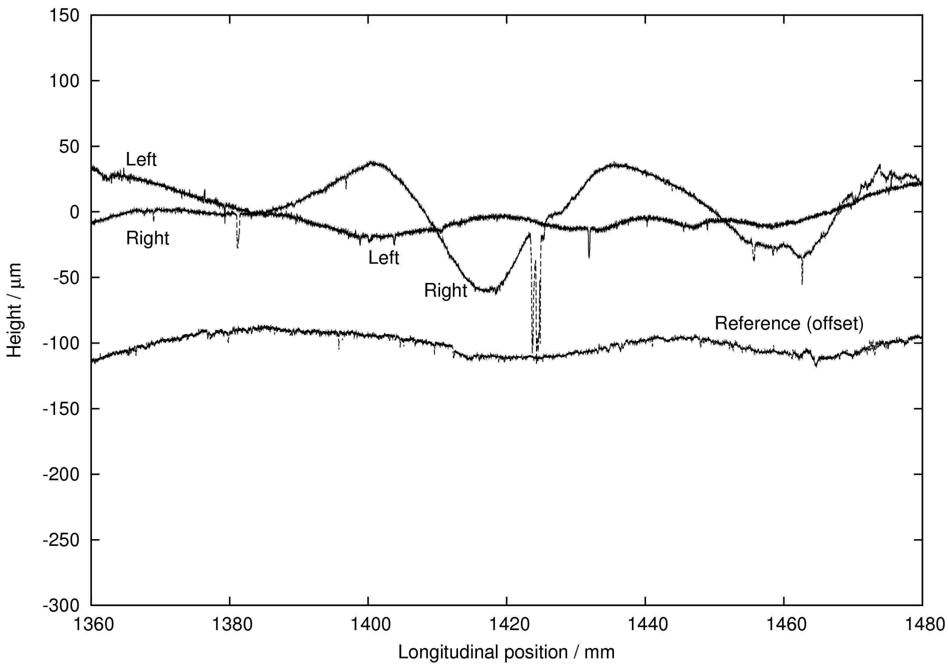
Figure 7

(a)



150
100
50
0
-50
-100
-150
-200
-250
-300
Height / µm
380
400
420
440
460
Longitudinal position / mm
Left
Reference (offset)
Right

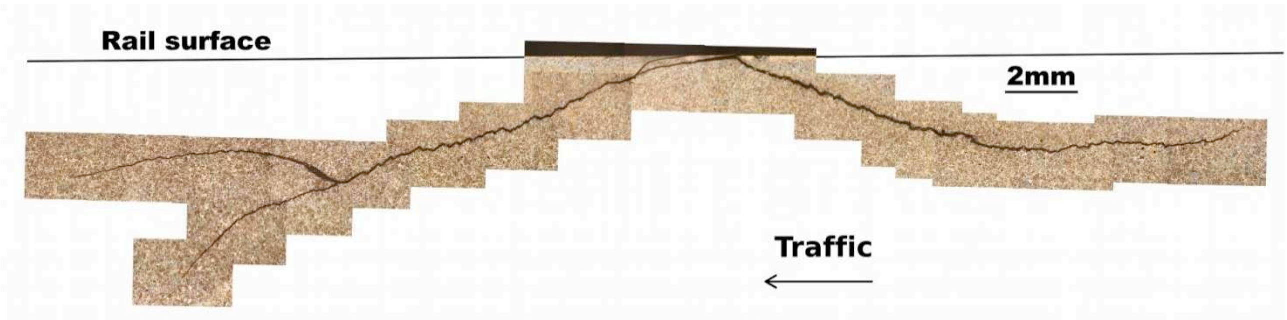
(b)



Height / µm
Longitudinal position / mm
150
100
50
0
-50
-100
-150
-200
-250
-300
1360
1380
1400
1420
1440
1460
1480
Left
Right
Left
Right
Reference (offset)

Figure 8

(a)



(b)

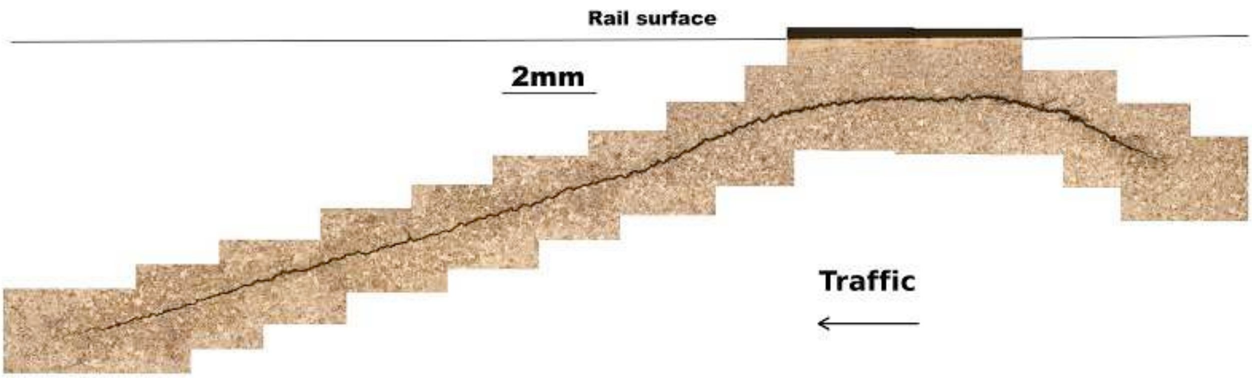
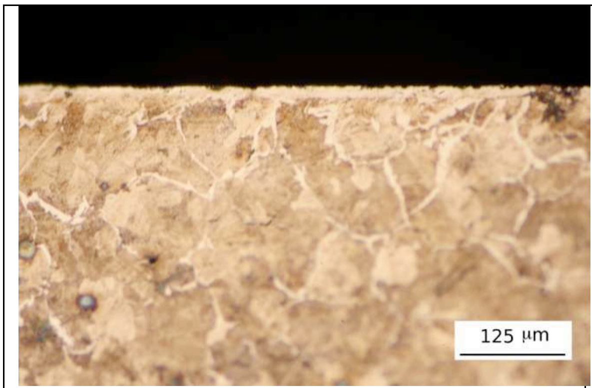
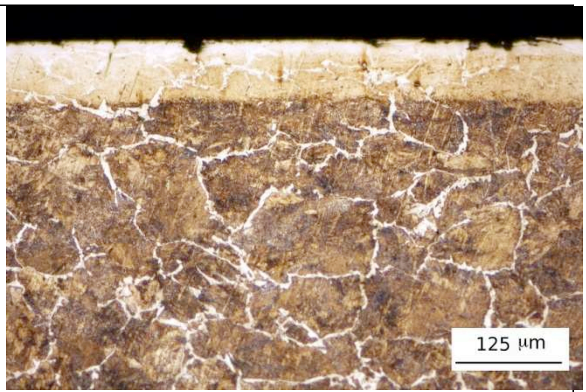


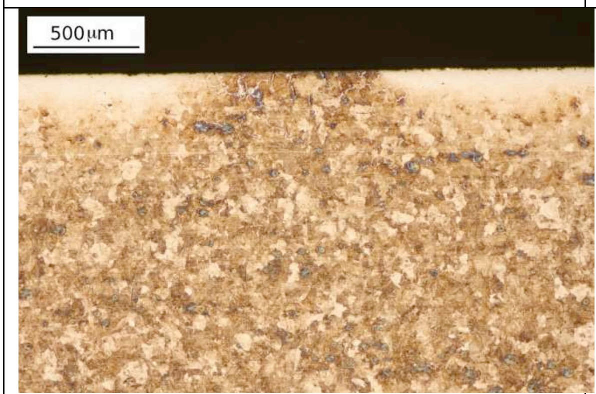
Figure 9



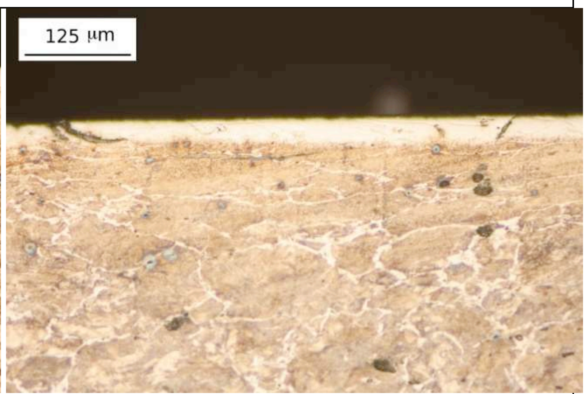
(a)



(b)



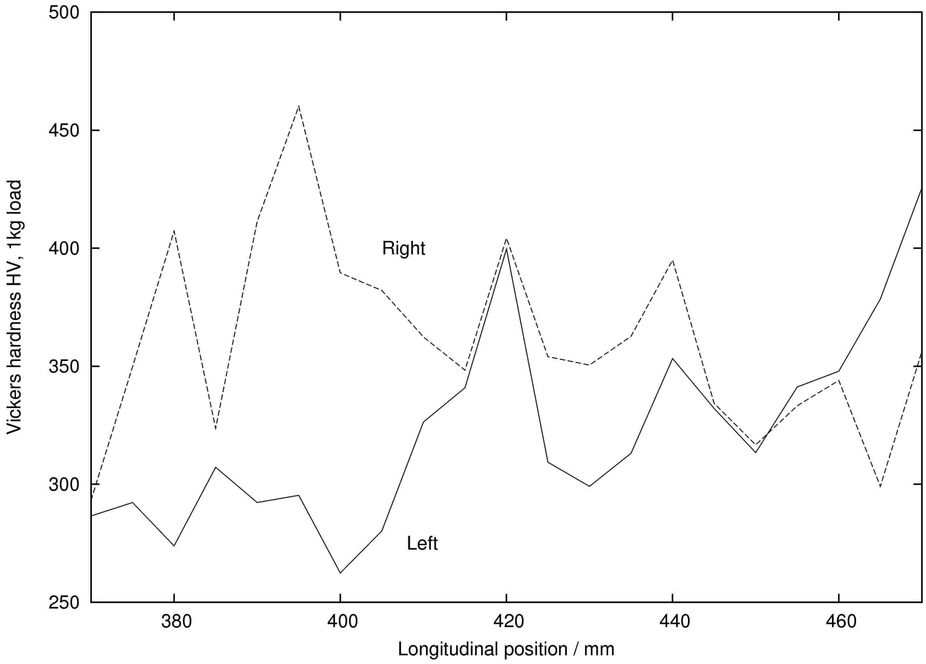
(c)



(d)

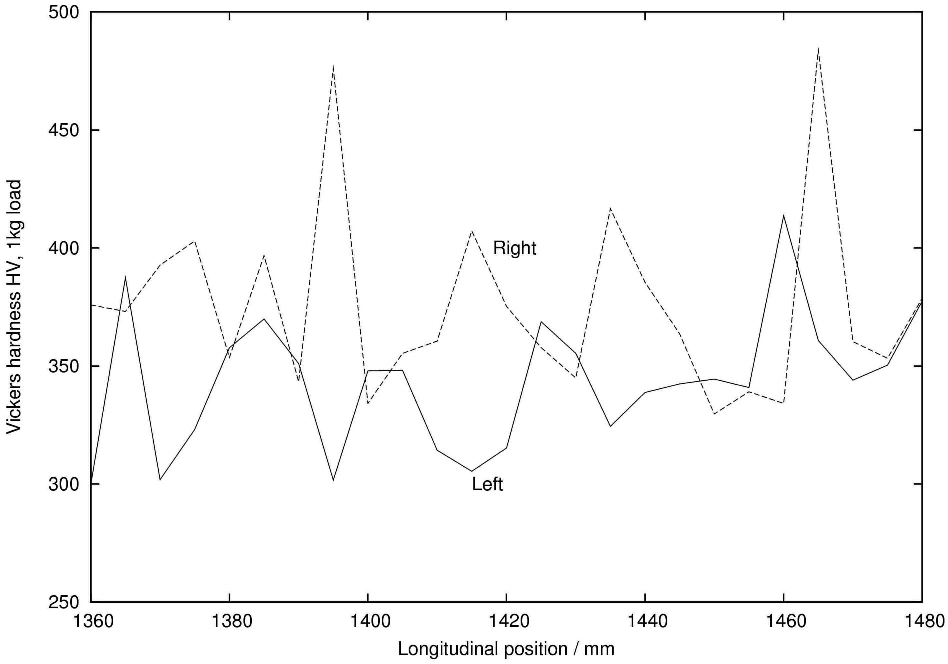
Figure 10

(a)



500
450
400
350
300
250
380
400
420
440
460
Vickers hardness HV, 1kg load
Longitudinal position / mm
Right
Left

(b)



500
450
400
350
300
250
1360
1380
1400
1420
1440
1460
1480
Vickers hardness HV, 1kg load
Longitudinal position / mm
Right
Left