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A new scaled testing methodology for the analysis of rolling contact fatigue in railway steels.

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A R T I C L E I N F O

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A B S T R A C T

Twin disc testing is a relatively cost effective and practical method of investigating the damage resistive properties of rail steels in a scaled environment. The loading conditions and dimensions used in testing are scaled in such a way that the Rolling Contact Fatigue (RCF) generated on a twin disc rig are representative of the conditions experienced at the full-scale. Typical methodologies to generate RCF on a twin disc rig involve the application of water to the contact patch throughout the test, with perhaps a few thousand dry cycles being run beforehand. This research explores the use of weather data to reflect the real-world contact conditions more accurately between a wheel and rail. Met Office weather data collected from 1981 to 2010 shows the average annual precipitation in the UK is around 133 days of rain or snow, which is nearly 36 % of the year. In this study, weather data was used to determine the ratio of wet to dry cycles in the testing methodology. 50k dry cycles are run in intervals of 5k and then transitioned to 25k of wet cycles, which is 30% of the total cycles. Intervals were kept at 5k so attaining 36%. If RCF is not initiated after the first 75k cycles, which ends with 25k wet cycles, then the same dry and wet cycles are repeated. RCF data generated using this methodology demonstrated expected differences in the RCF resistive properties of two rail steel grades, R260 and R350HT. In test 1 the point of initiation for each grade was not captured, though cracks were visible around the expected cycles to initiation, which was verified using optical microscopy. The cracks viewed on the softer R260 steel samples, "260" referring to the Brinell hardness value of the steel, were more developed at 85k cycles and showed signs of spalling, whilst the cracks on the harder R350HT sample were much smaller. In test 2 the point of initiation was found for each grade. Optical microscopy was also used to show the depth and direction of head check cracks to ensure the damage viewed from the head was RCF and not plastic flow or cyclic wear. This paper shows the necessity for considering the number of wet cycles applied during twin disc testing and demonstrates it is possible to run a high number of wet cycles which are more representative of real-world conditions when generating RCF on twin disc rigs.

Introduction

The potentially catastrophic effects of rolling contact fatigue (RCF) became most apparent on 17th October 2000, whereby RCF caused a rail break at Hatfield, with four people tragically losing their lives and a further 70 suffering injury in the subsequent derailment of the train (Smith, 2001). Since this disaster, significant research has been dedicated towards understanding RCF to prevent recurrence of such a critical system failure. Whilst an expensive undertaking, inspection of surface level RCF cracks has now become a regular preventative maintenance action in the rail industry

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to prevent growth and consequent rail fracture (Smith, 2001). RCF refers to small cracks which initiate on a rail or wheel due to excessive cyclical loading from rolling contact (Nielsen, 2009).

Reduction of RCF remains a key priority for the rail industry, and increasing RCF resistance of rail steels is core to this effort. To test the RCF resistive properties of rail steels, different researchers have developed methodologies to reproduce RCF under scaled conditions. There is much debate amongst researchers, highlighted by Yi Zhu, concerning how representative scaled testing is of the actual real-world conditions experienced on track and currently no standard test exists for RCF initiation. Differences in scaling techniques used in the industry and concerns of thermal scaling are such examples of why scaled testing may not be as accurate as some believe. The environment and contact will be more representative in field trials than the results from a twin disc rig. However, a twin disc test offers a cost effective and highly controllable method which allows measurements to be taken more easily (Zhu, et al., 2019).

The main inspiration for this research is to question the methodology currently employed by many researchers of how to apply water during RCF testing of rail steels. It is the opinion of the author of this article that the current method being used for generating RCF in the rail industry does not represent real weather patterns. Rails in tunnels/enclosed conditions are generally empirically observed to be less prone to RCF which could be attributed to a lack of water/wet conditions (Schalk, 2016). It has also been shown in many papers that either intermittent or continuous wet conditions increases fatigue crack growth rates (Beretta, et al., 2011). The aim of this research will thus be to trial a method of applying water in twin disc testing to reflect real-world weather data more accurately and to generate RCF. Figure 1 shows water applied to the contact patch of a twin disc sample. This may help in the construction of a new standard methodology for scaled RCF generation on twin disc rigs.

Figure 1: A 200x magnification photograph of a wet rail sample surface.

Background research

The foundation of this research contains a thorough literature review including topics such as scaled testing, weather data and rolling contact fatigue.

Scaled testing

Many examples of twin disc methodologies could be discussed in this section but as previously stated not many studies agree on a standard method of testing. Some scholars and institutes such as Burstow, M. C, British Rail Research and the University of Sheffield opt to use an energy-based method to scale conditions for twin disc testing, however, some may use the Royal Institute of Technologies (KTH) model for example which uses Archard's wear model. Archard's wear model uses a wear coefficient, hardness value, normal contact force and slip value to calculate a volumetric wear loss (Asadi & Brown, 2008).

The one common step agreed upon seems to be the application of water during RCF testing to aid in the propagation of cracks. An Example methodology created by W. Solano-Alverez and others at the University of Cambridge, used twin disc testing to develop neural networks of rolling contact fatigue characteristics versus various metallurgical properties. This method subjects samples to a 900 MPa normal contact pressure, a nominal creepage of 5%, and wet conditions from the beginning to the end of testing. The test is stopped every 10k cycles until RCF is initiated (Wilberth, Pickering, Peet, & Jaiswal, 2017). Another example of a twin disc methodology is used by Heinsch. This method shows testing for RCF initiation under various Tγ conditions and runs the samples for 3k dry cycles, with no creepage to begin with at 1000 N to trigger strain hardening. Tγ is a parameter developed by British Rail Research (BRR) in the 1970s to quantify wear (Crosbee & Allen, 2015). In essence it represents the energy dissipated in both bodies at the rail-wheel interface and is a widely accepted parameter in the industry (Crosbee & Allen, 2015). This is then followed by constant wet cycles (Hiensch & Burgelman, 2018).

Tγ Scaling

Twin disc tests are typically conducted to test the RCF and wear resistive properties of different rail steels in a scaled environment. The loading conditions and dimensions of the discs are scaled down in such a way that the wear or RCF expected on the twin disc will be representative of the conditions experienced on track, though there is the question of how representative they are of full-scale conditions. One such example is that due to the constant rolling contact experienced on the twin disc rig, as well as high angular velocity twin disc speeds, that the temperature experienced at the wheel-rail contact will not be representative of that at the full-scale, which could lead to a thicker white etching layer than at full-scale or accelerated wear (Lewis, et al., 2017).

The method of scaling used in this research will be that of maintaining the Tγ/Area value. Scaled Tγ would be expected to be at the same energy density to achieve the same level of damage as the full-scale conditions. However, for a greater representation of what occurs at the contact patch and at the full-scale conditions, Tγ/Area can be used which should be the same value at both full-scale and scaled conditions. This parameter was developed by the University of Sheffield (USFD) and shows similar trends as the BRR wear model, trends which can be seen in Figure 2 (Pombo, Ambrosio, & Pereira, 2010). Tγ/Area represents the energy dissipated in both bodies across the elliptical contact patch area of the wheel-rail interface.

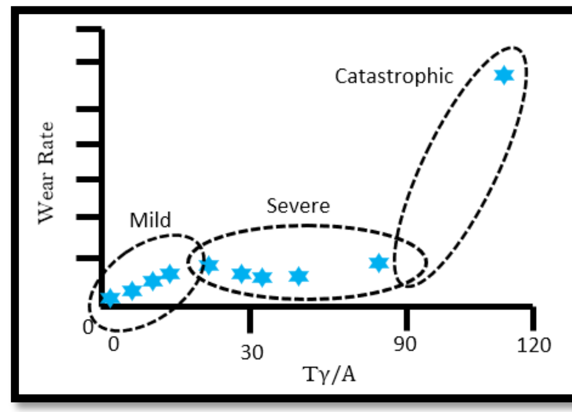

Figure 2: An illustrated USFD model graph.

Burstow's Whole Life Rail Model (WLRM) is based on the same premise as the BRR function, that energy is dissipated at the contact patch, and this should be related to damage. The WLRM relates Tγ to RCF damage, as seen in Figure 3. This function also captures the transition between the competing damage mechanisms of RCF and wear. Thus far this model has been well developed and validated for R260 grade steel although people have also tried to apply it to other grades of steels (Burstow, n.d). The "260" in R260 refers to the Brinell hardness value of the steel. The importance of Burstow's model is that it gives a wider understanding of the effect of loading conditions, such as normal contact force and slip, on RCF initiation and wear. As well as this it gives a greater understanding of the transition from RCF to wear. At a low range of Tγ values, after the fatigue threshold of the material has been exceeded at the contact patch, RCF is the dominant damage mechanism. RCF and wear are competing damage mechanisms. If a wheel or rail experiences a mid-range of Tγ values, then wear begins to increase and RCF initiation gradually reduces, though is still present until high values of Tγ. At high values of Tγ, wear becomes the dominant damage mechanism as wear removes the RCF cracks from the surface of the rail or wheel before they can develop (Burstow, n.d).

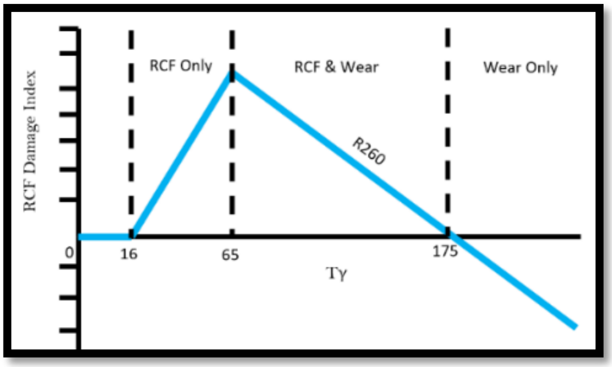

Figure 3: An illustrated Whole Life Rail Model graph.

Weather conditions

Rain and snowfall are important factors for rail manufactures to consider. This is because they act as friction modifiers which affect the third body layer of the rail. A dry track could be expected to have a coefficient of friction (COF) of around 0.5 at the wheel-rail interface, whilst a wet track can drop to 0.3 or below. Frost on tracks can drop the surface friction even lower to anywhere below 0.2 (The Contact Patch, 2013). As can be seen in Figure 4 the COF heavily affects the Tγ experienced at the wheel-rail contact. This will determine which damage mechanism is most prevalent according to the Whole Life Rail Model. Since the Tγ is reduced during low COF conditions it may be that RCF is more prevalent during rain or snow.

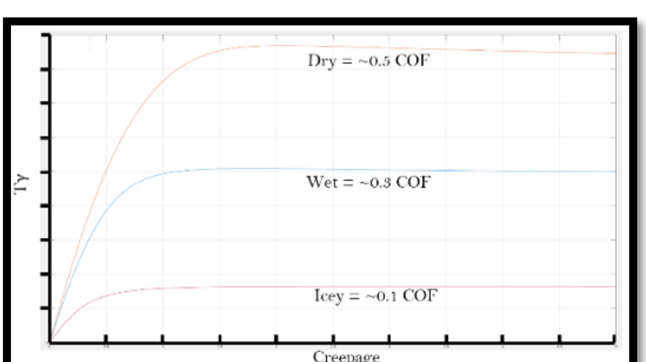

Figure 4: An illustrated Tγ vs Creepage graph.

Another phenomenon that occurs when a rail or wheel is wet is when surface water seeps into preexisting cracks and causes them to propagate (Harwick, Lewis, & Stock, 2017). The high hydro-pressure built up within the cracks causes them to enlarge and become more visible during twin disc testing, as demonstrated in Figure 5.

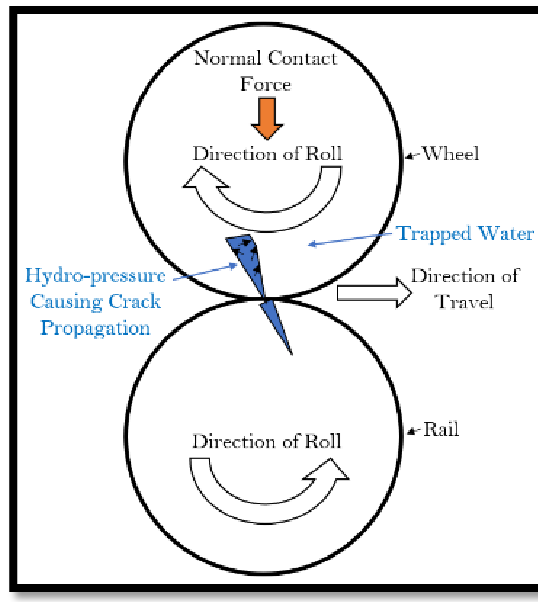

Figure 5: A diagram of how water causes crack propagation.

Met Office weather data collected from 1981 to 2010 shows the average annual precipitation in the UK is around 133 days of rain or snow, which is nearly 36% of the year (Current Results, 2010). In 2020 approximately 171 days were rain days in England, which is 47% of the time. Rain days are classified as days with more than one millimeter of rainfall (statista, 2021).

Rolling contact fatigue

RCF is a blanket term which describes many different defects. Typically, small cracks are initiated at the surface of a rail due to repeated, excessive cyclical shear stress (Nielsen, 2009). Plastic flow and deformation at the contact patch surface resulting from the shear limit of the material being exceeded repeated leads to the initiation, growth and propagation of cracks which can result in fracture. Typically, RCF is found along the gauge corner or gauge shoulder of the high rail (Grassie, 2018). Various factors that affect a wheel or rail's ability to resist RCF have been indicated in previous works (Marich S, 2009), including:

- Loading conditions
- Track geometries
- Radii of wheel and rail at the wheel-rail interface
- Creep forces
- Rail/wheel cleanliness
- Material characteristics
- Third body layers

Figure 6 shows how small cracks can initiate at the head of a rail and grow over time. The growth of cracks can be catastrophic as cracks can cross paths and result in spalling, the loss of material from the rail or wheel surface. This results in a change in contact conditions at the wheel-rail interface. In more severe cases RCF cracks can result in complete fracture of the rail and hence monitoring and further understanding of causation is required to control risk (Kapoor, Salehi, & Asih, 2013).

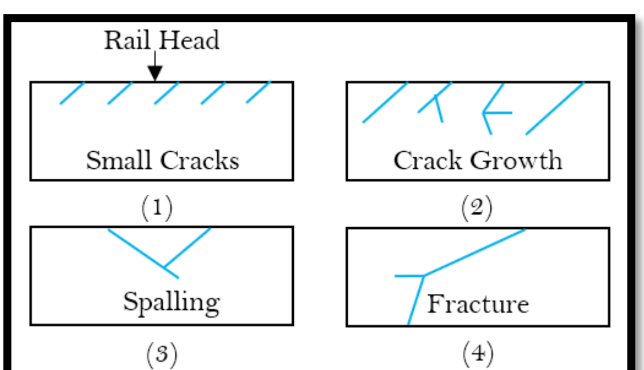

Figure 6: A diagram showing various stages of RCF crack growth.

RCF head check cracks initiate according to the direction of rolling, lateral (Y) and longitudinal (X) creep forces. Head checking refers to RCF found on the gauge corner of the high rail and is either quasi-continuous or continuous (Grassie, 2018). The crack plane (θ) is the same as the direction of the resultant creep force, as shown in Figure 7 (Naeimi, Li, & Dollevoet, 2020).

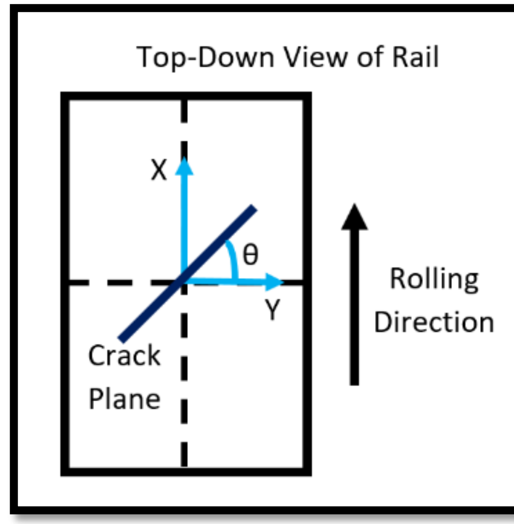

Figure 7: An illustration of a crack plane at the head of a rail.

A test conducted by the University of Sheffield compared running 4k dry cycles to 25k dry cycles on a twin disc rig, before running under wet conditions. The results showed a rise in damage at the surface of the sample when using 25k dry cycles and cracks were visible with no sign of significant material loss, where previously they were not visible using 4k dry cycles. The crack frequency observed also increased, with the crack depth reducing slightly between 4k and 25k cycles which they attribute to a two-times increase in wear, which would reduce the growth of cracks (Harwick, Lewis, & Stock, 2017). The use of a higher number of dry cycles before wet cycles are applied in this testing seems to make a significant difference on the RCF experienced by the specimen. This demonstrates a necessity to understand how to apply water in a manner that is more representative of real-world track conditions.

In the case of this research, it is believed this could be potentially linked to recorded weather patterns. Thus, the research conducted for this article is concerned with the potential to increase the validity of RCF data generated from scaled testing through the use of wet and dry test cycles influenced by real-world weather patterns.

Methodology

Twin disc rig

The Institute of Railway Research twin disc rig, as seen in Figure 8, uses a configuration where a nominally 300 mm tapered wheel disc runs in contact, atop a 300 mm profiled, 3 segment rail disc. A pneumatic loading device with a load cell, attached to a rocker arm applies a vertical force of up to 9810 N between the discs to simulate the normal contact force. The motor/belt system that drives the discs ensures a 91:90 ratio between the wheel and rail which introduces a longitudinal creepage of 0.55%. The longitudinal creepage can be further tuned via control of the sample diameter and the contact position of the tapered profile to influence the rolling radius. Two taper profiles exist for the wheels (8.5° and 30°) which have been calculated to simulate either flange or tread contact between the rail and wheel. The bed to which the rail is fixed allows rotation, which provides an angle of attack, thus setting the lateral creepage. The bottom of the rig utilises a multi-axis piezoelectric force sensor which records the lateral, longitudinal, and vertical forces acting on the rail due to the applied contact conditions. To aid in testing where propagating RCF cracks is desired, a controlled drip of water is applied at the contact patch using a pump and pipe configuration.

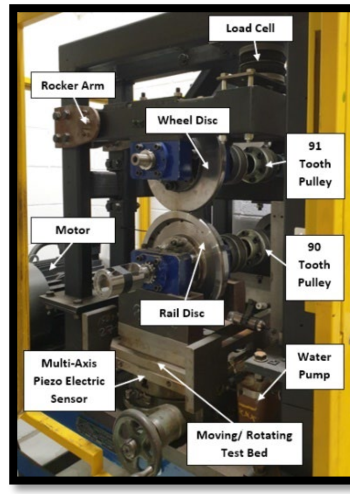

Figure 8: An annotated photograph of the Institute of Railway Research's Twin Disc Rig (Woodhead, 2021).

Procedure

Steel samples (4x R260 and 2x R350HT) were tested under RCF conditions in a series of two identical tests and observed using optical microscopy. The RCF conditions were calculated using the Whole Life Rail Model. A Tγ of 65 J/m has been validated as the maximum RCF case for R260 steel and hence conditions that represented 65 J/m at the scaled conditions were chosen. This article uses full-scale 65 J/m Tγ data generated in Vampire, "an industry standard software package that simulates rail vehicles on track," (Ensco Rail Inc, 2020) and adequately scaling the contact force to maintain the same contact stress at the scaled conditions. The longitudinal creepage was maintained from the full-scale conditions. The lateral creepage is adjusted throughout testing to account for wear, in order to ensure that Tγ is maintained at the desired value. Wear leads to a change in the contact area over time which decreases the contact stress if the area is larger. This, for example, is accounted for by increasing the lateral creepage, which in turn increases the Tγ value. This maintains the Tγ value at the desired overall value. The full parameters used in the tests can be seen in Table 1. In the first tests conducted, due to an error in calculating the active coefficient of friction during dry testing, the actual average Tγ experienced under dry conditions was around ~35

J/m, though the desired was 65 J/m. In the second test the Tγ was maintained much better at an average 67 J/m.

Table 1: A table of the twin disc input parameters for testing.

Normal Force (N)	Longitudinal Creepage (%)	Lateral Creepage (%)	Spin Creepage	Motor Drive Speed (Hz)	Equivalent Tγ
9650	0.351	0.29	0.99	25	65

All samples were run for 50k dry cycles in intervals of 5k and then transitions to 25k wet cycles. If RCF was not initiated during the dry cycles, then wet cycles were repeated, as can be seen in Figure 9. The principle behind this being that 50k dry cycles would fatigue the rail disc and water would then help propagate the cracks. 50k cycles was chosen as R260 was the softest material tested and is cited in literature as likely to experience crack initiation at this number of cycles. However, this methodology may be changed in future tests to extend the number of wet cycles before transitioning back to dry cycles if RCF is not generated. To identify the initiation of RCF, the disc is inspected every 5k cycles for any damage and if crack initiation is evident this is marked. If cracks are then viewed at this location on the next cycles the previous cycles are taken as the RCF initiation point. Running 50k dry cycles then 25k wet is more representative of real-world weather conditions where it rains or snows approximately 36% of the time.

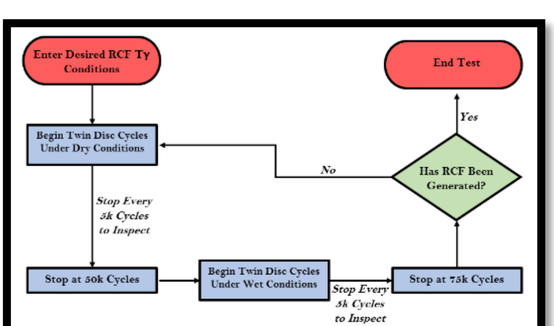

Figure 9: A flow chart of the proposed testing matrix.

Results analysis

From the twin disc tests conducted as a part of this research a full timeline of forces acting at the wheel-rail contact were recorded. 200x magnification photos were taken at two locations per rail segment each time the test was stopped using a Dino-Lite USB capture camera. This was done to help view and record any cracks, damage, or irregularities at the surface.

Tγ vs No. Cycles

Figure 10 shows the change in Tγ throughout the first test. This is useful for understanding the conditions experienced at the wheel-rail interface. Cycles above 50k are experiencing wet conditions and thus a significant drop in Tγ can be observed which is expected.

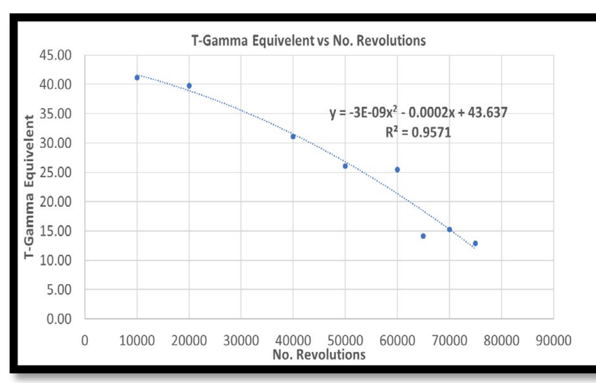

Figure 10: A graph of Tγ vs number of cycles (Test 1).

As previously stated, the Tγ should be maintained at 65 J/m during the dry section, however, the active coefficient of friction in the first test was lower than predicted and thus the conditions began at 42 J/m which declined during dry rolling to a minimum of 26 J/m. In the second test this value was much more optimally maintained at an average of 67 J/m, as can be seen in Figure 11.

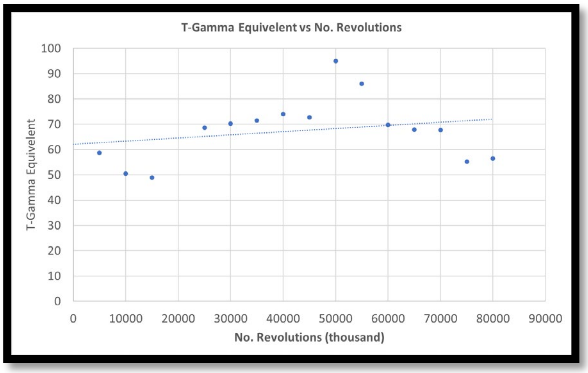

Figure 11: A graph of Tγ vs number of cycles (Test 2).

It is difficult to predict and alter the parameters on application of the water, hence the peak shown at 50k cycles is to be expected.

Coefficient of Traction vs No. Cycles

The drop off in Tγ during the dry section of test 1 and test 2 could be attributed to the machining lines visible on the surface of each specimen. Over the 50k dry cycles it is most likely that they were worn away which would have reduced the coefficient of traction (COT) between the wheel and rail over time. A reduction in the COT within the dry section of testing can be observed in the testing especially approaching over 40k cycles. The COT would be expected to drop when water is applied which is seen from 50k cycles onwards in both tests. The COT seems stable during the wet section of test 1 but the fluctuation in COT could be the cause of the less optimally maintained Tγ, as can be seen in Figure 12. Figure 13 shows the COT is much more consistent in test 2 which is why the Tγ is more optimally maintained.

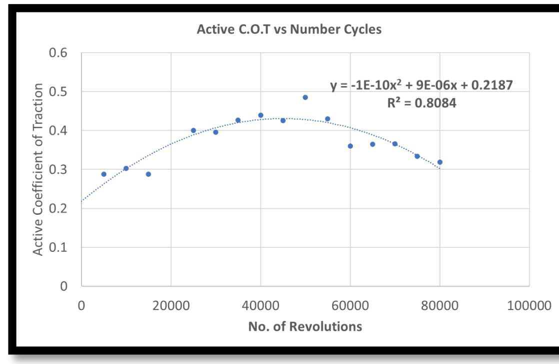

Figure 12: A graph of COT vs number of cycles (Test 1).

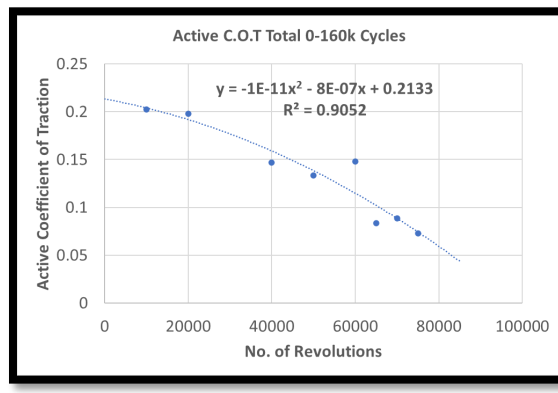

Figure 13: A graph of COT vs number of cycles (Test 2).

Alternatively, the drop off in COT and Tγ could be attributed to any drift in the yaw angle during testing causing a decrease in lateral creepage over time. The rotating test bed in the twin disc test rig has a small amount of backlash which could have been the cause. The longitudinal and lateral creepages were set at the parameters mentioned in Table 1 using the lateral offset and yaw angle controls on the rig and maintained as best as possible.

Sample Examination

Material Analysis

After each test was completed full timelines with forces and surface photos were compiled. This was to show any cracks with their corresponding number of cycles and contact conditions.

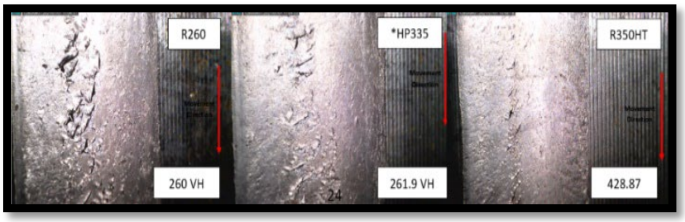

Figure 14: An illustrated compilation of 200x magnification photographs showing cracks and damage (Test 1).

Figure 14 shows cracks and flaking behaviour around 85k cycles. The softest R260 sample measured at 260 HB shows the most damage at the surface. Cracks are visibly long and wide, showing more developed cracks, and the material seems to be almost flaking away, possibly due to spalling. The second, softer R260 sample appears to have less developed cracks but they remain visibly long and noticeably wide. The flaking-like behaviour of the 260 HB steel is not visible on the 261.9 HB sample. The hardest steel in the test, the R350HT sample has a measured hardness of 428.87 HB which is far harder than expected. The sample seems to show short and narrow cracks at the surface, by far the least developed of the samples but still visible. The point of initiation was not captured in test 1 for each grade, but damage and cracks are visible on the samples through the proposed methodology. Hardness values were provided with the samples of steel, with results demonstrating that harder steels are more resistant to cracking.

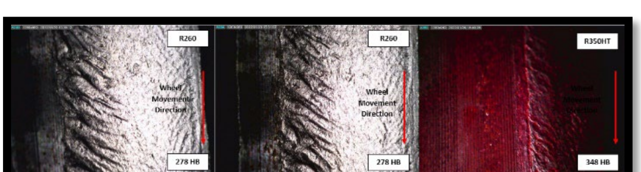

Figure 15: An illustrated compilation of 200x magnification photographs showing cracks and damage (Test 2).

Figure 15 shows the test 2 samples. Unlike the test 1 results, the cracks in the photos are taken at 50k cycles for the R260 samples and 80k cycles for the R350HT sample. These are not taken as the initiation point for each grade as notes on damage were made on each segment, hence the initiation for each was taken as 45k for the R260 samples and 75k for the R350HT sample, which is close to values presented in literature from other twin disc tests. In contrast to test 1, the more precise control of Tγ during test 2 allowed for the point of initiation to be captured. However, both samples show cracks generated from the proposed methodology of wet and dry cycles.

Optical Microscopy Observation

To further validate the generation of RCF cracks through the proposed methodology, optical microscopy of a dissected twin disc sample was conducted. This made it possible to confirm if cracks visible on the surface had depth and were oriented as expected with regards to the rolling direction and contact conditions.

Figure 16: A 100 x magnification photograph showing RCF cracks on a R260 sample subjected to RCF twin disc conditions.

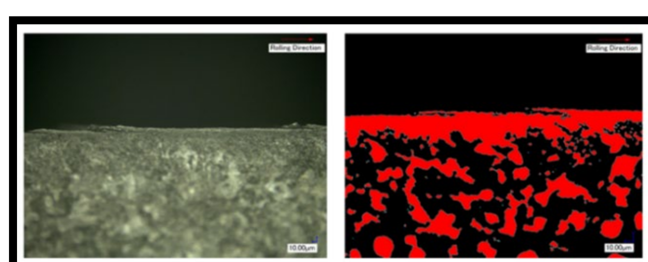

Figure 17: A 250 x magnification photograph showing RCF cracks on a R260 samples subjected to RCF twin disc conditions.

The cracks visible in Figure 16 and Figure 17 are correctly orientated with regards to rolling direction, as shown in Figure 5. The cracks have a reasonable average depth of 12.6 µm.

Crack Angle Analysis

When considering the direction of the creep forces, the resultant force and rolling direction, the observed crack plane from a top-down view of the specimens is orientated correctly according to the theory discussed in *Section Rolling contact fatigue* and can be seen in Figure 18.

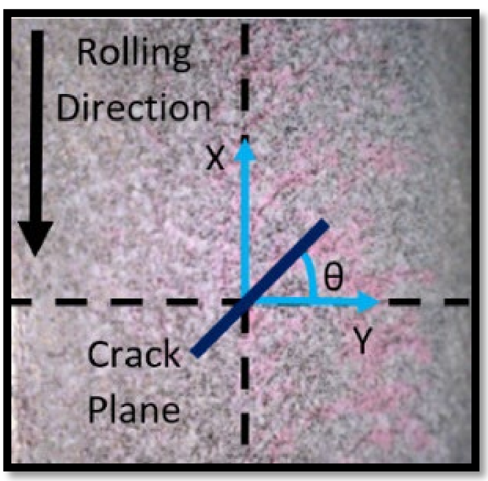

Figure 18: An annotated 200x photograph of a sample surface showing the expected crack angle plane against the cracks visible on the surface (Test 1).

The expected observed crack angle changes throughout the dry portion of testing due to changes in the longitudinal and lateral forces. These are possibly due to factors mentioned in *Section Coefficient of traction vs no. cycles*. The expected head check angles (θ) of the cracks throughout the 50k dry cycles has an average angle of 32 degrees for test 1. The forces estimated produce a crack angle of 45 degrees throughout the testing. From observation of the samples at 85k cycles the cracks seem to have varied angles depending on the sample of steel. The harder R260 sample has surface cracks measured around 35 degrees. The softer R260 sample cracks are measured at around 50 degrees. The R350HT sample shows surface cracks around approximately 45 degrees.

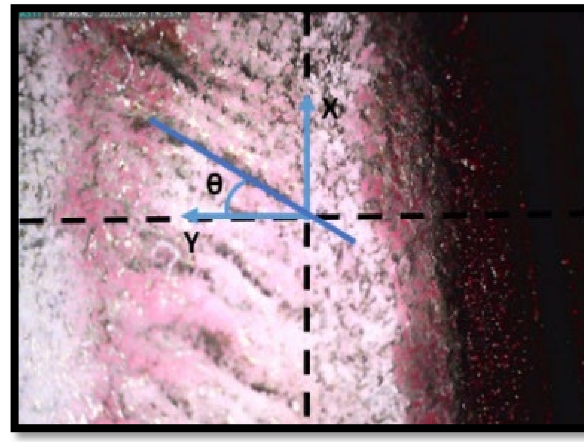

Figure 19: An illustrated 200x photograph of a sample surface showing the expected crack angle plane against the cracks visible on the surface (Test 2).

In test 2 the samples all display cracks at around 35 degrees. The orientation of cracks in Figure 19 is different to the ones in Figure 18 due to the Dino-Lite camera being upside down during recording of test 2. The crack angles are measured using the images of the surfaces and a protractor and drawn guidelines. The angles of the cracks observed are near the values predicted using Heuristic force data and the force data from testing, produced by the piezo-electric sensor.

Discussion

Analysis of the various sample surfaces taken from RCF twin disc testing conducted in this research could help support the use of applying wet and dry cycles in a ratio more representative of real-world weather data. In this research 25k wet cycles are run after 50k dry cycles to represent the approximate 36 % rain days that occur in the UK more accurately. The cracks visible on each sample grade surface, shown in *Section 4.3.1 Material Analysis*, are consistent with literature. It is thought that R260 will experience RCF initiation around 50k cycles, whilst R350HT is expected to initiate cracks at around 80k cycles.

The crack angles observed at the surface of each sample are also within an acceptable range of what is expected from the theory cited in *Section Rolling contact fatigue*. The average angle of cracks observed across all samples at 85k cycles in test 1 is approximately 43 degrees. The average angle of cracks observed across all samples in test 2 is approximately 38 degrees. The expected average angle using the force data from the twin disc rig was 32 degrees and the expected average crack angle using Heuristic predicted creep forces was 45 degrees.

As well as the head check cracks visible on each sample, the dissection of a sample and use of optical microscopy further helps aid in the validation of this methodology, as the cracks are shown to be frequent and have significant depth. The cracks are shown to have ridges form which would be expected, and these ridges and cracks are correctly oriented when considering the direction of travel of the twin disc rig. The testing was conducted twice. The first test was not in ideal conditions, as the Tγ was not properly maintained at 65 J/m, but yielded damage at around the expected cycles to initiation for each grade. The second test which was ideally maintained at the maximum Tγ case for R260, allowing the point of initiation of each steel grade to be captured.

The findings of this research, along with that reviewed within this article, show that running a high number of dry cycles before applying water, results in RCF cracks around the predicted number of cycles. As stated previously, the results from the Harwick et al. (2017) study show a difference in the crack frequency and depth between running a low and high number of dry cycles before applying wet cycles. This study shows that the ratio of wet to dry cycles is a relevant variable in RCF testing, as one may be more representative of the full-scale conditions than the other. It is suspected that applying water to the contact in scaled testing in a manner reflecting real-world weather patterns would be more representative, hence applying a higher ratio of dry to wet cycles. This may suggest that current RCF data generated through applying constant wet cycles may have less frequent and longer cracks than would be expected at the full-scale. Only by applying the correct dry to wet cycle ratio would the cracks generated at the scaled represent the full-scale.

Conclusion

In conclusion, this article has summarised current methods of RCF testing and their possible limitations. Weather data has been analyzed to create an RCF initiation methodology which applies dry and wet cycles in a manner thought to be more representative of real-world weather patterns. Although some issues arose in test 1 with regards to the active COF being incorrectly calculated, the Tγ was well within the RCF region throughout the testing. The Tγ in the dry section should have been maintained in this testing and ideally would have been at Tγ 65 J/m as this was the maximum case for RCF in R260 grade steel. Though, for the purposes of demonstrating the application of water to replicate weather conditions more accurately, RCF is generated at around the correct number of cycles expected and head cracks are correctly orientated when considering the direction of travel and creep forces. Test 2 showed better success at maintaining the Tγ at the maximum case and the cycles to initiation found agreed with literature and previous tests to within 5k cycles.

This research along with literature reviewed from Hardwick, Lewis and Stocks (2017) shows that it is possible to generate RCF by applying higher amounts of dry cycles before applying wet and thus there needs to be some comparison of both methods to the full-scale to find the most representative. This research suggests using real-world weather patterns as the deciding factor for determining the required ratio of wet and dry cycles to generate RCF in twin disc testing. Applying constant wet conditions during scaled testing is not representative of real-world weather patterns and the cracks experienced under higher amounts of wet cycles are shown in both *Section Weather conditions* and Hardwick, Lewis and Stock's (2017) paper to propagate more due to hydro-pressure and hence will probably be longer than what is being observed on track under the same Tγ conditions. This could suggest that RCF data from twin disc testing shows longer cracks than experienced on track and thus overestimates the damage caused by RCF to the rail and thus underestimates the rail's life expectancy. The conclusions and future work suggested by this research hope to contribute to improving scaled testing of RCF conditions by making them more representative of the full-scale.

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