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Bevan, Adam and Klecha, Stephanie

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Use of Magnetic Flux Techniques to Detect Wheel Tread Damage

Dr Adam Bevan*, Institute of Railway Research, University of Huddersfield, UK
Stephanie Klecha, MRX Technologies, Derby, UK

* Corresponding author: a.j.bevan@hud.ac.uk

Abstract

Rail vehicle wheelsets are regularly maintained to ensure safe operation on track and prolong life. This is achieved through measurements to inspect roundness, profile shape, rim thickness and visual inspections of surface damage. If necessary, wheels are reprofiled on a lathe to preserve the optimal wheel shape and remove any visible surface damage.

Surface damage is difficult to classify visually, leading to highly subjective results. It is also not possible to establish defect depth through visual inspections. Magnetic flux leakage technology has been successfully applied to the detection of defects in rails. This technology has been adapted for the evaluation of wheel damage resulting in a fast, repeatable method of quantifying damage on railway wheels.

This paper describes the theory behind the magnetic flux leakage technique and how it has been applied to the detection of wheel damage. This includes a summary of the assessment of the depth of damage into the wheel tread for a range of wheelsets. The benefits to train operators of adopting this technology is also presented.

Keywords

Railway systems; Maintenance & inspection; Fatigue

List of notation

HHU	*Handheld Unit*
MFL	*Magnetic Flux Leakage*
RCF	*Rolling contact fatigue*
RSSB	*Rail Safety and Standards Board*
SCM	*Surface Crack Measurement*

1. Introduction

The maintenance and renewal activities of wheelsets accounts for a large proportion of the whole-life costs of railway rolling stock. Wheelsets are regularly maintained to ensure their safe operation on track and prolong their life. This is achieved through measurements to inspect roundness, profile shape (wear), rim thickness and visual inspections of surface damage. If necessary, wheels are either reprofiled on a lathe (typically about once a year) to preserve the optimal wheel shape/profile and remove any visible surface damage or renewed (typically every 4 to 5 years). These activities have significant labour and material costs, but also require the train to be taken out of service which impact fleet availability and service provision (Bevan et al, 2013a; Molyneux-Berry et al, 2013).

Surface damage is difficult to classify visually, leading to highly subjective results. It is also not possible to establish the depth of defects through visual inspections. Wheel turning on a lathe removes this damage, but there is a crucial balance between removing enough material to eliminate the defects whilst taking the minimum cut to preserve the rim thickness and prolong the life of the wheel. As such, wheel lathe operators will take multiple small cuts to prevent excessive material removal. This increases the time that the vehicle is on the wheel lathe (out-of-service) rather than in revenue-earning service.

Magnetic flux leakage (MFL) technology has been successfully applied to the detection of surface and sub-surface defects in rails (Baldwin, 2015; Trueman, 2015). Recently, work has been undertaken to adapt and validate the use of this technology for the evaluation of wheel tread damage. This produces a fast, repeatable method of quantifying damage on railway wheels. Resulting in reduced inspection times and optimised wheel turning; saving time and increasing wheelset life. Management and trending of the recorded data also enables maintainers to identify problem vehicles or wheelsets and plan maintenance in advance. This will also assist train operators when evaluating wheelset performance and costs.

This paper describes the theory behind the MFL technique and how it has been applied to the detection of wheel tread damage. This includes a summary of the assessment of the surface size, shape, position and depth of damage detected on a range of in-service wheelsets. The benefits to a train operator of adopting this technology are also presented.

2. Wheel Tread Damage and Maintenance Practices

The contact between the wheel and rail provides a harsh operating environment. The loading conditions and contact geometry cause high stresses that are significantly higher than the yield stress of the as-manufactured wheel material. Additionally the transmission of traction, braking and steering forces apply tangential stresses and thermal inputs resulting in material flow, wear and cracking damage (such as rolling contact fatigue (RCF)) to the wheel tread. Due to these demanding operational conditions it is difficult to prevent all forms of damage occurring on wheel treads. Optimising the life of a wheel is therefore a matter of limiting the rate of damage, managing the consequences, and preventing the development of unsafe conditions. This can be achieved through careful wheelset inspections combined with effective data recording at the wheel lathe to help determine the root cause of the observed damage and optimise the life of the wheel.

Typically a wheelset is reprofiled 3 or 4 times during its lifetime and renewed when the wheelset reaches the permitted minimum diameter. This reprofiling is either carried out as a planned maintenance activity at a given distance interval, based on an understanding of the damage rates for a particular fleet, or when the surface condition of the wheel tread has degraded (due to wear, cracking or other forms of damage) to an extent that requires reprofiling. To identify if a wheelset requires reprofiling the condition of the wheel tread (in terms of wear (typically flange height and thickness), out-of-roundness and surface condition) is regularly inspected using a combination of automated and manual monitoring techniques. But there is currently no technology available for inspecting and quantifying the surface condition of railway wheels. Maintainers are reliant on visual inspections which are highly subjective and lead to non-repeatable results. It is also not possible to establish damage depth from visual inspection. This makes consistent corrective action, data assessment and trending difficult.

Generally the amount of material removed from the wheel during reprofiling is governed by the level of flange wear and severity of any tread damage. This is demonstrated in Figure 1. Figure 1(a) shows a worn P8 wheel profile (red profile) after approximately 61,000 miles of running with 1 mm of flange wear. Restoring the full flange requires the removal of approximately 2.5 mm of material from the wheel radius, as illustrated by the green profile and shaded area. In this case the cut depth required to restore the profile removes all the RCF damage (cracks indicated by the angled red lines on the field side of the wheel). In comparison, Figure 1(b) shows a worn P8 wheel profile (red profile) after approximately 178,000 miles. Flange wear generally occurs early in the life of the profile and then stabilises, therefore only a small increase in flange wear is seen (1.1 mm), resulting in approximately 2.7 mm of material cut from the wheel radius to restore the profile (green line and shaded area). As the wheelset has run to a greater mileage the depth of RCF damage has also increased and therefore in this case a greater cut depth would be required to remove the RCF damage. As the wheel lathe operator has no information on the depth of the damage (only surface appearance), the operator will either take a series of multiple smaller cuts or an excessively large cut (based on experience) to ensure that all damaged material is removed from the wheel. This increases the time that the vehicle is at the wheel lathe (rather than in-service) and generally results in more material being removed from the wheel diameter than necessary, reducing the life of the wheelset.

During previous research (Bevan et al, 2013b; Bevan et al, 2013c), the interaction between the amount of material loss at the lathe to recover the profile (due to tread and flange wear) and to remove the RCF damage has been investigated. Figure 2 shows an example of the radial material loss due to wheel wear, tread damage and the cut depth required to recover the profile shape due to flange wear, expressed as a function of vehicle running distance. Due to the trend in flange wear, the depth of cut on the lathe required to restore the wheel profile remains fairly constant with mileage after the higher initial flange wear rate when the profile is new. As the mileage increases, RCF cracks propagate more rapidly, so the depth of RCF damage increases. At this stage it is necessary to take a deeper cut on the lathe to remove the damaged material. Therefore, there is an optimum turning interval where the material removal needed to restore the profile shape due to flange wear is the same as that required to remove the RCF damage.

This example highlights that for a wheel lathe operator a crucial balance exists between:
(a) removing enough material to eliminate the damage, (b) minimising the cut depth to preserve the rim thickness of the wheel (to prolong wheelset life) and (c) minimising the time at the wheel lathe by not taking multiple smaller cuts. Providing the ability to reliably and accurately measure the depth of damage on the wheel tread would significantly assist in the decision making of the wheel lathe operator and optimisation of the management of wheel surface damage.

3. Development of Wheel Surface Crack Measurement Device

MRX's Surface Crack Measurement (SCM) technology has been successfully used to quantify the severity of defects in rails for over 8 years. This SCM technology has recently been adapted to measure surface damage on wheels using a specially developed hand-held unit (HHU). The prototype HHU is illustrated in Figure 3 and is described in more detail below. As part of the Rail Safety and Standards Board (RSSB)/Future Railway Rail Operator Challenge Competition, funding was awarded to validate and further develop the SCM HHU.

3.1 Magnetic Flux Leakage (MFL) Technology

SCM technology uses MFL measurements to assess the depth of RCF defects. This is achieved by magnetising the specimen and then measuring the remnant magnetic flux with an array of sensors. In a defect free specimen, the flux lines travel undisturbed trough the specimen, as illustrated in Figure 4(a). If a defect is present, the flux cannot easily travel through it, causing some flux to leak at the position of the defect. This is demonstrated in Figure 4(b). This flux leakage is measured by sensors located in the SCM device. As illustrated in Figure 3, the wheel SCM HHU uses 16 magnetic field sensors to measure and record the flux leakage. These sensors are positioned at a 5 mm pitch across the wheel tread and data is sampled every 0.5 mm as the unit is moved around the circumference of the wheel. This gives a high resolution scan of the surface condition of the wheel tread.

The measured signals are assessed using algorithms developed to relate the magnitude and frequency of the leaking flux signatures to the type and depth of the damage. The SCM technology reports the depth of the deepest defect in the scan and has been calibrated to quantify the amount of material to remove from the wheel to eliminate the damage. Experience from similar rail SCM products shows that the technology can detect and quantify both macro (such as cracks and cavities) and micro (such as thermal damage resulting in martensite or an abrupt change in metallurgical grain structure) discontinuities in the material. Work is currently on-going to optimise and validate the algorithms to assess both micro and macro defects in wheels.

The benefits of MFL over other non-destructive inspection techniques (such as eddy current) is that MFL can detect surface and near-surface defects up to 10 mm into the material, whereas eddy current technology can only inspect the top 3 mm of the material. MFL also gives a direct measurement of the damage depth, whereas eddy current is reliant on the operator assuming the defect angle into the material which is often unknown. Using the MFL technique the HHU provides an upper and lower detection limit of 10 mm and 1 mm respectively and a system accuracy of ± 0.5 mm.

The damage measured by the SCM HHU is output from the software as a damage map. Figure 5 shows an example of the real time damage map output. The vertical axis shows the length of the scan (in metres) around the circumference of the wheel. The horizontal axis shows the position of the damage on the wheel tread (flange to field side of the wheel) in mm. Measured data which has been classified as a defect is presented as a coloured output. The colour scale ranges from minor damage (blue) to severe damage (red), with grey indicating no detected defects. The damage map can be used to determine both the position and severity of the damage on the wheel tread. The maximum depth of all the defects assessed in the scan is also shown underneath the damage map.

3.2 Validation of SCM Outputs

Investigations have been conducted to assess the validity of the output from the SCM HHU when scanning a range of typical wheel surface damage types and severities, in addition to damage free wheels. The observed damage types have been classified according to the Wheel Tread Damage Guide produced by RSSB (Bevan et al, 2013c). This guide groups damage into the following mechanisms: wear, flow, fatigue and thermal damage. This study has focused on fatigue and thermally initiated damage since the SCM technology is currently optimised to detect these damage mechanisms.

Wheelsets from a range of electric and diesel multiple units have been magnetised and scanned using the HHU to identify the severity of the identified damage (if any). In a number of cases these scans were conducted on a wheel lathe and included a pre-cut scan, to assess the severity of the damage in the un-cut wheel, and a post-cut scan to ensure that all the measured damaged material had been removed from the wheel.

The following section provides example outputs from the HHU for a range of common wheel damage types. A description of the damage mechanism and comparison of the SCM HHU damage map and observed damage is also provided.

3.2.1 Field side RCF

RCF cracks are typically observed in three regions on the wheel tread, associated with the different running conditions of the wheel. These are highlighted in Figure 6 and include: flange root (typically 35 mm to 55 mm from the flangeback), running band (typically 60 mm to 80 mm from the flange back) and field side RCF.

Field side RCF is a very common form of surface damage for disc braked vehicles. As detailed in (Bevan et al, 2013c; Deuce 2007), it is categorised as surface fatigue cracks towards the field side of the wheel, typically in the region between 90 mm and 110 mm from the flange back of the wheel. It is usually the most severe type of wheel RCF, with cracks often propagating several millimetres into the depth of the wheel rim and eventually leading to cavities and out-of-roundness.

Figure 7 illustrates a scan of a wheel with mild to moderate field side RCF damage. In this case the cracking was difficult to identify visually on the surface of the un-cut wheel, but apparent in the HHU output and confirmed during turning on the wheel lathe. Figure 8 illustrates a scan of a wheel with severe field side RCF damage. In this case cavities have formed resulting in a 10 mm damage depth measurement.

3.2.2 Running band RCF

Running band RCF is less common than field side RCF, but is still a concern for wheelset maintenance. As detailed in (Bevan et al, 2013c; Deuce 2007) , running band RCF is categorised as surface fatigue cracks which occur in the centre of the wheel tread, typically between 60 mm and 80 mm from the flange back of the wheel. Usually, this type of damage starts slowly in the initiation phase, but accelerates. As the cracks propagate they can join up to form crack networks, eventually leading to pieces of material becoming detached from the wheel surface (shelling). This can result in the removal of a significant amount of material from the diameter of the wheel (typically 10-20 mm) if left unattended. It is often more economical to turn wheels with running band RCF at an earlier stage when the damage is shallower and the use of the HHU provides opportunity to identify the optimal turning interval.

Figure 9 shows an example scan of a wheel with running band RCF following first cut on the wheel lathe. In this case the running band RCF was measured by the HHU, but only visible following the first cut on the wheel lathe.

3.2.3 Cavities

Cavities can result from a range of initial damage mechanisms including both fatigue and thermal damage. Cavities associated with RCF cracks typically appear once a network of cracks has been created. These cavities are typically 1 mm to 3 mm in length and up to 1 mm deep, but can develop into larger cavities over time. Cavities can also develop following an incident of a wheel lock-up (where a wheelset stops rotating during braking). These are usually in discrete locations around the wheel and normally appear in the same locations on the opposite wheel of an axle. They are typically round or oval in shape and 20 mm or greater in length.

Figure 10 shows the surface appearance and HHU output for an RCF initiated cavity, whereas Figure 11 shows the surface appearance and HHU output for a thermal initiated cavity. In this case the damage measured by the HHU (with a maximum damage depth of 7.3 mm) was not visible in the un-cut wheel (Figure 11(a)) and only became apparent following the first cut on the wheel lathe (Figure 11(b)).

3.2.4 Wheelflats

Wheelflats are caused when a wheelset stops rotating while the vehicle is still travelling at speed, resulting in a wheel slide. As the wheel slides along the rail, the resulting friction heats the contact patch locally to very high temperatures (ca. 800 °C-850 °C). Following the slide the contact patch rapidly cools resulting in a very hard and brittle form of steel, known as martensite. Following further mechanical load cycling in the contact patch, fine cracks can develop in the heat affected zone. These then propagate until the hardened heat-affected martensitic steel starts to spall out of the wheel tread, leaving cavities. SCM technology relies on macro or micro discontinuities in the wheel steel to generate detection signals. In the case of thermal damage, such as wheelflats, the abrupt change in microstructure due to martensite causes a microscopic discontinuity at the defect position. Once the martensite progresses to cracking and spalling, these introduce macroscopic discontinuities.

Figure 12 illustrates a thermal induced wheelflat identified using the HHU. In this case the flat could be visually classified by a flattened portion of the wheel tread (leading to wheel out-of-roundness).

3.2.5 Non-visible damage

As previously discussed the potential benefit of the HHU is the ability to identify damage that is not visible in the un-cut wheel. The example presented in Figure 13 shows a maximum damage depth of 4.2 mm measured by HHU on the un-cut wheel. This damage was not visible on the surface of the un-cut wheel, but was visible following the first cut of 3 mm on the wheel lathe.

The HHU has also been shown to confirm when a wheel is damage free, either before or after turning on wheel lathe (to confirm all damaged material has been removed).

4. Benefits to Fleet Maintainers

A review of wheel lathe practices undertaken by the Association of Train Operating Companies (ATOC) highlighted the importance of better management of wheel lathe operations. This included decisions on the minimum cut depth required to remove a particular type of damage. In some instances the benefits from better management of wheel lathe operations were far greater than the benefits achieved from other mitigation measures (such as changing wheel steel or vehicle suspension characteristics) (Lawton, 2008).

An initial cost benefit analysis has been undertaken to demonstrate the use of HHU during regular inspection in order to optimise cut depths at the wheel lathe. As previously mentioned; currently a wheel lathe operator will either take a series of multiple smaller cuts or an excessively large cut (based on experience) to ensure that all damaged material is removed from the wheel. Through using the HHU the cut depth can be identified prior to reporifling resulting in less material being removed from the wheel diameters, increasing the life of the wheelset.

This has been demonstrated by tracking the life of a wheelset based on the observed wear rates and cut depths (with and without the use of the HHU). This can be visualised in Figure 14, which shows in the reduction in wheel diameter, due to wear and reprofiling, with running distance. Optimising the cut depth by using HHU results in two additional wheel reprofiling activities (which in this case equates to approximately 370,000 miles of additional running) prior to reaching the assumed wheel scrapping distance.

Taking into account the typical costs associated with reprofiling (e.g. labour, materials, energy and disposal), replacement, inspection and the cost associated with having a train out-of-service suggests a potential cost saving in the order of 25% in wheelset life.

Providing a solution to measure the defect depth offers the following additional benefits to rail vehicle operators and maintainers:

- Repeatable assessment of the severity and location of wheel surface damage and less reliance on judgement associated with visual inspection. Reduces the risk of surface damage being missed or inconsistently classified.
- Identification of the depth of cut required to remove the damage which might not be obvious/visible in the un-cut wheel. Reducing the time that the vehicle is at the wheel lathe, the risk of removing too much material during reprofiling and the variability

between wheel lathe operators. Provides the opportunity to optimisation of cut depths at the wheel lathe.

- Confirmation that all damage has been removed following reprofiling – preventing unnecessary extra cuts and giving confidence that wheelsets are being returned to service with all damage removed (as there is some evidence that damage returns more quickly if not completely removed).
- The ability to trend the type and severity of damage on a given vehicle or wheelset to better understand damage rates. Highlight problem wheels/vehicles and support specific case studies (e.g. performance of alternative wheel steels or vehicle design modifications).
- Improved planning and scheduling of wheelset maintenance activities. Minimising the time that the vehicle is out-of-service for maintenance.

5. Conclusions

SCM technology has been successfully adapted to the evaluation of surface and sub-surface defects in wheels. The developed SCM HHU uses 16 magnetic field sensors to measure and record the MFL around the circumference of the wheel. The measured signals are assessed using developed algorithms to relate the signature of the flux leakage to the type and depth of the damage. The damage measured by the HHU is output on a damage map which can be used to determine both the positon and severity of the measured damage on the wheel tread.

Through a serious of depot trials, the HHU was demonstrated to have significant advantages over visual inspection. In many cases, especially for cracking and damage masked by grease and dirt, the HHU output has been shown to give an instant and clear indication of the severity and position of the damage on the wheel tread for a range of common wheel damage mechanisms. In contrast, visual inspection required a detailed and time consuming assessment to identify the same damage.

Damage was also detected on a number of wheels by the HHU which was not visible on the surface prior to reprofiling and therefore impossible to detect during visual inspection. In these cases the damage was revealed during reprofiling on the wheel lathe and included examples of clusters of RCF and near-surface, thermally initiated, cavities. Knowing this information prior to wheel reprofiling allows the wheel lathe operator to program the required cut depth to remove the measured damage, reducing the time that the vehicle is over the wheel lathe. The HHU has also been shown to provide confirmation when a wheel is defect free. This is useful for identifying if a wheel actually requires reprofiling and also to confirm that all damage has been removed following reprofiling, as there is some evidence that damage returns more quickly if not completely removed.

Further work is currently on-going to examine a number of scrap wheel samples to optically determine the deformation depth, crack length and crack depth. This information will be correlated with the damage measured by the HHU from the scrap wheels to provide additional confidence in the developed defect depth algorithms. A business case detailing the benefits of the HHU for trending and maintenance planning will also be developed.

Acknowledgements

The results and findings included within this paper were developed from the RSSB/Future Railway-managed Rail Operator Challenge Competition. Arriva Trains and Bombardier Transportation, along with the other operating companies/vehicle maintainers, who supplied data to validate the HHU are acknowledged for their support during this work.

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Figures and captions

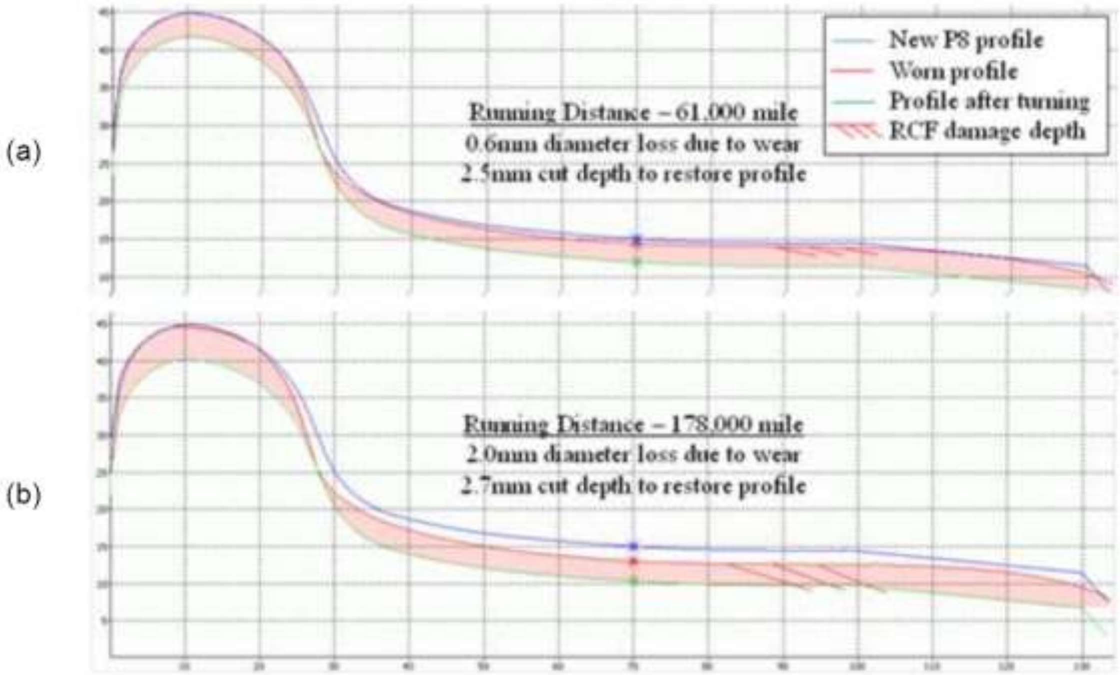


Figure 1. Example radial material loss from the wheel during reprofiling

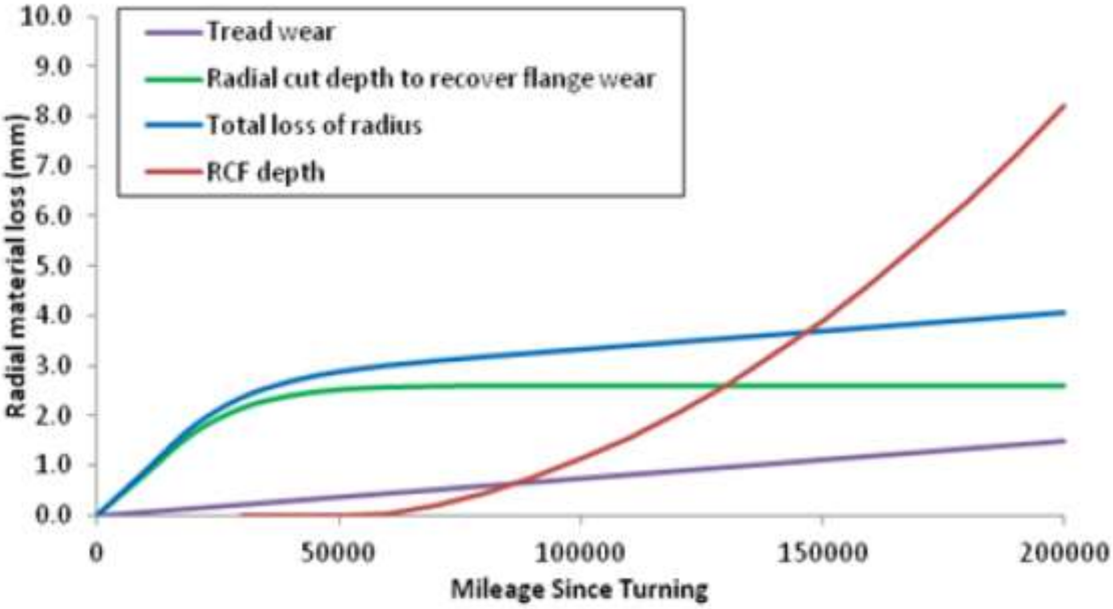
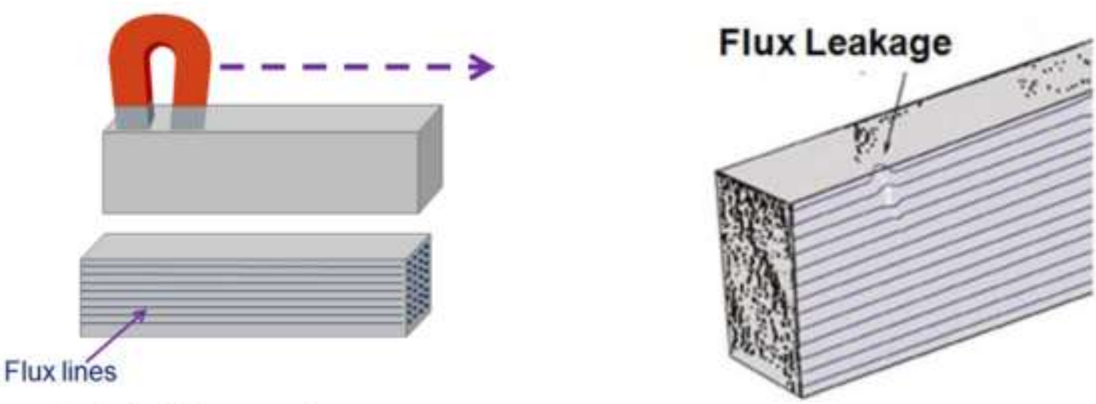


Figure 2. Influence of RCF damage depth on radial material loss (Bevan et al, 2013b)

Figure 3. Wheel surface crack measurement hand-held unit and sensor array



(a) Defect free specimen

(b) Magnetic flux leakage

Figure 4. Magnetic flux leakage theory

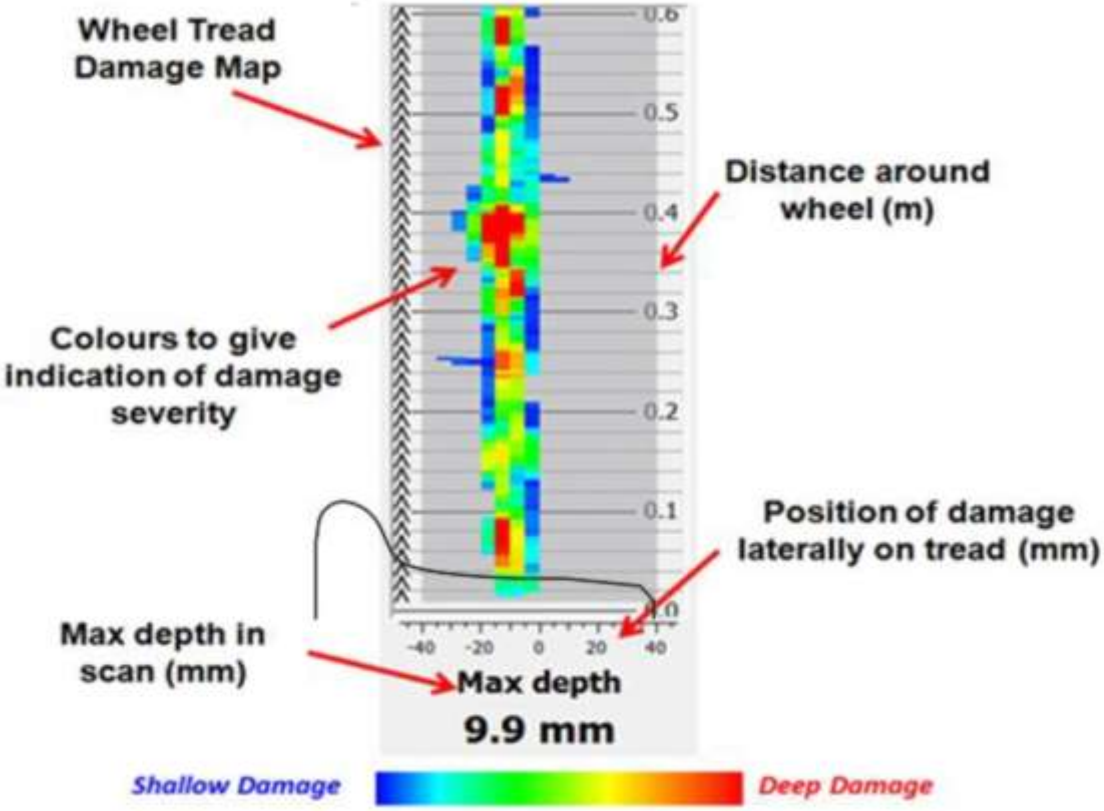


Figure 5. Example HHU damage map output

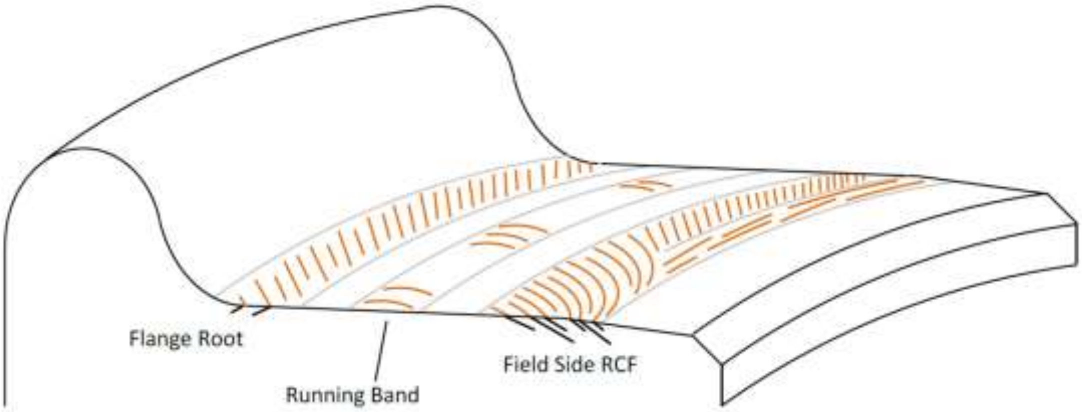


Figure 6. Three typical bands of RCF (Bevan et al, 2013c)

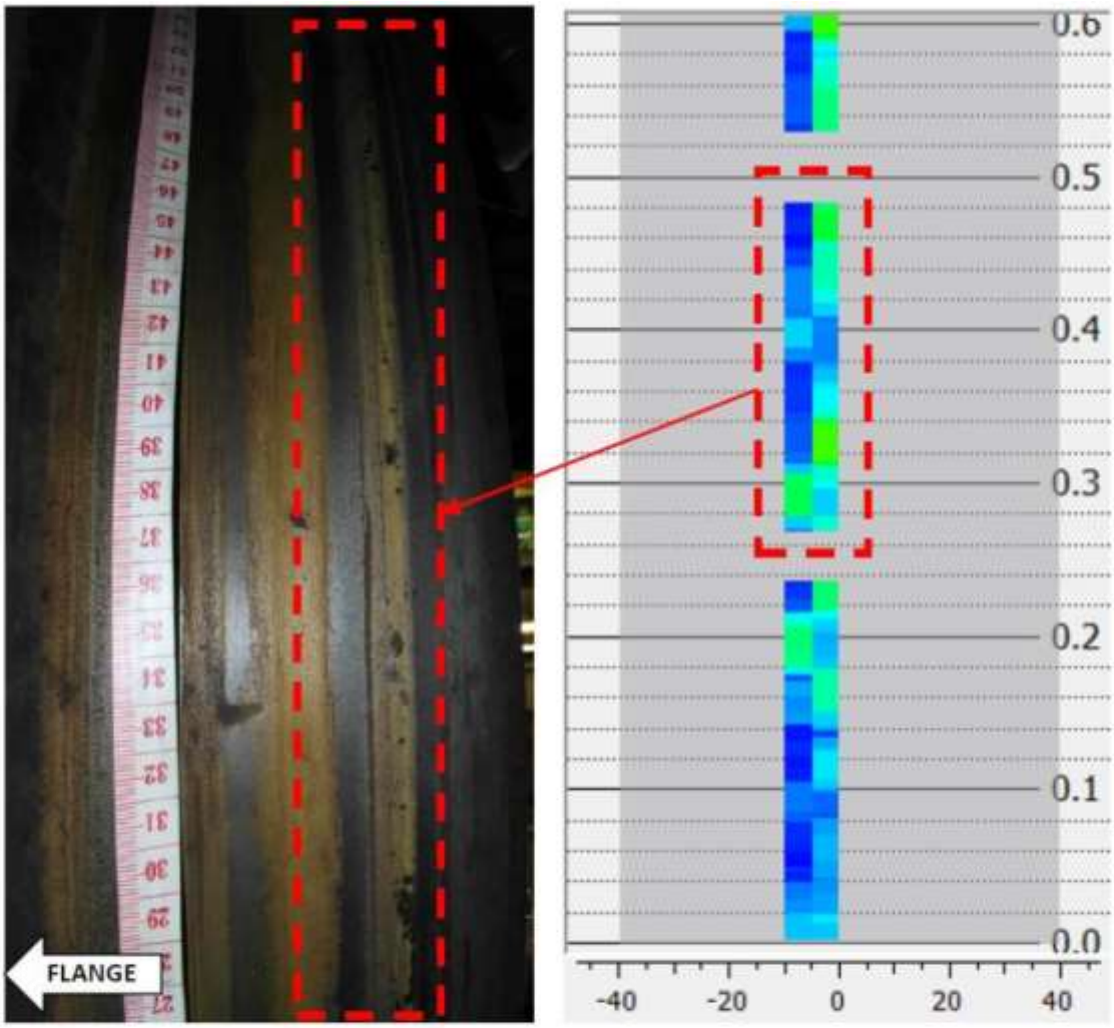


Figure 7. Mild to moderate field side RCF

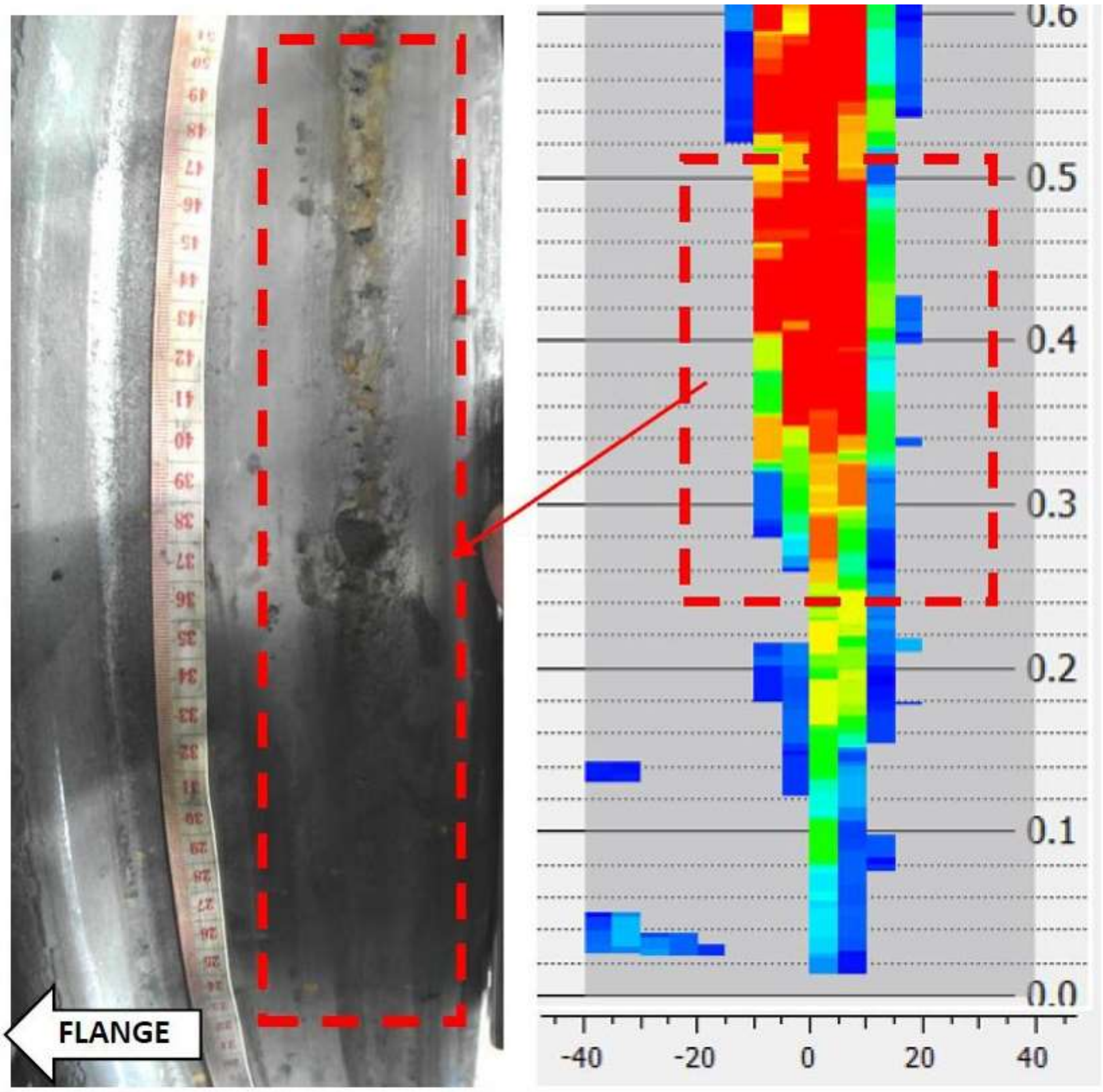


Figure 8. Severe field side RCF

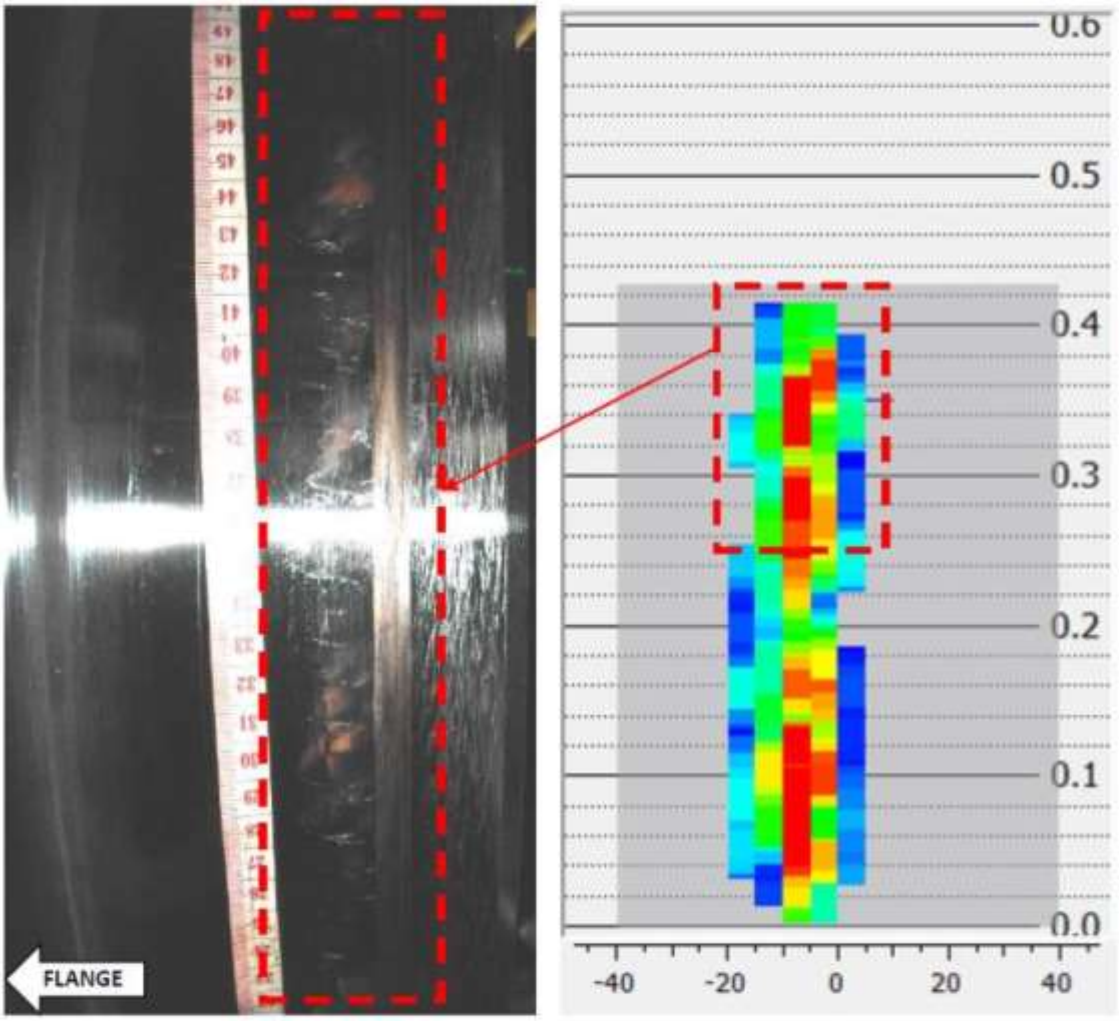


Figure 9. Running band RCF

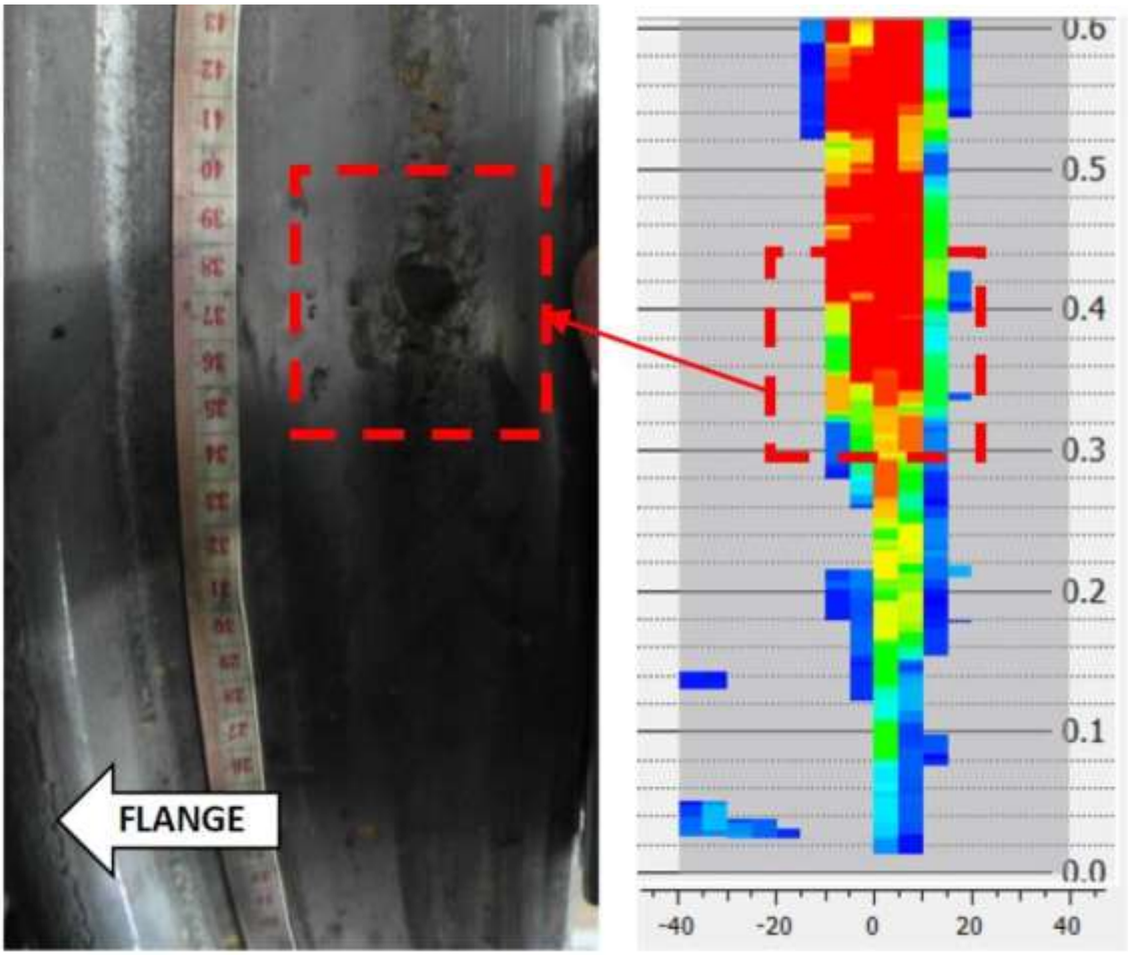
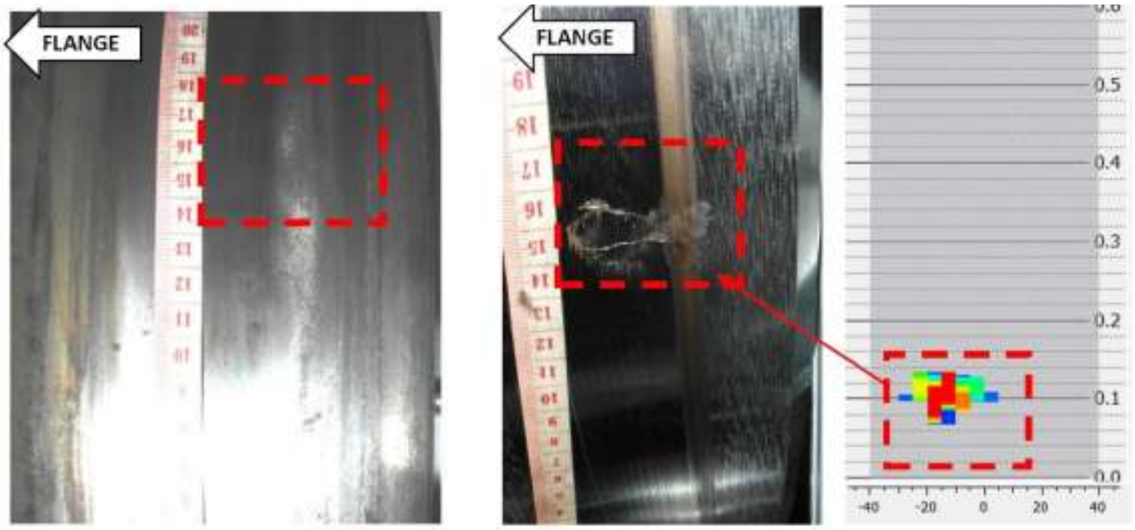


Figure 10. RCF initiated cavity



(a) (b)

Figure 11. Thermal initiated cavity

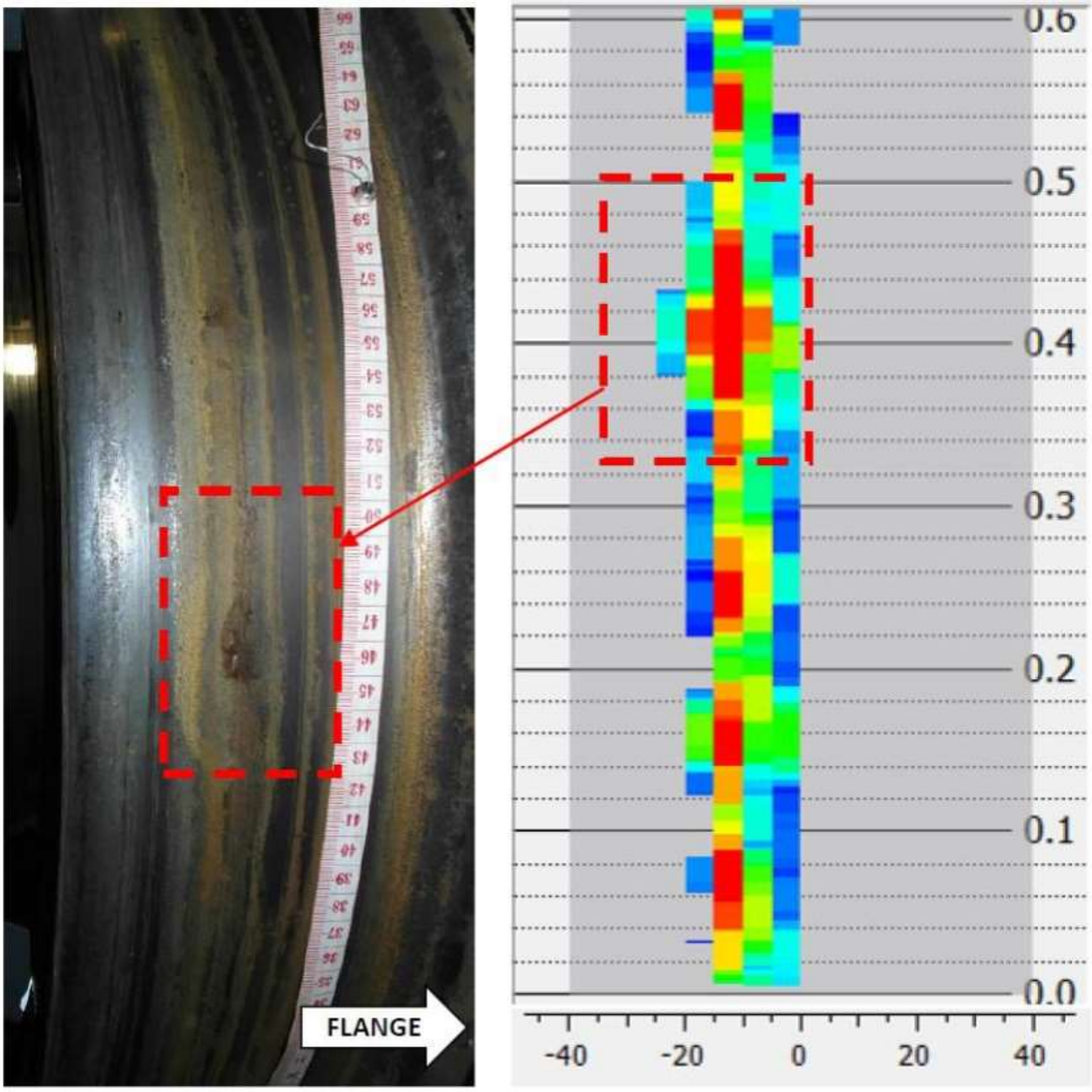


Figure 12. Thermal wheelflat

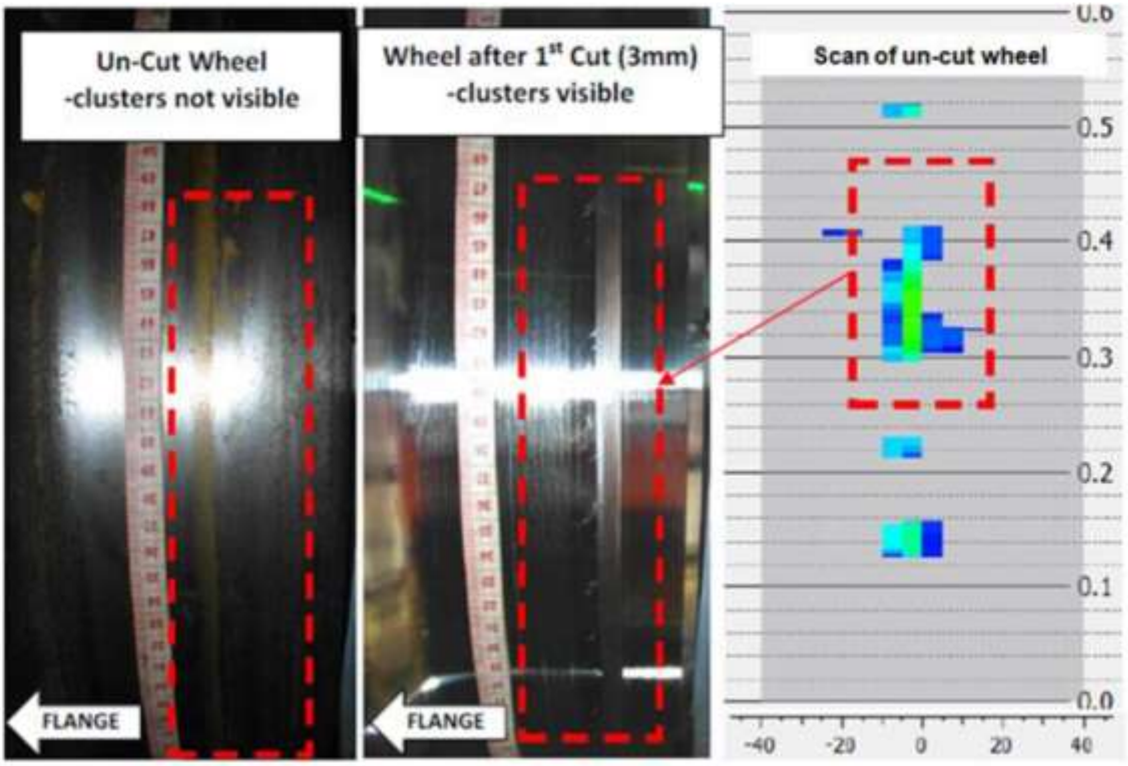


Figure 13. RCF damage not visible during visual inspection but measured by HHU

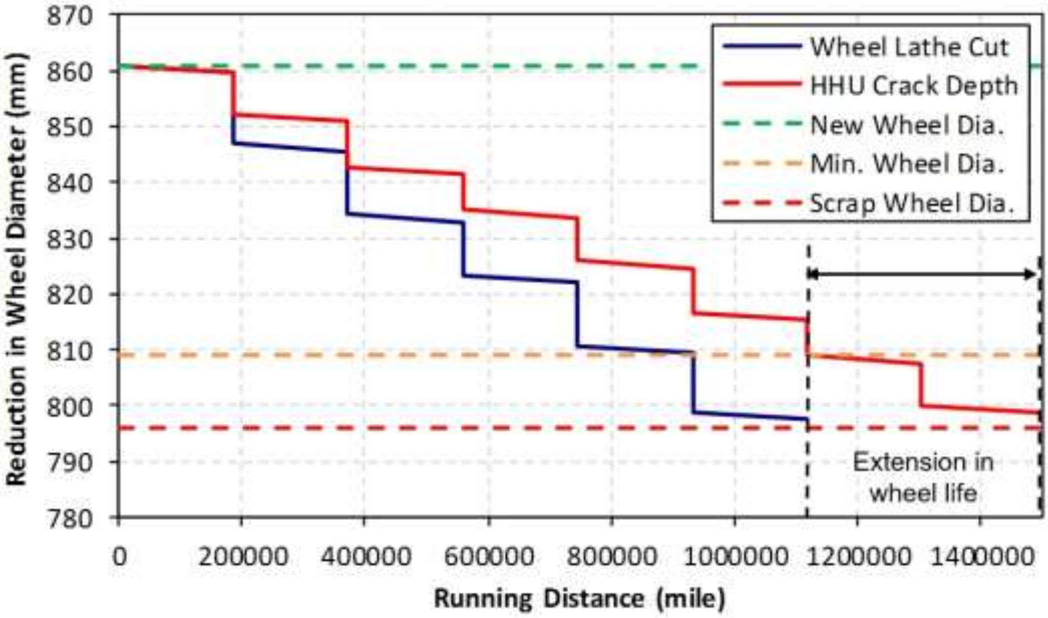


Figure 14 Wheelset life – with and without the use of HHU