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WEAR AND FATIGUE OF RAILWAY TRACK CAUSED BY CONTAMINATION, SANDING AND SURFACE DAMAGE

R.S. Dwyer-Joyce, R. Lewis, N. Gao and D.G. Grieve

The University of Sheffield, Department of Mechanical Engineering,
Mappin Street, Sheffield, S1 3JD
UK
r.dwyerjoyce@sheffield.ac.uk, roger.lewis@sheffield.ac.uk

Abstract

The wheel rail contact operates in an arduous environment. Damage to the surface of either component is possible during manufacture, installation, or operation. The question arises as to how tolerant is the railway wheel or section of track to surface indentation or damage.

In this work a twin disc simulation has been used to relate the level of surface damage (as well as the way it is generated) to the fatigue life of the surfaces. A related problem is the presence of solid contamination on the track. Sand (applied for improved adhesion) or track ballast material can cause damage to the rail and wheel surfaces. These mechanisms have been explored to assess the effect on contact fatigue life and wear. The disc specimens have been either artificially damaged (with dents and scratches) or run with particles of sand or ballast material. The discs were then loaded and rotated at realistic conditions of contact pressure and controlled slip.

For normal operation of the contact, either dry or with water lubrication, surface dents and scratches have little effect on fatigue life. The normal plastic flow in the rail surface layer acts to close up dents. The failure of the disc is then by fatigue cracking across the whole surface with no particular preference to the dent location. Alternatively, if the contact is lubricated with oil then this plastic flow is greatly reduced and the dents act as stress raisers and fatigue cracks initiate from their trailing edge.

Sand or ballast particles are crushed as they enter the wheel/rail contact. The fragments indent the surfaces and rapidly roughen the contact faces. The surface indentation is relatively minor, but the presence of particles increases the level of traction (over the wet case) and promotes further surface plastic flow. This can reduce the residual fatigue life of the contact. Further, high concentrations of sand were shown to promote a low cycle fatigue process that caused very high wear by the spallation of material.

The twin disc simulations have shown that, under conditions similar to that of wheel/rail operation, surface damage is not a primary cause of fatigue failure. However, wear is greatly accelerated by the presence of solid contaminants and some evidence of a low cycle fatigue process was observed for sanded contacts.

INTRODUCTION

Railway track operates under severe tribological conditions. Loads are high and the contact is usually unlubricated. Each passage of the wheel causes an increment of plastic shear strain in the rail head. This strain accumulates in the near surface region; this is known as ratchetting [***1***]. Eventually the ductility of the material is exceeded and rupture occurs. This is thought to be the point of initiation of the crack.

A common manifestation of this kind of rail fatigue failure is the surface initiated 'head check'. They are found on the rail head running surface and typically grow for 25 to 50 mm at a shallow angle beneath the rail surface before branching, either towards the rail surface causing a spall, or down into the rail leading to a transverse rail break. Typically these defects are usually (but not uniquely) found on heavy duty curved track (i.e. regions of high slip and tractive loading) [***2***, ***3***].

It has been the objective of this work to investigate the significance of rail surface damage, under typical wheel/rail contact conditions, and determine whether localised surface damage is in anyway an initiator of head check type cracks. Damage is considered to be either already present (i.e. a surface dent) or caused by the over rolling of a solid particle (i.e. ballast rock or adhesion enhancing sand). The approach has been experimental using disc machine based tests on artificially indented and contaminated surfaces.

Three rail surface damage scenarios have been investigated:

- Simulation of the presence of a surface dent or scratch on the rail surface. The disc surfaces were artificially indented or scratched and run under oil, water, or dry conditions. Tests were continued until a fatigue crack was detected. Interruptions were made to determine mass loss.
- Simulation of the rolling over of ballast rock. Crushed particles of ballast material were fed into

the contact over a few running cycles. Discs were inspected for surface damage and then run clean and wet until fatigue cracking initiated.

- Simulation of damage caused by track sanding. Sand was fed under compressed air into the disc machine contact. Discs were inspected for surface damage. In practice wear rates were so high that only a short testing duration was possible.

DISC MACHINE TEST APPARATUS AND PROCEDURES

The Twin Disc Test Machine

A twin disc testing machine was used to carry out the rolling contact experiments. The machine has been specifically designed to investigate wheel/rail contacts and is described in detail elsewhere [***4***]. A pair of steel discs is orientated one above the other with their axes horizontal and parallel (*figure 1* shows a picture of the disc test head).

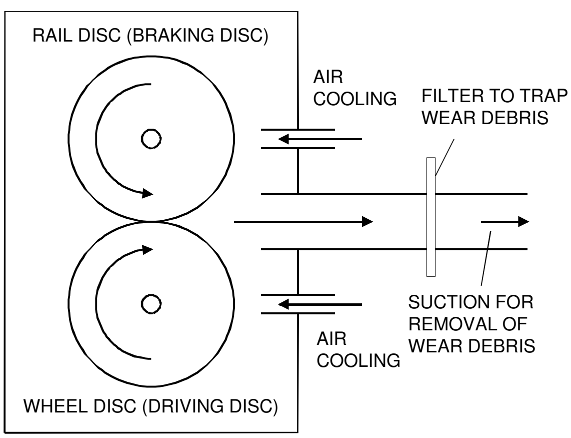

figure 1 *Schematic of the test head from the twin disc machine*

The discs are loaded together hydraulically and driven independently by two electric motors. An advanced control system allows the discs to be driven at fixed stable slide roll ratios. The driving torque and rotational speeds were measured by means of a torque transducer and rotary shaft encoders. A load cell continually monitors the force compressing the two discs. The wheel discs are rotated faster than the rail discs so that the wheel acts as a driver whilst the rail disc is driven (i.e. the follower disc).

Test Specimens

The test discs were machined from rail head of UIC60 pearlitic steel and the rim of W8A wheel steel. The discs were manufactured to the dimensions of 47 mm diameter and 10 mm width. All cutting and machining operations were conducted to maintain the original microstructure and properties. The running surface of each disc was ground to an average roughness of R_a = 0.35 μm.

Contact Conditions

The test discs were loaded to achieve a peak contact pressure of 1.5 GPa. This results in a contact patch of dimensions 10 mm (i.e. the track width) by 0.7 mm. The rail disc is rotated at 400 rpm with the wheel disc controlled to rotate to give a constant slide to roll ratio of 1% slip (except for the sanding tests where slips were increased to 20% to simulate wheel start-up in a low traction environment).

Artificial Surface Defects

Five types of defect were manufactured on the follower rail disc: transverse and longitudinal scratches, conical dents, pyramidal dents, and drilled holes. The width and length of the furrows were approximately 0.1-0.3 mm and 5 mm respectively. They were made by scoring with a carbide tipped cutting tool (tip radius 0.05 mm). The conical and pyramidal dents were of 0.4-1.2 mm diameter and produced using Rockwell and Vickers testing machines under different loads. The diameter of drilled holes ranged between 0.5 mm and 1.5 mm.

Lubrication and Contamination

Lubricants (oil or water) were applied using a gravity drip feed system so as to maintain a constant meniscus of liquid in the inlet region. The contact area was lubricated by supplying approximately 1 drip per second for water, or 1 drip per 3 second of mineral oil.

Ballast particles were prepared from track-side granite ballast rock that was subsequently crushed. In the wheel/rail application a piece of ballast on the line will be crushed into fragments by the passage of the wheel. In this work the ballast is pre-crushed so the fragments can easily enter into the twin disc contact. Laser particle sizing indicated that the particles had an initial mean diameter 0.29 mm. These particles were fed into the contact by hand as uniformly as possible (an estimate of the feed rate of 6.5 mg/cycle is obtained by dividing the total mass of fed particles by the number of test cycles). This feed method was somewhat crude, but since this test is designed only to simulate the rolling over of single ballast rock, it was thought sufficient.

The sand particles used in the testing were a standard commercial grade commonly used on the UK railway network [***5***]. The particles were fed from a hopper directly into the contact by entrainment with a stream of compressed air (in a similar manner to the normal way it is applied by a railway vehicle). The air pressure was adjusted to give controlled sand flow rates (in the range 250 mg/cycle to 1875 mg/cycle). However, much of this sand is not entrained between the disc surfaces. Some of the sand passes around the disc sides and some bounces back from the faces.

Analysis of Specimens

Tests were regularly interrupted to take replicas of the disc surface, and record the weight. At each interruption the discs were removed from the machine, cleaned, weighed, measured before replacing and continuing with the test. In these tests an eddy current detector was used to monitor crack growth. Typically, a triggering point was set for a crack to have reached a length 500 μm (the probe sensitivity was determined using a set of calibration discs pre-machined with slots of various depth). However, in many of these tests failure became quickly apparent when a spall was formed on the disc surface.

Sanding tests resulted in so much wear, that only a short duration of testing was possible (the discs became dimensionally un-useable). Mass loss per cycle is thus approximated from the total mass loss over the test.

SURFACE INDENTATION AND TRACK FAILURE

The test using indented rail discs clearly showed two very different kinds of behaviour depending on whether the contact was operated under water or oil lubrication.

Figure 2 shows a series of photographs from a single oil lubricated test captured at different stages during the test. The initial dent was generated using a Rockwell indentor and is rapidly reduced in size during the first few cycles. This process occurs by plastic flow of the dent side walls. Over the whole test, the weight loss is negligible so there is little effect of dent removal by a surface wear process. The Rockwell indentation leaves some dent shoulders on the rail surface. These shoulders and the side walls of the indentation collapse under contact loading. The dent then shakes down to a stable shape and little further deformation occurs (see *figure 3a*).

A fatigue crack initiates at the trailing edge of the defect that later propagates to a spall. Interestingly, the initiation point appears to be coincident with the edge of the original dent and not the final deformed dent. It is likely that the edge stresses are relieved by the plastic flow thus making a site slightly away from the edge the point of peak stress. In this case we expect an elastohydrodynamic lubricant film to be present during testing. The thickness of the film will be modified by the presence of the dent [*6*]. At the trailing edge the slope change (i.e. convergent) is more favourable for generation of fluid pressure. This location then suffers a higher stress and is the initiation point.

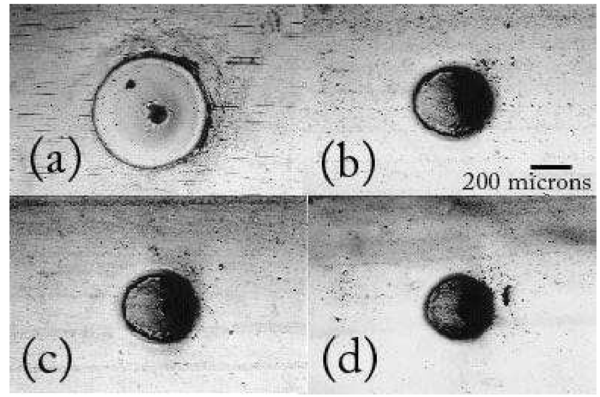

figure 2 *A sequence of micrographs of a conical surface indent during an oil lubricated test (a) at the start of the test, (b) after 131k cycles, (c) after 465k cycles, and (d) after 866k cycles. Rolling and traction directions from right to left*

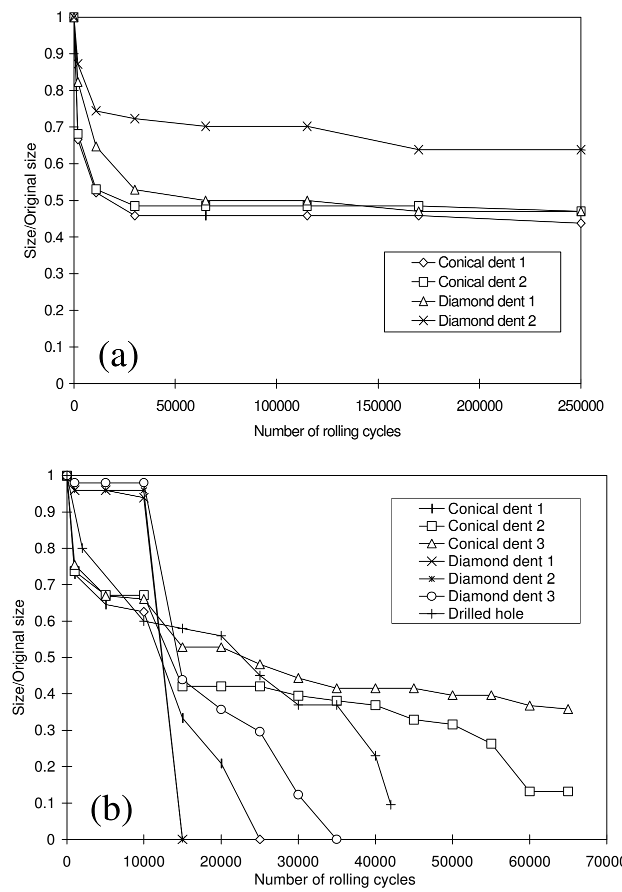

figure 3 *The change in size of the indentations during (a) oil, and (b) water lubricated tests*

Other indentations (different size Rockwell and Vickers dents) showed a similar behaviour [***7***]. Fatigue cracks and spalls formed at the dent trailing edge typically resulting in fatigue lives in the range 300-900k cycles. However the transverse and longitudinal scratches had no effect on fatigue failure in these tests. The reasons for this are not fully understood. They were slightly shallower than the dents, but perhaps more significantly they were manufactured by cutting away material rather than indentation. The former method will not result in the presence of shoulders around the damage; these will lead to higher stress.

If water is used as the lubricant a different process takes place (see *figure 4*). Again the dent is deformed, but this time deformation continues throughout the test until the dent is completely closed (see *figure 3b*).

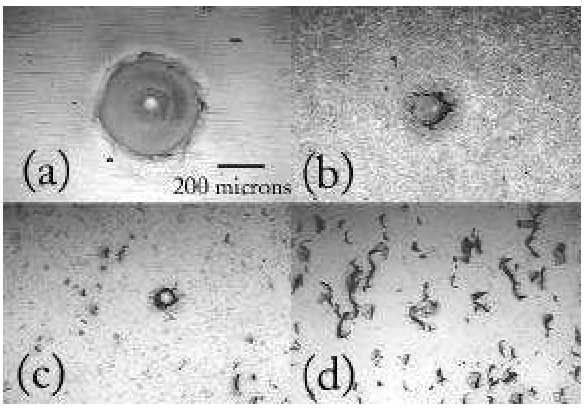

figure 4 A sequence of micrographs of a conical surface indent during a water lubricated test (a) at the start of the test, (b) after 5k cycles, (c) after 15k cycles, and (d) after 40k cycles. Rolling and traction directions from right to left

Weight loss was monitored throughout and, although slightly higher than the oil lubricated case (see *table 2*), was not large enough to wear out the dent. The test was continued until 40k cycles were elapsed at which time the whole surface was covered with cracks. The 40k cycle represents a typical life of a rail steel material under these conditions [***8***]. Clearly the dent has no preferential effect on fatigue crack initiation. The same was observed to be true for all sizes and shapes considered, even a 1.5mm diameter drilled hole did not cause crack initiation.

Table 1 summarises the effect of all dents and scratches on observed failures and fatigue.

Running the damaged discs dry also showed the indentations to have no effect. In this case wear rates are high and the dents are simply worn out of the surface. Crack initiation did not occur at any location on the surface. This is as expected; presence of a fluid is known to be required for rolling contact fatigue crack propagation in rail steels [***2***]. The fluid penetrates into the crack and when the surface is loaded, the fluid is pressurised and causes a mode I loading at the crack tip [***9***]. It is this mode I loading which causes crack propagation; without it, the normal mode II crack growth is limited.

A main difference between these tests is the level of surface traction involved. In the oil lubricated contact an elastohydrodynamic oil film will separate the surfaces; the traction is therefore low and thus the surface shear low. For the water and dry cases there is a much higher surface traction (the measured friction coefficients are shown in *figure 11*); this causes plastic flow of the near surface region and the build up of shear strain in the sliding direction.

Figure 5 shows sections through oil, water, and particulate (ballast) contaminated surfaces. For all except the oil case, the surface layer is sheared across in the direction of sliding (left to right). The severest plastic flow is caused by the presence of dry solid particles.

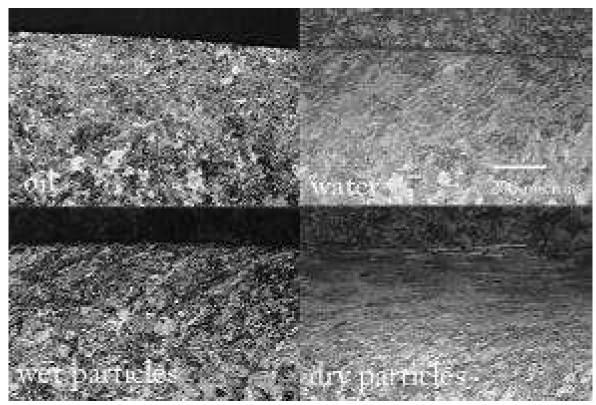

figure 5 Cross section through the running surface showing different morphologies for lubricated and contaminated situations. (a) oil, 1150k; (b) water, 50k; (c) wet contaminant 0.5k + water 27k; (d) dry contaminant, 40k cycles. Rolling and traction direction from left to right

The normal fatigue failure of rail track occurs when this accumulated surface strain exceeds the ductility of the material [***1***, ***8***]. At this point rupture occurs. If a liquid is present it can penetrate into a crack and cause fast propagation [***9***]. Clearly the presence of oil dramatically reduces this strain accumulation. The dent then becomes the critical feature and acts as a stress concentration. However, with water or dry contact, the strain accumulation occurs rapidly and becomes the fatigue initiation route. The strains associated with the indentations (typically less than 8% [***10***]) are much less than the strains which accumulate at the surface (100-1000%) [***11***].

TRACK DAMAGE BY BALLAST CONTAMINATION

Tests run with crushed ballast material were in two stages; firstly a short period where particles were fed into the contact followed by operation in clean water until fatigue cracking was detected. Weight loss was monitored at stages throughout the contaminated operation. *Figure 6* shows the surfaces of the rail and wheel discs after the period of ballast contaminated running.

The wheel and rail surfaces have two very different appearances. The ballast particles (already pre-crushed) are further crushed in the inlet region to the contact. It is these final fragments which pass into the contact. They then are trapped in the softer wheel surface and accommodate the relative sliding motion by scratching the harder rail surface. Thus the wheel shows debris indentation damage; whilst the rail show debris grooving damage. The length of the groove is consistent with the 7 μm distance a particle would have slid through the contact. This process is then one of two body abrasion (i.e. a loose abrasive is trapped in one surface). The softer surface traps the particle and causes preferential wear to the harder surface. In this case rail (hardness 2.7 GPa) wear rates were a factor 2.5 times that of the wheel (hardness 2.6 GPa). So clearly the small hardness differential still permits this process. This has been observed to occur with rolling bearings [***12***], where the balls, which are about 10% harder than the raceways, wear faster.

The surface damage is, however, still relatively minor; no deep dents were found, and the roughness was only increased to $R_a = 1 – 2$ μm. The ballast material is brittle and crushing the particles did not cause severe damage. The remaining fragments then indent the surface (as shown in *figure 7*); interestingly these fragments tend to agglomerate and there is evidence that the agglomerated fragments plastically shear under the very high local pressures [***13***].

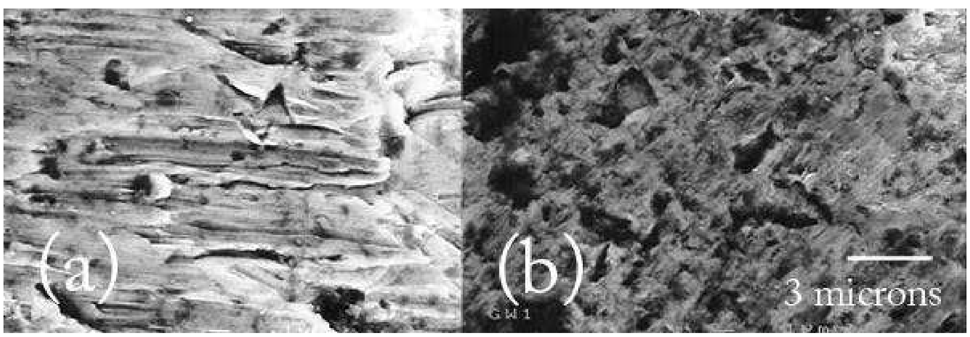

figure 6 *Legend numbered. Times 10 italic. Tab and indent at subsequent lines 1.8 cm. Space after 18 points. No adjustment of the right side. Picture courtesy Peter Sotkovszki*

p_0, MPa	Lubrication	Defect	Original Defect Size, mm	Size Reduction, %	Effect, Y/N	Life, Cycles	Location of failure
1500	Oil	●	0.45-0.65	52-65	Y	>1000k	At trailing edge
		●	0.76-1.20	40-57	Y	700-900k	At trailing edge
		◆	0.34-0.55	49-56	Y	>800k	At trailing edge
		◆	0.70-1.10	27-41	Y	300-700k	At trailing edge
		▬	0.21-0.26	23-24	N	>1000k	All over surface
		▮	0.10-0.25	60-88	N	>1000k	All over surface
		none	-	-	-	>1000k	All over surface
1500	Water	●	0.48-0.70	100	N	50k	All over surface
		●	0.80-1.06	64-88	N	50k	All over surface
		◆	0.17-0.98	100	N	50k	All over surface
		▬	0.21-0.27	100	Y	35-40k	Along scratch
		▮	0.11-0.16	100	N	50k	All over surface
		none	-	-	-	50k	All over surface

table 1 *Summary of experimental results on the effect of defects on rolling contact life with oil and water lubrication*

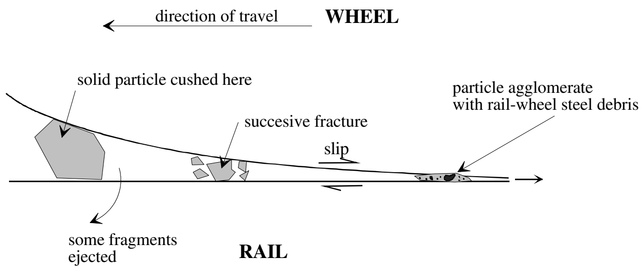

figure 7 Detail of the 'mechanism' of ballast debris entrainment in a rolling/sliding rail wheel contact. The contaminant is trapped, crushed, entrained and finally agglomerated as it passes through the contact of the wheel/rail

After the initial period of 500 cycles of running with ballast contamination the disc were run with clean water. Fatigue cracks formed on the rail disc across the whole surface at 27k cycles. This compares with a 50k cycle life of an artificially indented rail disc. So whilst the level of surface damage is very much less than that of the indents it appears that a period of ballast over rolling can accelerate fatigue damage. This is probably due to the increased surface strain accumulation (as observed in *figure 5c and d*). The particles will act as cutting tools and will be surrounded by plastically flowing rail material. The surface is thus subjected to high normal and shear stress. This will enhance the rate of shear strain accumulation and result in faster crack initiation.

SURFACE DAMAGE BY TRACK SANDING

In this series of tests, sand was entrained into the disc contact by a stream of compressed air (to reproduce the method by which it is applied in railway applications). This was performed both with the absence and presence of water drip fed into the contact. In both cases the sand particles were crushed to a fine powder. Again the surface indentation to the wheel and rail discs is small scale. However, wear rates were very high. There was severe plastic flow on the disc surfaces and high material loss. *Figures 8 and 9* show pictures of the disc specimen contact surfaces after testing. Abrasive score marks are visible on both although they were more severe on the rail disc. Again the wheel steel seems to be trapping most of the abrading particles and scoring the rail disc surface. Surface cracks and voids from which material has been removed are also evident on the surface of the wheel disc.

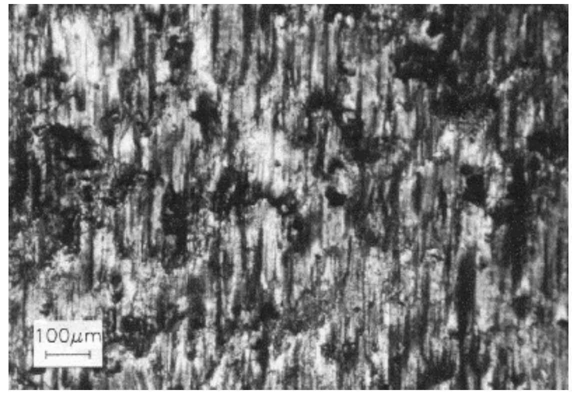

figure 8 Rail steel disc surface after 3000 cycles of operation with sand particles

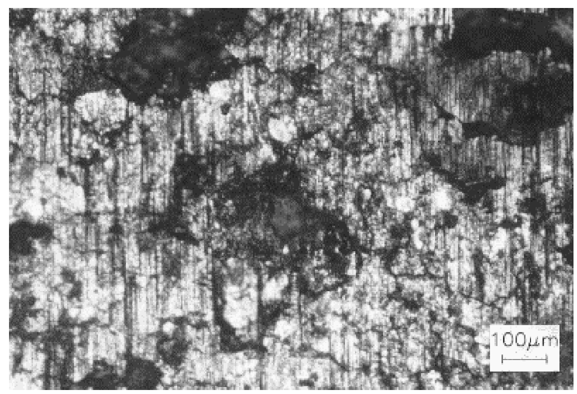

figure 9 Wheel steel disc surface after 3000 cycles of operation with sand particles

Inspection of the wear debris showed that it consisted of the fine crushed sand particles and large chunks of steel. *Figure 10* shows the sand particles before and after testing, and photographs of two opposite faces of a steel debris particle.

Evidently the sand is crushed to a fine (sub-micron) dust powder. However, the steel debris particle is also of interest; the form indicates that two wear mechanisms have taken place. Firstly the top surface (*figure 10d*) shows abraded scratches, these have been caused by the sand particle fragments as they are entrained into the contact and undergo relative motion. The reverse side (*figure 10c*) is rough and irregular similar to the appearance of a fatigue spall. It appears some fatigue wear process is also taking place, whereby a large chunk of material is removed from the surface, probably by the growth of a crack subsurface. The blocky shape of the wear debris is also typical of fatigue [***14***].

Clearly the removal of the steel debris particles that has led to the formation of the voids observed on the wheel disc surface (see *figure 9*). The greater severity of the abrasive score marks on the rail disc surface indicates that initially a similar two body abrasive process to that with ballast dust is occurring, with crushed sand particles embedding in the softer wheel steel and abrading the harder rail material. The low cycle fatigue process observed leads to the greater wheel disc wear since it is the softer of the two materials.

The resulting traction values are shown in *figure 11*. The sand has a large influence on traction for wet rail surfaces, but actually slightly reduces friction in the dry case. In this case it appears that the sand is acting as a (poor) solid lubricant. This is likely to be because the relative sliding between the disc surfaces is accommodated by the fine sand grains sliding over one another rather than sliding metal to metal contact. Wear rates are very high and dependent on the flow of sand into the contact (typically wear rates of 1000-9000 μg/cycle were recorded).

DISCUSSION

The results of this work indicate that the wheel/rail contact, operating under normal conditions, is tolerant of surface damage. Essentially the surface damage caused by an indentation (i.e. the strain) is small compared with that which accumulates during normal operation of the rail. The rail disc then fails all over the whole surface and the surface dents have no effect. The strain ratchetting rate is dominated by the traction force (the product of the traction coefficient and the normal load). Thus, when the discs are lubricated with oil, the strain accumulation rate is low and now the surface defect strain is significant. This then becomes the site of failure, but at a much higher number of cycles than the water lubricated case.

Table 2 shows the wear rates from the various test cases. Clearly the addition of solid particles results in greatly accelerated wear. It is only possible to make qualitative comparisons here. The particle entrainment rate is critical and this can only be crudely estimated from the rate at which particle are fed into the inlet zone. As an example of this phenomenon it is observed that wet sand causes significantly more wear than dry. This was apparently due to the ability of the wet sand fragments to adhere to the disc surfaces and thus be entrained into the contact more easily. Also the sand tests were carried out at 20% slip whilst all others were carried out at 1% slip. However, perhaps these data indicate the levels of wear one might expect for each of the three rail damage scenarios considered in this work.

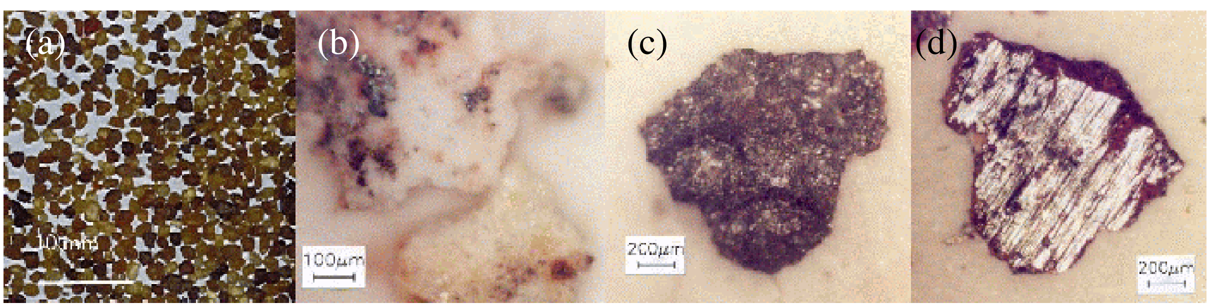

figure 10 (a) Sand particles before testing, (b) crushed sand particles (agglomerated with metal debris) after testing, (c) bottom and (d) top faces of a steel debris particle

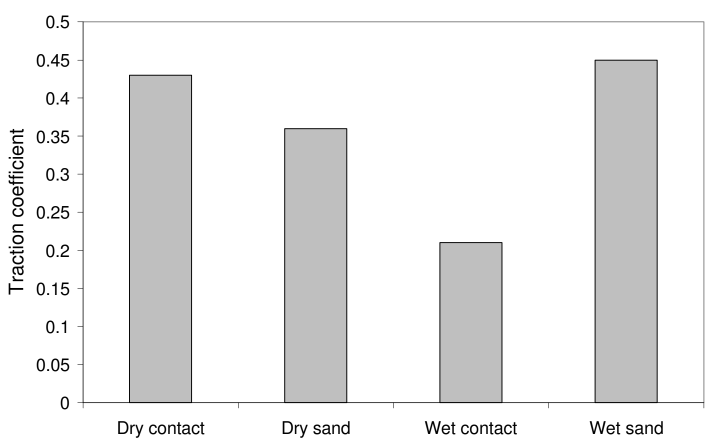

figure 11 Comparison of the traction coefficients recorded for disc machine tests with and without sand and/or water

Test Case	Wear rate, μg/cycle	Contact Conditions
Dry	15 - 20	1% slip, 1500 MPa
Water lubricated	0.8	1% slip, 1500 MPa, drip fed water
Oil lubricated	0.02	1% slip, 1500 MPa, drip fed oil
Dry ballast	10 - 100	1% slip, 1500 MPa, hand fed particles at ~6.5 mg/cycle
Dry sand	1000 - 4000	20% slip, 1500 MPa, air borne sand at ~1250 mg/cycle
Wet sand	6000 - 9000	20% slip, 1500 MPa, air borne sand at ~1250 mg/cycle

table 2 Comparison of combined average wear rates (wheel disc + rail disc mass loss) for the different test cases

An unusual observation from this work has been the presence of metal fatigue debris in the sanding tests. Under water lubrication the rail steel suffers contact fatigue at around 50k cycles. With the presence of sand we see evidence of severe fatigue after only 3k cycles. The sand has acted to induce a low cycle fatigue process. At this stage we can only speculate as to the mechanism. The sand fragments enter the contact and will virtually coat the contact surfaces. Each will act like a hard indentor and cause local very high pressure (equal to the hardness of the wheel/rail material) and be scored along the surfaces. It would be expected, therefore, to have very high normal stress and shear stress in the near surface region. The contact pressure will therefore be increased from around 1500 MPa to nearer 2600 MPa. This appears to be enough to initiate cracks that then propagate to spalls.

The results deduced from the disc machine testing are clear; surface damage is not a major concern; but solid particulate contamination can lead to excessive wear. Whether these results can be extrapolated to the wheel/rail contact is a matter for speculation. The 3D wheel/rail contact under goes variable loading and intermittent lubrication/contamination. This has been simulated in the twin disc arrangement by a, steady load and speed, 2D contact with constant lubrication condition. The tests were carried out with a range of dent to contact patch size ratios (by change the dent size) all showing similar effects. Perhaps of more concern is the effect a large size defect might have on the dynamics of the wheel set. The disc machine contact is stiff and it is not expected to receive significant impact loading from the presence of a surface defect. But in a real railway contact, the wheel rolling over a large defect may cause some excitation of the bogie and lead to additional impact stresses. Further the rail is subjected to bending loads which could also increase the stress at a damage site. The entrainment of solid particles also represents a broad approximation to the real application.

The contaminating particles are fed into a contact where both elements are rotating. In the real application the particles are either resting on a stationary element (the rail) or fed by compressed air into the wheel/rail conjunction. In both cases there is a considerable freedom for particle motion away from the contact and a low likelihood that fracture fragments will become entrained into the contact. Care should be taken, therefore, in extrapolating these disc machine based simulations to the full size application. Whilst the tests show clear trends, a series of field trials are necessary for a full picture of the link between wheel/rail damage and failure.

CONCLUSIONS

Three sets of disc machine based trials have been performed to assess the effect of surface damage, rolled over ballast rock, and traction sand, on the life of a wheel/rail contact. The following conclusions are drawn:

- Under conditions of water lubrication, surface indentations had no effect on the resulting contact life. The failure of the surface was by normal strain accumulation in the surface layer. The dents were removed by plastic flow of the surrounding material.
- Under conditions of oil lubrication surface damage acted as a fatigue initiation site. Cracks propagated from the trailing edge of surface indents. In this case the dents were reduced in size by 40-50% during early cycles of operation but then achieved a stable state.
- Particles of ballast rock fracture in the inlet to the contact. The fragments are entrained, embed in the softer wheel surface and abrade the harder rail surface. Surface damage is minor but wear rates are enhanced.
- Tests with sand as a contaminant showed very high wear rates (which was dependent on sand entrainment). In addition to abrading the surfaces, the sand particles caused a low cycle fatigue process to occur. This resulted in severe wear by the removal of fatigue spalls from the surfaces.
- The trials demonstrate that, at least, in a disc machine simulating normal rail operation, the presence of surface dents is not serious, but the

entrainment of solid particles can result in very high wear and the onset of early fatigue.

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