A review on non-destructive evaluation of rails: state-of-the-art and future development

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Abstract: Rails are systematically inspected for internal and surface defects using various non-destructive evaluation (NDE) techniques. During the manufacturing process, rails are inspected using automated optical cameras and eddy current sensing systems for any surface damage, while the presence of internal defects is assessed through ultrasonic inspection. Similarly, ultrasonic transducers and magnetic induction sensors have been extensively used by the rail industry for the inspection of rails in-service. More recently, automated vision techniques and hybrid systems based on the simultaneous use of pulsed eddy current probes and conventional ultrasonic probes have been introduced for the high-speed inspection of rail tracks. Other NDE techniques, such as electromagnetic acoustic transducers, laser ultrasonics, guided waves, and alternating current field measurement probes, are also under development for application in the rail industry.

This paper comprehensively reviews NDE methodologies in use around Europe and North America for rail defect detection. This includes a detailed overview of the background theory and the techniques used to incorporate condition data into maintenance procedures. It also presents a review of the current state-of-the-art in NDE of railways coupled with a discussion of future developments and novel inspection methodologies in the field.

Keywords: non-destructive, inspection, rail, maintenance

1 INTRODUCTION

Rail tracks are subjected to intense bending and shear stresses, plastic deformation and wear, leading to degradation of their structural integrity with time [**1**]. In the past, the vast majority of failed in-service rails were attributed primarily to the propagation of internal defects in the rail web and head due to fatigue and excessive wear [**2**, **3**]. Following the introduction of head-hardened rails and higher carbon rail steels with superior resistance to wear, such as the 260 steel grade, in combination with cleaner steelmaking processes, rail failures caused by surface defects in the rail head have become much more commonplace within the rail industry [**4**].

The dynamic axle loads sustained by rails are massive, with the weight of an average six-carriage train being supported by an overall area equivalent to the surface of a compact disc. Under normal operating conditions, contact stresses between the wheel of a train and the rail can reach 1500 MPa. However, contact stresses can exceed 400 MPa due to poorly conforming wheel and rail profiles [**5**]. Such high stresses, combined with the high resistance to wear exhibited by modern rail steels, have led to a substantial increase in the significance of rolling contact fatigue damage in rails [**6**]. An example of RCF damage is shown in Fig. 1.

Rail failures can be distinguished into three types: those that have occurred due to the presence of a manufacturing defect; those that have arisen due to improper usage, handling or installation of the rail (*e.g.* damage caused by wheel flats, wheelburns, excessive movement, and bending of the rail due to failed sleepers); and finally, structural degradation due to fatigue or corrosion of the rail (e.g. head checking, web cracking, foot corrosion) [**7**]. Figure 2 shows

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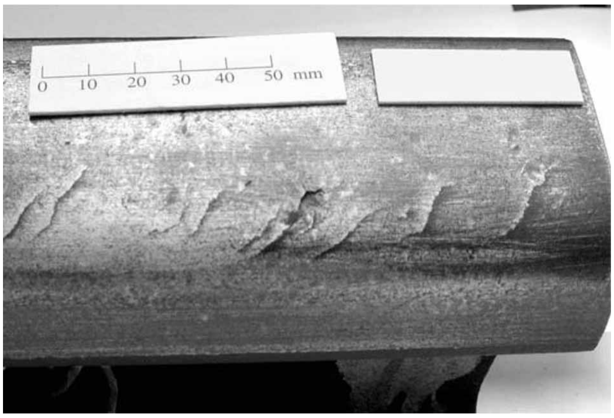

Fig. 1 RCF damage on a rail section

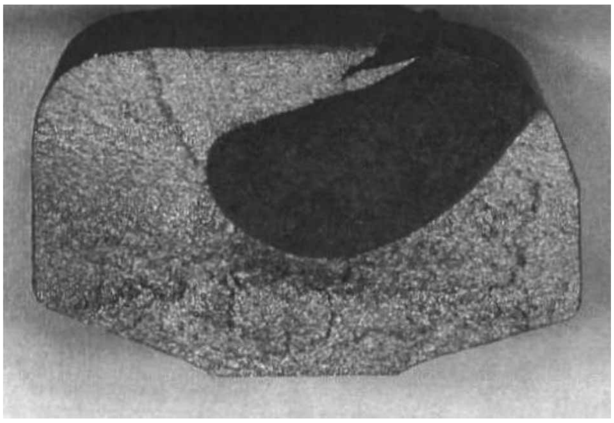

Fig. 2 Development of transverse cracking from a head check (taken from reference [**7**])

the development of transverse cracking from a head check.

To minimize the probability of in-service rail failures due to the presence of manufacturing defects, steel manufacturers have been constantly improving and refining their production processes. To increase the reliability of their product, rails are routinely inspected using highly automated non-destructive evaluation (NDE) systems during production. These systems involve the use of automated optical cameras and eddy current sensors for the inspection of the rail surface and ultrasonic probes for the detection of internal manufacturing defects [**8–10**]. The probability of surface defects going undetected during production is low, but in certain cases smaller (i.e. <5 mm) or awkwardly orientated internal defects, such as hydrogen shatter cracks, can be missed during the inspection.

Significant progress has been made in understanding and modelling structural degradation of rails, particularly the development of RCF damage. The fatigue models that have been developed for rails can be applied to estimate the expected level of structural degradation in particular parts of the rail network depending on the existing service conditions and schedule inspection intervals accordingly [**11–15**]. Although existing fatigue models can account for a wide range of applied loads, the input data on these loads (i.e. wheel flats) is not readily available or is unreliable and therefore their actual effect on the structural integrity of the rails is very difficult to be evaluated accurately.

The occurrence of defects caused by improper use, handling or installation is perhaps the most difficult to control. Apart from the fact that these defects can occur in a random (chaotic) fashion, their severity can also be unpredictable, since they result from abnormal and uncontrolled processes. Defects caused by normal fatigue mechanisms can initiate earlier than predicted by the design lifetime of the rail or exhibit accelerated growth due to improper use. For that reason, 'improper use' type defects and 'normal fatigue' type defects can be related to each other in certain cases. Rail failures that fall into these two categories have been the subject of the 'Rail Defect Management' (RDM) scheme employed by infrastructure managers in order to maximize the efficiency of the maintenance process [**16**].

As part of the RDM scheme, the rail industry has employed rail-failure reporting and archiving to monitor the occurrence of rail failures in the network over time. Rail-failure reports contain some useful data, providing information with regards to the location where the rail failure took place, the type of damage, route, date of discovery, track, and type of rail [**16**]. These reports can therefore be used to build a general statistical picture of the occurrence of rail failures, their causative factors and their frequency within the rail network. Based on the network usage, defect occurrence and rail failure statistics it is possible to adjust the inspection and maintenance schedules accordingly, prioritizing certain parts of the rail network over others, in order to achieve increased efficiency in the allocation of effort and available resources [**16**].

The development of defects due to uncontrolled and random processes or events is very difficult to be meaningfully represented in a statistical model. These defects can occur anytime, anywhere and unless detected in time can lead to rail failure without any previous indication. Maintenance schedules employed by the infrastructure managers are primarily designed to address structural degradation of the rail tracks caused by fatigue and wear. If maintenance scheduling takes into account the probability of failure due to defects that initiated from random events then the structural reliability of the network is increased but the efficiency of the maintenance process becomes questionable.

To achieve maximum reliability of the railway network and enhance the efficiency of the maintenance procedures, it is absolutely necessary to conduct sufficient and reliable inspection of the rail tracks [**17**]. For that reason, in-service rails are systematically inspected for internal and surface defects, using various NDE techniques, including ultrasonics, magnetic induction (or magnetic flux leakage, MFL), eddy current sensing and visual inspection [**18**].

2 RAIL DEFECTS

Steel manufacturers have made significant progress in minimizing the occurrence of defects during rail production through improvements in the technology of the manufacturing process [**19**, **20**]. Automated visual and eddy current inspection systems are used to detect any hot marks, protrusions, scratches, rolled in scale, seams, cold marks and microstructural damage on the surface of the rails, while ultrasonic transducers can detect internal cracking and large inclusions (>5 mm). Residual stresses introduced in the rails during the manufacturing and straightening processes can be assessed non-destructively using ultrasonics, electromagnetic or X-ray diffraction equipment and software. These residual stress measurement techniques also require calibration on a sample made of the same steel type and with a known (usually free) residual stress state prior to evaluation of rails. However, the assessment of the levels of residual stresses in rails by non-destructive means does not currently constitute common practice for rail manufacturers [**21**].

Defects in in-service rails can be present in the rail head, web or foot. The rail head is the part of the rail where the defects occur more often [**22**]. Rail head defects can be distinguished to those having internal origin, such as progressive transverse cracking or kidney-shaped fatigue cracks, horizontal cracking with or without transverse cracking of the rail head, horizontal cracking beneath the gauge corner, and longitudinal-vertical cracking, and those having surface origin, such as RCF damage (including gauge corner cracking, head checks, squats, shelling, and corrugation), wheelburns, and indentures. Rail web and rail foot defects include longitudinal and vertical cracking, cracking occurring at fishplate bolt holes (Fig. 3) or other holes found in the web (star-cracking), transverse fatigue cracking, and rail foot corrosion.

Profile irregularities and low levels of conicity that develop with time due to wear of the rail head can also be considered as rail defects [**1**, **16**, **23**]. Optical rail measurement using automated visual inspection systems is extensively used by the industry in order to assess the level of conicity of the rail head and the percentage of gauge and vertical head loss. The data acquired during visual inspection can then be used to develop an appropriate grinding plan to restore rail

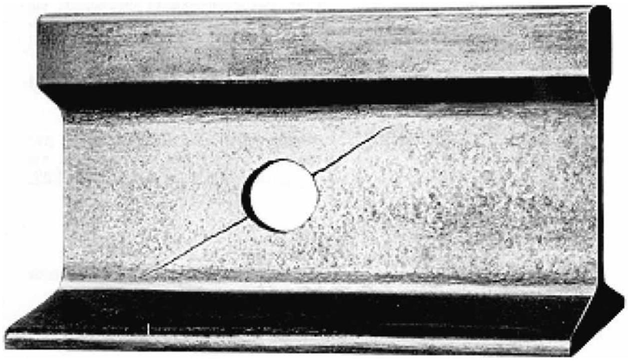

Fig. 3 Star-cracking from a fish-bolt hole (taken from reference [**7**])

Fig. 4 Photograph of a grinding train (taken from reference [**38**])

head conicity to the required level [**24–26**]. A grinding train is shown in Fig. 4.

Rail joining using alumino-thermic welds poses a significant problem for the rail industry, since internal defects such as shrinkage cavities, microporosities, inclusions and a coarse dendrite microstructure, which may develop during the solidification process, can affect the structural integrity and fatigue performance by acting as crack initiation points [**27**]. As a result, failure of alumino-thermic welds can take place very rapidly with no indication of fatigue cracking. Furthermore, the inspection of alumino-thermic and flash butt welds using ultrasonic transducers is not straightforward as the defects that initiate from these welds often do so from locations where it is difficult to get any form of energy transfer to perform a valid ultrasonic inspection [**28**]. Radiographic inspection using gamma-ray and X-ray sources has been used as an alternative NDE method for the detection of internal defects in alumino-thermic welds [**18**, **29**, **30**]. A significant advantage of the radiographic technique is that it can be used not only to detect but also size any shrinkage defects (Fig. 5), slag inclusions, and deep cracks

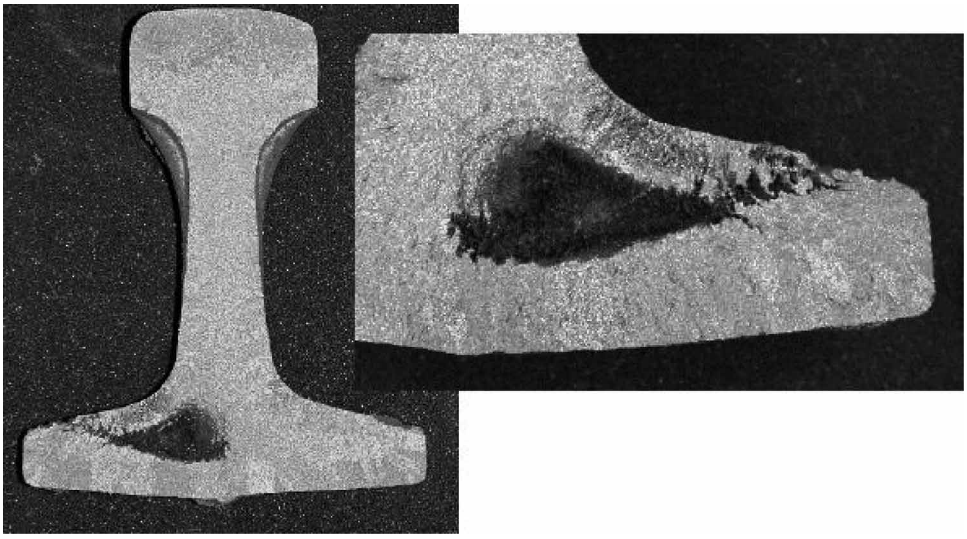

Fig. 5 Centreline shrinkage defect in foot of short-preheat alumino-thermic weld (taken from reference [**30**])

that may be present. However, radiography cannot detect any defects that lie in the transverse direction (i.e. through the web thickness). Furthermore, radiographic techniques involve health and safety issues for the staff members and therefore they tend to be avoided whenever an alternative reliable inspection methodology can be used.

3 RAIL TRACK INSPECTION

Rail failures have been a significant problem for more than 150 years. Maintenance procedure models developed based on rail damage present in the rail network are neither sufficiently accurate nor efficient enough to eliminate the need for inspection. Broken rails are still found in the rail network from time to time [**22**], but remarkably enough they do not always lead to train derailments. Figure 6 shows a photograph of the Hatfield site, UK where a major train derailment took place in October 2000 due to fatigue failure of part of the rail track as the train was moving over it [**31**].

Research on the application of NDE methods for the detection of defects in rails began as early as 1877 [**32**], almost 50 years before Dr Sperry set out to develop the world's first rail inspection vehicle using magnetic induction sensors [**33**, **34**]. Magnetic induction was the only technique available for the high speed inspection of rails until 1953 when ultrasonic transducers were added to the Sperry test vehicles for the first time [**34**]. Since then, the NDE concept for the high speed inspection of rails has remained largely unaltered.

Ultrasonic inspection is carried out by a variety of different instruments ranging from hand-held devices, through dual-purpose road/track vehicles to test fixtures that are towed or carried by dedicated rail cars.

Fig. 6 The Hatfield rail track site (taken from reference [**31**])

Unfortunately, the performance of existing conventional ultrasonic probes in detecting small (<4 mm) surface defects such as head checks and gauge corner cracking is inadequate during high speed inspection. In addition, the presence of larger and more critical internal defects can be shadowed by smaller surface cracks during inspection. This is also one of the reasons that the current international practice is to combine non-destructive evaluation of the rail network with preventative maintenance procedures, such as rail head grinding, in order to optimize the trade-off between maintenance cost and structural reliability [**25**, **26**, **31**, **35–38**].

Inspection systems based on the simultaneous use of conventional ultrasonic transducers with MFL sensors have a higher probability of detecting smaller near-surface and surface-breaking defects in the rail head. However, as inspection speed increases, the performance of MFL sensors tends to deteriorate rapidly due to a reduction in the magnetic flux density [**39–41**]. More recently, pulsed eddy current (PEC) probes have been added on certain ultrasonic test trains to offer increased sensitivity in the detection of surface defects at high inspection speed [**17**, **38**, **42–45**]. PEC probes perform far better than MFL sensors at higher inspection speeds but are affected more by lift-off variation.

Automated vision systems can operate at very high velocities (speeds up to 320 km/h are possible depending on the nature of the inspection) and are typically used to measure the rail profile and percentage of wear of the rail head [**46–48**], rail gauge [**49**], corrugation [**50**] and missing bolts [**51**, **52**]. Certain advanced vision systems can be used for the detection of RCF and other types of surface damage such as wheelburns at slow inspection speeds (~3–4 km/h).

The following sections describe the concept of each of the aforementioned NDE techniques for the inspection of rails in more detail.

3.1 Rail inspection using ultrasonic transducers

Ultrasonic rail track inspection can be typically performed either manually, using dedicated portable ultrasonic equipment placed on push-trolleys as shown in Fig. 7, or by using special high-speed test vehicles carrying ultrasonic probes.

During the inspection of rails using conventional ultrasonic probes, a beam of ultrasonic energy generated by a piezoelectric element is transmitted into the rail. The reflected or scattered energy of the transmitted beam is then detected using a collection of transducers. The amplitude of any reflections together with when they occur in time can provide valuable information about the location and type of the defects detected and the overall structural integrity of the rail under inspection [**53**].

Since defects can be located in various parts of the rail, the energy is transmitted at several different incident angles in order to maximize the probability of detection (PoD) of any detrimental features present in the rail [**53**]. The refracted angles generally used are 0°, 37° or 45° and 70° [**17**]. The ultrasonic transducers are also positioned to look across the rail head for longitudinal defects such as vertical split heads and shear defects [**17**].

The transducers are contained within a liquid filled tyre, known as a roller search unit or a sled carrier [**17**, **45**]. The ultrasonic probes are coupled to the rail using water sprayed on the rail surface by a special sprinkler as the test train moves along the track [**17**]. The inspection speeds achieved by test trains varies from 40 up to 80 km/h [**17**, **45**]. In reality, however, actual inspection speeds can be as low as 15 km/h, particularly when the defects detected by the test train need to be verified by manual inspection. Recent advances in the technology of ultrasonic equipment have enabled the development of a new generation of test trains that can achieve inspection speeds as high as 100 km/h [**45**, **54**]. However, there is very limited information available on the quality of the performance of these inspection vehicles at such speeds.

There are several difficulties related to the adjustment of the signal threshold (amplitude of the signal) and the position of the time window (or acquisition time – the acquisition time window is usually widened more than strictly needed to accommodate for variations in the water path, sound velocity and material inhomogeneities) that need to be overcome to enable reliable inspection of the rail track at high speeds.

If the threshold is set too high, the system will miss cracks while if it is set too low it will generate many false alarms [**17**]. Similarly, if the time window is set too close to the origin (i.e. to correspond to the rail surface) then the detector will be prone to excessive noise. On the other hand if the time window is too far from the origin then sub-surface cracks will go undetected. In the past, due to these difficulties in the fine tuning of the equipment, the number of false readings during inspection tended to be very high, and considerable staff time was spent during the verification of each of the readings obtained. This problem has been partly addressed by setting more realistic detection thresholds and by a programme of comparing the train results with results from manual systems in order to refine the detection criteria [**17**]. However, false alarms

Fig. 7 Example of an ultrasonic walking stick (taken from reference [**17**])

still outnumber the defects that are actually detected on the rail network.

In general, ultrasonic test trains perform relatively well in detecting deep surface-breaking and internal defects, particularly in the rail head and web. Unfortunately, RCF defects that are smaller than 4 mm deep are usually not detected by these high-speed systems. Such surface defects can shadow critical internal defects and thus give a false picture of the structural integrity of the rail. Ultrasonic test trains can also miss some defects in the rail foot, especially corrosion, as this part of the rail can only be scanned partially. They also perform relatively poorly when inspecting alumino-thermic welds [**28**].

3.2 Rail inspection using magnetic induction or MFL

The MFL method has been broadly used for NDE of ferromagnetic structural components in the petrochemical, rail, energy and metal industries [**55–57**]. MFL sensors incorporate permanent magnets or DC electromagnets that are used to generate a strong magnetic field in order to magnetize the specimen to saturation [**55–57**]. The magnetic flux lines are coupled into the specimen using metal 'brushes' or air coupling.

In rail inspection with MFL, search coils positioned at a constant distance from the rail are used to detect any changes in the magnetic field that is generated by a DC electromagnet near the rail head [**17**]. In the areas where a near-surface or surface transverse defect is present in the rail, ferromagnetic domains in the steel do not support the magnetic field flux and some flux leaks. The sensing coil detects a change in the magnetic field and the defect indication is recorded.

MFL sensors are particularly good at detecting near-surface or surface transverse defects, such as RCF cracking. Unfortunately, transverse fissures are not the only types of defects found in rails, which can include deep internal cracks and rail foot corrosion [**7**]. These defects are not detectable with the MFL method either because the fissures run parallel to the magnetic flux lines and hence they do not cause sufficient flux leakage, or they are too far away from the sensing coils to detect (i.e. the rail web and foot). MFL is also adversely affected by increasing inspection speed. As speed increases the magnetic flux density in the rail head is reduced. As a result, the signal becomes too weak for detection of defects at speeds that exceed 35 km/h. However, the incorporation of Hall probes in MFL systems can improve their performance at higher speeds [**17**]. MFL is commonly used as a complementary technique to ultrasonic inspection. The maximum inspection speed achieved by these combined ultrasonic/MFL systems is typically 35 km/h [**17**]. Figure 8 shows an ultrasonic/MFL hi-rail vehicle.

Fig. 8 Hi-rail ultrasonic-MFL inspection vehicle (taken from reference [**17**])

3.3 Rail inspection using PECs

For several years, the application of eddy current technology in the rail industry was limited to surface inspection of individual rail welds. Some eddy current systems were then developed to perform manual inspections in order to detect the presence of RCF damage and wheelburns on the railhead surface.

Typical eddy current sensors comprise one exciting and one sensing coil. An alternating current (AC) is fed to the exciting coil in order to generate a magnetic field near the surface of the rail head. Changes in the magnetic field cause eddy currents to be induced just below the surface of the rail head. Changes in the secondary magnetic field generated by the eddy currents are detected by the search coil in the form of an induced voltage. If the inspected area is free of defects then the impedance of the eddy current sensor remains constant. However, when a near-surface or surface defect is present in the rail head, the eddy currents are disturbed causing fluctuations in the secondary magnetic field giving rise to changes in the impedance. Thus, during manual inspection for near-surface or surface damage of the rail head with eddy current systems the operator looks for any changes in the impedance signal recorded in order to detect the presence of defects.

As mentioned earlier, conventional ultrasonic transducers have limited detection capability when small surface-breaking or near-surface defects are involved. An eddy current sensor has a far better ability of detecting RCF, wheelburns, grinding marks, and short-wave corrugation [**38**, **42–45**]. However, this type of sensor is very sensitive to lift-off variations. For that reason, the probe needs to be positioned at a constant distance (no more than 2 mm away) from the surface of the rail head and particular attention needs to be given to any lift-off variations that may occur during inspection [**45**].

Newt International Ltd. reported the development of a novel electromagnetic rail inspection system based on the field gradient imaging (FGI) technology, known as Lizard [**58**, **59**]. The Lizard system comprises an FGI array arranged in the form of an electromagnetic camera. The system is pushed by the operator along the track using a walking stick to detect RCF damage, particularly gauge corner cracking and head checking. The operation of the electromagnetic camera relies upon the interaction between eddy currents and defects in order to detect and quantify them. A customized software package allows the automated analysis of the data acquired during the inspection.

Further advances in eddy current technology have led to the development of high-speed rail inspection eddy current systems in order to complement the performance of ultrasonic transducers in detecting surface and near-surface defects [**42–45**]. The sensors are placed on a sled carrier as shown in Fig. 9 which guides the probes along the surface of the rail track. During inspection, it is very important to guide the eddy current probes so that the signals are not influenced and the sensitivity does not fluctuate due to lift-off variations from the test surface. This is necessary if reliable information with regards to the location and criticality of the detected defects is to be obtained. The rail inspection test situation is especially complex, since the probes have to be positioned at an angle relative to the guiding surface [**45**]. The inspection speed achieved by the combined ultrasonic/eddy current systems is typically 75 km/h, but higher speeds of up to 100 km/h have been reported [**42–45**]. Although, the eddy current signal will remain largely unaffected at speeds even above 100 km/h, it is very likely that the performance of the ultrasonic transducers will be adversely affected at such speeds limiting the chances of detecting any internal defects that may be present.

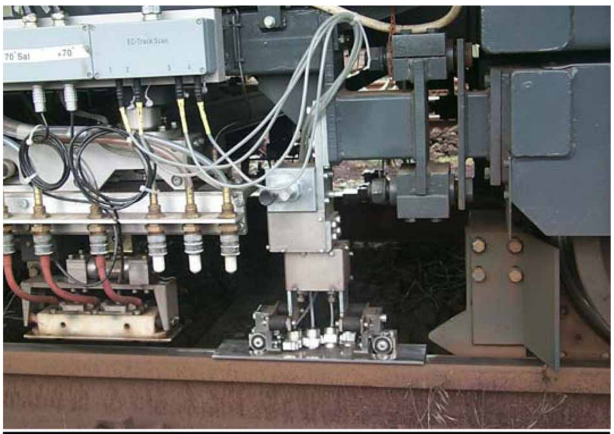

Fig. 9 Eddy current probe holder and guide for high-speed rail inspection (photograph is courtesy of Mr R. Krull, Deutsche Bahn AG)

3.4 Rail inspection using visual cameras

Until recently, visual inspection was carried out only by experienced personnel walking along the rail track and physically looking for defects. This potentially dangerous practice, although largely unacceptable due to the levels of subjectivity it involves, is still being employed by infrastructure managers. Over the last few years, however, various visual camera-based systems for railway applications have been implemented. These may be classified according to their functionality into four major groups: (a) track inspection systems; (b) train inspection systems; (c) systems for maintenance and operation; and (d) passenger related systems [**60**].

The concept of automated visual systems is based on the use of a high-speed camera capable of capturing video images of the rail track as the train moves over it. The captured images are then analysed automatically using customized image analysis software. Software analysis is based on identification of objects or defects detected using cross-correlation techniques while data are classified using a supervised learning scheme. Object recognition by using a learning-from-examples technique is related to the image processing speed capability of the system. In order to achieve real-time performances the computational time to classify patterns should be small. When trying to detect small objects, such as rail defects on the surface of the track, the resolution of the captured video image needs to be higher in order to provide reliable data for analysis while blurring effects due to the movement of the camera have to be kept to a minimum. However, as the resolution of the image increases, so does the amount of data acquired and hence more computational time is needed to complete the analysis. As a result, the speed of inspection needs to be adjusted to keep pace with data analysis. If real-time evaluation is not possible then data analysis is conducted off-line to identify any defective areas of the track section inspected.

Automated visual track inspection systems can be used to measure the rail head profile and percentage of wear, rail gap, moving sleepers, absence of ballast, base plate condition in the absence of ballast, pincers position, missing bolts, and surface damage, including RCF and rail corrugation [**46–52**]. The speed of operation of these systems can vary from 1 to 320 km/h depending on the type of inspection carried out and the quality of resolution required. For example, inspection for the detection of rail corrugation can be performed much faster than that for the detection of RCF cracking. Unfortunately, automated vision systems do not provide any information with regards to the presence of internal defects and therefore cannot be used to substitute ultrasonic inspection.

3.5 Rail inspection using radiography

Radiographic inspection of rails can be carried out using either gamma or X-ray sources. In the past radiography was carried out more often using a gamma-ray source and film to obtain a radiograph of the inspected area of a rail [**61**]. With the advent of portable digital X-ray detectors, the use of X-ray sources became more commonplace [**62**].

Radiography, although a particularly efficient NDE method for inspecting rails for internal flaws, inherently involves several health and safety drawbacks. Furthermore, the inspection is time consuming and for that reason, radiography can only be applied as a means of verification in places where defects have already been detected using other NDE techniques or in rail areas, such as alumino-thermic welds, and switches and crossings, where inspection with other NDE methods is unreliable [**28**].

Radiographic inspection can provide information on the location, size and nature of an internal defect. It can also be used to evaluate the rail for any significant variation in the composition of rails and X-ray diffraction can be used to evaluate the residual stresses near the surface of the rail head [**63**, **64**]. Unfortunately, radiography is not very efficient in detecting transverse rail defects.

4 NOVEL INSPECTION METHODS

Novel NDE techniques that are currently under different stages of development for the high-speed inspection of rails are discussed next. These include long-range ultrasonics [**65–72**], alternating current field measurement (ACFM) sensors [**73–75**], electromagnetic acoustic transducers (EMATs) [**76–85**], laser ultrasonics [**86–89**], ultrasonic phased arrays [**89–93**], acoustic emission (AE) [**94–96**], acoustic emission pulsing (AEP) [**18**] and magnetic anomaly distortion (MAD) [**18**]. Most of these techniques have been already developed enough to be used in portable systems or to be installed on hi-rail vehicles for the inspection of rails at speeds up to 15 km/h.

4.1 Rail inspection using long-range ultrasonics (guided waves)

Long-range ultrasonics is a technique based on transmitting ultrasound as volumetric waves along a structure such as a rail. The technique may employ a range of wave modes including Lamb, Plate, Rayleigh, but have become commonly known as the Guided Wave UT technique. In most cases, piezoelectric transducers are designed and placed so that the appropriate wave modes can be excited and transmitted in the structure on which they are coupled. Reflections from fixed reference points, such as alumino-thermic welds or fish plated joints, can be detected as well as changes in cross sectional areas, such as cracks or corrosion. These reflections are recorded and analysed to produce information on the probability, approximate size and location of the reflections. The data analysis requires suitable software in addition to trained and experienced personnel.

Long-range ultrasonics can be effective over distances up to 30 m from the sensor array. However, various factors can significantly attenuate the signal to an extent that in some cases, the effective distance may only be a few metres. The wave mode and frequency selected determines the most effective inspection range. The technique is generally sensitive to change in the cross-sectional area of the component. As such a 5 per cent change in the cross-sectional area of the inspected structure is needed in order to produce an interpretable response indication. Long-range ultrasonics could be adversely affected by rail clips or other fastenings present on the rail, due to the stresses they induce, however, it appears that the extent of this effect has not been sufficiently evaluated in the relevant studies reported so far in this field.

Several researchers have reported results in the field of rail inspection using long-range ultrasonics [**65–71**] and a commercial guided waves hi-rail vehicle, known as Prism, has been developed by Wavesinsolids LLC in the USA [**72**]. Prism has a maximum inspection speed of 15 km/h and it has been reported to be capable of detecting large transverse rail head defects (i.e. equivalent to 20 per cent of the cross-sectional area of the rail) [**72**].

Under certain setup conditions, the technique has the potential to be applied for the inspection of the whole rail and not just the rail head for the presence of transverse defects [**67**]. However, unless the defects have already reached a critical size, they are very likely to be missed during inspection using this NDE technique.

A US research study reported results on the development of a non-contact ultrasonic guided waves system under laboratory conditions [**97**]. Successful static tests were conducted on a piece of rail that contained simulated transverse cracks in the rail head that extended below 20 per cent of the total cross-sectional area [**97**].

4.2 Rail inspection using laser ultrasonics

Laser-based ultrasonics is a remote implementation of conventional ultrasonic inspection systems that normally use contact transducers. Laser ultrasonic systems operate by first generating ultrasound in a sample using a pulsed laser [**98**]. When the laser pulse strikes the sample, ultrasonic waves are generated through a thermoelastic process or by ablation [**98**]. Pulsed lasers can be used to generate all types of

Fig. 10 The LAHUT system (taken from reference [**89**])

ultrasonic waves, including compressional, shear, surface, and plate waves. When ultrasonic waves reach the surface of the sample, the resulting surface displacement can be measured with a laser ultrasonic receiver based on an adaptive interferometer [**98**].

The laser-air hybrid ultrasonic technique (LAHUT) combines generation of ultrasonic waves using pulsed lasers and detection using air-coupled acoustic transducers [**86–89**]. Transportation Technology Centre Inc. (TTCI) together with Tecnogamma Spa developed a LAHU system especially designed for rail inspection (Fig. 10). Early tests showed that the developed laser ultrasonic system can be used to inspect the entire rail section including rail head, web, and base. During early tests, the system was loaded on a hi-rail vehicle and inspection speeds between 8 and 15 km/h were achieved [**89**].

4.3 Rail inspection using ACFM

The ACFM technique is a non-contact electromagnetic inspection method which is now widely accepted as an alternative to magnetic particle inspection (MPI) in the oil and gas industry, both above and below water [**74**]. Although developed and patented by TSC Inspection Systems initially for routine inspection of structural welds, the technology has been improved further to cover broader applications across a range of industries. Figure 11 shows the theory behind the operation of the ACFM sensor. Increases in inspection speeds (from a few centimetres per minute to a few metres per minute), application to non-planar crack morphologies and extension of sizing models to accommodate different crack types have all been achieved [**75**].

The technique is based on the principle that an AC can be induced to flow in a thin skin near the surface of any conductor. By introducing a remote uniform current into an area of the component under

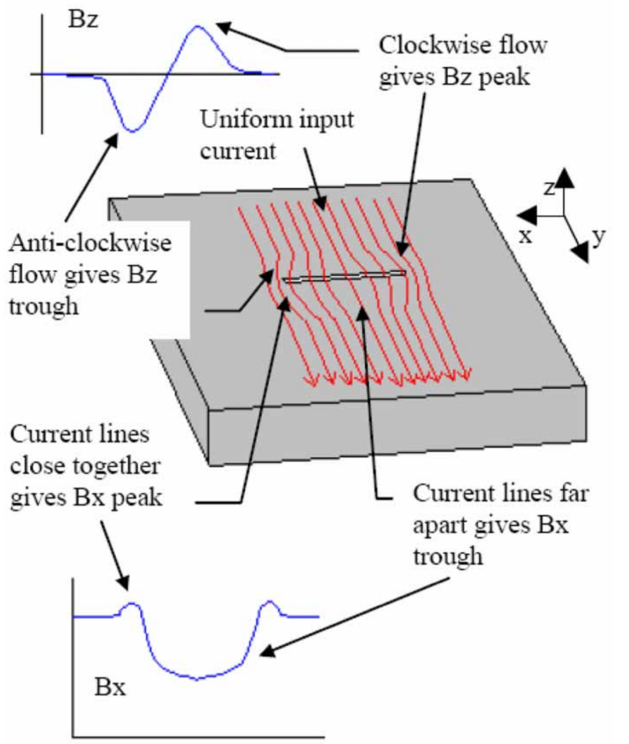

Fig. 11 Definition of field directions and co-ordinate system used in ACFM (taken from reference [**74**])

test, when there are no defects present, the electrical current will be undisturbed. If a crack is present the uniform current is disturbed and the current flows around the ends and down the faces of the crack. Because the current is an AC, it flows in a thin skin close to the surface and is unaffected by the overall geometry of the component [**99**].

In contrast to eddy current sensors that are required to be placed at a close (<2 mm) and constant distance from the inspected surface, a maximum operating lift-off of 5 mm is possible without significant loss of signal when using ACFM probes [**73**]. This is due to the fact that the signal strength diminishes with the square of lift-off, not with its cube which is the case for eddy current sensors. This enables the ACFM technique to cope with much greater lift-off [**73**].

ACFM probes are available as standard pencil probes and multi-element array probes. These probes can be customized to optimize inspection of particular structural components and maximize the PoD of critical-sized defects. ACFM pencil probes can detect surface-breaking defects in any orientation. Nonetheless, in order to size defects, they need to lie between 0°–30° and 60°–90° to the direction of travel of the probe [**75**]. This drawback is overcome in ACFM arrays by incorporating various field inducers in order to allow a field to be introduced within the inspected surface in other orientations [**75**]. This is particularly useful in situations where the crack orientation is unknown or variable. In this case, additional sensors are also incorporated in order to take full advantage of the additional input field directions.

In 2000, TSC with the support of Bombardier Transportation, began the development of an advanced ACFM system for application in the rail industry. The objectives of this effort were to develop a highly portable ACFM system, with friendly user interface capable of detecting, automatically sizing and thresholding defects for the inspection of train wheelsets. During initial tests on previously rejected train axles either due to failure on MPI or because of excessive surface corrosion, the developed ACFM system achieved an 84 per cent PoD in comparison to 44 per cent PoD for MPI. Following the experimental work on the train axles, it became evident that an ACFM system could be deployed to both detect and size RCF cracking on rails. This led to the development of a pedestrian-operated ACFM walking stick [**73–75**]. The incorporated ACFM array has been shaped to conform to the shape of the head of the rail and can be used to detect surface breaking-defects regardless of their orientation by employing multiple field inducers. This allows the application of the ACFM system in both new and worn rails. The inspection of the rail head is carried out by sequentially scanning across the group of sensors enabling the uninterrupted inspection of the rail. Based on the data acquired through extensive metallographic work on rails with RCF cracking, a customized software package incorporating the appropriate defect sizing algorithms has been developed in order to enable the automated sizing of the RCF cracks that are detected with the walking stick. The system can detect and size gauge corner cracks and head checks smaller than 2 mm in depth. However, the ACFM sensors cannot quantify squats accurately and are unable to detect short-wave corrugation and wheelburns.

By increasing sampling rates to 50 kHz, the walking stick system has achieved scanning speeds of up to 1 m/s (approximately 3 km of rail can be inspected within an hour). The ACFM walking stick underwent rigorous tests for approval of use on the UK railways. The ACFM system performance was evaluated under various operating conditions by Balfour Beatty Rail Technologies on a wide number of sites on the UK rail network and has been proved not to be affected by the presence of track circuits or vice-versa.

Further experiments are currently under way in an effort to develop a high-speed ACFM sensing system for the detection and quantification of RCF damage in rails in collaboration with the University of Birmingham. High-speed ACFM tests, using a special rail rig capable of rotating at speeds up to 80 km/h, have been carried out up to a speed of 32 km/h and varying lift-offs between 1–6.5 mm with very encouraging results.

4.4 Rail inspection using EMATs

EMATs may be used to generate and detect ultrasound in an electrically conducting or magnetic material. This is achieved by passing a large current pulse through an inductive coil in close proximity to a conducting surface in the presence of a strong static magnetic field, often provided by a permanent magnet [**100**]. The orientation of the magnetic field, geometry of the coil and physical and electrical properties of the material under investigation have a strong influence on the ultrasound generated within the sample. EMATs have the advantage that they operate without the need for physical coupling or acoustic matching as it is an electromagnetic coupling mechanism that generates the ultrasound within the sample skin depth [**100**]. This also means that the perturbation that physical coupling causes is insignificant, and operation at elevated temperatures is possible. EMATs are therefore suitable for rail inspection. Figure 12 shows the EMAT principle.

A commercial hi-rail inspection vehicle based on a novel EMAT system called RailPro has been developed by Tektrend (now NDT Olympus) in Canada [**76**, **77**]. The RailPro system uses several EMAT configurations for the generation of surface and bulk ultrasonic waves in order to inspect the whole section of rail [**76**, **77**]. The system has been successfully tested on a special evaluation track containing several types of defects, including transverse fissures, horizontal and vertical head splits, split webs, bolt hole cracking, and RCF damage at inspection speeds between 5–9 km/h [**76**, **77**].

Advances in EMAT sensor technology for high-speed rail inspection and quantification of RCF damage on rail has been reported by several researchers [**78–85**]. The technique is based on the generation of Rayleigh waves using a send-receive (or 'pitch-catch') sensor setup in order to detect and quantify RCF defects [**78–85**]. In principle the EMAT sensors cannot detect any defects smaller than 2 mm deep. For that reason, the possibility of combining EMAT sensors with PEC

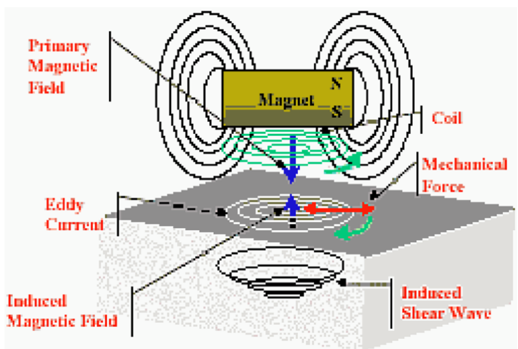

Fig. 12 EMAT principle (taken from reference [**77**])

probes in order to increase the system's overall sensitivity on shallow cracks has been investigated [**101**].

4.5 Rail inspection using ultrasonic phased arrays

Ultrasonic phased arrays are a relatively novel technique for non-destructive evaluation of structural components. Instead of a single transducer and beam, phased arrays use multiple ultrasonic elements and electronic time delays to create beams by constructive and destructive interference [**102**]. As such, phased arrays offer significant technical advantages for non-destructive testing over conventional ultrasonics since the ultrasonic beam produced by the array elements can be steered, scanned, swept and focused electronically [**102**]. Beam steering permits the selected beam angles to be optimized ultrasonically by orienting them perpendicular to the predicted defects (*e.g.* lack of fusion, shrinkage, porosity, etc.) that may occur in alumino-thermic rail welds. In inspection using conventional ultrasonic transducers neither beam steering nor beam focusing are possible. Due to the microstructural nature of alumino-thermic welds (i.e. large dendritic grains) most of the energy injected in the weld is attenuated in the upper sections of the rail and therefore defects that are present deeper can remain undetected. In the case of ultrasonic phased arrays, this problem can be addressed by steering and focusing the beam at the sections of the weld where defects may be present. Although signal attenuation is a problem for ultrasonic phased arrays too, the energy of the interrogating beam can be increased through focusing and therefore inspection of the deeper parts of the weld becomes possible. Electronic focusing therefore permits optimizing the beam shape and size at the expected discontinuity location, as well as optimizing the PoD.

In addition, electronic scanning permits very rapid coverage of the components to be inspected, typically an order of magnitude faster than a single transducer mechanical system. Beam steering (usually called sectorial or azimuthal scanning) can be used for mapping components at appropriate angles to optimize the PoD of discontinuities. Sectorial scanning is also useful when only a minimal footprint is possible. Overall, the use of phased arrays permits optimizing discontinuity detection while minimizing testing time.

Unfortunately due to the large amount of data generated during inspection with ultrasonic phased arrays, data processing is not as straightforward as with conventional ultrasonic transducers. For that reason, maximum inspection speeds currently achieved by ultrasonic phased array systems do not exceed 5–6 km/h.

A lot of research is dedicated to developing novel ways of signal processing as well as optimizing the electronics hardware of ultrasonic-phased array systems in order to achieve significant increase in the speed of inspection without compromising the inspection advantages offered by such systems. A new in-parallel analysis concept (known as the fast automated angle scan technique, FAAST) has been recently developed by Socomate to address the processing problem [**93**]. The 128-channel system developed for rail inspection is capable of processing in real time the data obtained from a multi-element probe in order to detect and characterize in one shot all reflectors inside the acoustic sound field of the probe. The system can achieve inspection speeds of up to 100 km/h and has a control pitch of 4 mm. The main inspection angles are -70°, -35°, 0°, $+35^\circ$, and $+70^\circ$ [**93**]. Several research groups in Europe and North America are currently involved on the development of ultrasonic phased arrays for rail inspection applications [**89–92**, **103**].

4.6 Rail inspection using AE

AE techniques are commonly employed to reliably evaluate the structural integrity of large industrial structures such as bridges, oil tanks and pressure vessels as well as for the detection of gas and liquid leaking [**104**]. AE can also be used to assess the performance of rotating or reciprocating parts. AE sensors are typically sensitive piezoelectric transducers which can be mounted using a couplant on the surface of the structure to be evaluated [**104**]. Air-coupled AE sensors are also extensively used, especially when AE is employed to detect gas or liquid leaking.

Typical AE systems consist of signal detection, amplification, data acquisition, processing and analysis. Various parameters are used in AE to identify the nature of the source, including: count, duration, amplitude, rise-time, energy, frequency and root mean square (RMS).

The most important aspect of AE testing perhaps, is signal processing. The importance of signal processing arises from the fact that it is usually necessary to separate genuine stress-wave emissions, originating from within the material, from external signals, such as environmental noise (rain, wind with sand particles), mechanical noise (movement of the component during testing), electric noise, etc. Much of this is achieved by careful electronic filtering of the received AE data and advanced signal processing software. The frequency of the stress waves emitted is normally in the range 30 kHz to 1 MHz [**104**]. Triangulation and other techniques can give positional information, localize the sources of the emissions, and amount of crack growth.

In 2002, AEA Technology Rail (now DeltaRail) developed an AE system, named NoiseMon, for the inspection of rail tracks. The operation of the NoiseMon system is based on the detection and evaluation of the noise produced in the wheel–rail interface when the test train moves along the rail track. The AEA system evaluates the level of rolling noise over 200 m and applies a speed correction to produce a single-figure 'Acoustic Track Quality' measure [**94**]. AE systems such as the NoiseMon have the potential to detect several types of defects, such as rail breaks, wheel burns, squats, wet spots, worn rail profiles, deterioration in the ballast, poor adhesion conditions and track alignment, and gauging problems on curves [**94**].

The sensor(s) used during this type of inspection is an air-coupled piezoelectric transducer or microphone placed in the undercarriage of the test train. To minimize the noise generated by airflow as the test train travels at speed, foam windshields are used. However, even with the use of windshields, noise from airflow can still be generated close to the microphone and therefore, the sensor is placed in an aerodynamically 'dead area'. The use of foam windshields can also protect the sensor from being damaged by debris or water. Initial tests performed by AEA on the route London Euston–Birmingham New Street at inspection speeds of up to 160 km/h showed that an AE system can be successfully used to detect certain defects [**94**]. Other laboratory-based studies on the potential of the AE technique for defect detection have also been reported by other authors [**95**, **96**].

4.7 Acoustic emission pulsing

AE testing is a passive non-destructive evaluation technique, since the sensors used do not generate an interrogating signal but only detect signal emissions that are produced from the source (i.e. the defect). In certain cases, a defect may not emit a signal at all or the emitted signal may be too weak or attenuated too much in order to be detected by an AE sensor. Less often, high levels of external noise may cover the signal emitted by a defect. If the signal analysis and the electronic filters cannot cope with the level of the external noise present in order to clearly identify a defect then alternative methods need to be employed.

AEP is the active concept of the AE technique. In AEP, a transducer generating ultrasonic waves is employed instead of trying to detect emissions from a growing defect [**18**]. The noise spectrum produced by the generating transducer is picked up by one or more sensing transducers placed at pre-chosen points. In the case where a rail is free of any defects, the noise spectrum emitted by the generating transducer will remain constant. However, if defects are present the spectrum will change indicating the presence of damage in the rail. AEP systems are calibrated for different types of defects and in conjunction with signal analysis they can provide useful information on the severity and type of damage present in the inspected rail. Although AEP is conventionally used as a static inspection technique, advances in laser ultrasonics and air-coupled AE transducers could potentially be deployed to conduct AEP inspections at speed.

4.8 Magnetic anomaly distortion

Magnetic anomaly distortion or detection (MAD) is based on the original concept developed by scientists to detect the presence of submarines underwater. The principle of the technique is based on the fact that the presence of a magnetic material disturbs the magnetic flux lines produced by the Earth's natural magnetic field. If the structure or composition of the magnetic material changes there is likely to be a change in the level of the disturbance detected.

MAD detectors, apart from military applications, have been used in geology to map naturally occurring magnetic fields and in medicine, using superconductors, in order to measure brain, muscle and cardiac activity. Qinetiq developed the MAD concept further by applying it in the rail industry for the detection of defects in rails [**18**]. It was found that rail defects could lead to areas in the rail where the pattern of the magnetic fields is different to that expected in a defect-free rail. The field changes would be very localized and a rail vehicle carrying appropriate detection equipment could be used for detection of these defects. Initial static experiments conducted by Qinetiq found that very little magnetic noise was recorded for defect free rails. MAD sensors were used to detect discontinuities associated with rail joints. It was also found that the signal variations recorded by the MAD sensors were dependent on the size of the gap between the rails [**18**].

4.9 Evaluation of residual stresses in rails

The importance of residual stresses in rails has risen profoundly over the last two decades due to the constant increase in axle loads, train speed, and traffic density. The accurate assessment of residual stresses in rails can be used to give an early indication of the onset of cracking and thus preventative remedial action such as rail grinding can be undertaken [**105**]. As a direct consequence several methods – destructive, semi-destructive, and non-destructive – have been researched and developed in order to accurately evaluate the nature and level of residual stresses in rails in-situ, during production and in a laboratory environment [**64**, **105–109**]. Non-destructive evaluation methods of surface residual stresses in rails can be achieved through X-ray or neutron diffraction measurements, evaluation of the velocity variation of ultrasonic waves and measurement of the Barkhausen noise [**65**, **105–109**].

X-ray diffraction is probably the most widely used technique for the evaluation of rails. This method is based on the measurement of the changes in the diffraction angle of X-rays that occur due to lattice strains and the variations in the spacing between the crystallographic lattice planes that are caused by residual stresses. Thanks to considerable advances in hardware, X-ray diffraction measurements can be conducted in-situ, during production or under laboratory conditions.

The concept of the neutron diffraction measurement method is largely similar to the X-ray diffraction technique. The main difference is that neutrons, instead of X-rays, are used to evaluate the residual stresses in a rail. Neutrons are far more penetrative than X-rays and therefore information on residual stresses from deeper sections of the rail head becomes possible. Nonetheless, the complexity of the neutron diffraction technique is far greater than X-ray diffraction and can only be performed under laboratory conditions. A synchrotron needs to be used to generate the neutrons required for the measurement, while the health and safety precautions are far stricter due to the difficulty in containing neutrons and their harmful effects on human health.

An alternative method of assessing residual stresses in rails is by measuring the variations in the velocity of the ultrasonic waves due to stress. In order to accurately determine the residual stress levels ultrasonically, it is important that the elastic constants of the steel rail are determined accurately prior to testing. Ultrasonic characterization of residual stresses can be performed in-situ, during production or under laboratory conditions.

Magnetic anisotropy and permeability system (MAPS) technology was developed by AEA Technology following a patent by the UK Atomic Energy Authority. The MAPS system, which is now owned by MAPS Technology Ltd., can be used to measure the residual stresses in the rail crown [**110**]. The presence of residual stresses in a ferromagnetic material such as a rail steel, cause the magnetic domains to change in both size and magnetization direction in a process known as the magnetorestrictive effect. These changes will cause variations in the relative magnetic permeability of the material. The MAPS technique is based on the evaluation of permeability variations across the rail head by measuring the Barkhausen Noise in order to assess residual stresses.

MAPS is a portable system with manual probe that can be moved along the rail at walking speed with a controllable depth of inspection from 0.1 to 5 mm as shown in Fig. 13 [**110**]. The system requires calibration on a sample free of residual stresses and made of the same steel grade with that of the rail to be inspected before residual stress measurements can be carried out. Comparison of the MAPS system performance with X-ray and neutron diffraction has confirmed the reliability of the MAPS technique.

Fig. 13 Photograph showing the MAPS system (taken from reference [**110**])

Another electromagnetic technique for the evaluation of residual stresses in rails is alternating current stress measurement (ACSM). ACSM was developed by TSC as a spin-off from ACFM to evaluate residual stresses in the rail crown. The ACSM technique involves inducing currents into the metal surface and taking measurement of the magnetic fields produced above the surface being inspected. Small changes in the strength and direction of the magnetic field can be related to both the type (i.e. tensile or compressive) and magnitude of the residual stresses present locally [**74**].

5 CONCLUSIONS

Rail networks in Europe and North America are constantly getting busier with trains travelling at higher speeds, carrying more passengers and heavier axle loads than ever before. The combination of these factors has put considerable pressure on the existing infrastructure, leading to increased demands in inspection and maintenance of rail assets. The expenditure for inspection and maintenance has thus, grown steadily over the last few years without, however, being followed by a significant improvement in the efficiency of the maintenance schedules employed by the infrastructure managers.

Despite the significant developments in NDE technology which have found extensive application in various industrial sections such as aerospace, oil and gas, and power generation during the past two decades, the rail industry has largely remained attached to equipment and techniques that were initially developed for the high speed inspection of rail tracks back in the 1960s. Only recently, have there been some advances towards more reliable high speed inspection techniques by the incorporation of eddy current sensors in combination with conventional ultrasonic probes and the advent of automated visual inspection systems. Nonetheless far more needs to be done by the rail industry if the reliability of high-speed rail inspection and thus the efficiency of the maintenance procedures currently employed are to be substantially improved.

The authors of this paper are convinced that none of the aforementioned inspection techniques, either established or under development, can achieve a substantial improvement in the evaluation of rails if it is not applied in combination with other techniques in such a way so as to complement the deficiencies of each other. A careful examination of the capabilities of each of the techniques analysed earlier in the paper reveals that certain techniques have advantages over other but there are always certain disadvantages which cannot be overcome either due to restrictions posed by the nature of the technique or due to lack of sufficient technical development so far.

It is our opinion that systems which are based on conventional ultrasonics probes will remain the main rail inspection method in the foreseeable future. However, an integrated high-speed system which will combine automated visual inspection, with eddy currents or ACFM and conventional ultrasonics could offer a novel and far more efficient and reliable method for inspecting rails. Such a system (based on the integration of inspection technologies that are already mature and have seen considerable development in the past twenty years) could deliver a step change in rail inspection practices currently employed by the rail industry. Furthermore, since these technologies are already proven, an integrated system could be developed and made available to the rail industry within a few years time. Current developments in the rail industry already point to this direction, with conventional

Table 1 NDT techniques for the rail industry

NDT technique	Systems available	Defects detected	Performance
Ultrasonics	Manual and high-speed systems (up to 70 km/h)	Surface defects, rail head internal defects, rail web and foot defects	Reliable manual inspection but can miss rail foot defects. At high speed can miss surface defects smaller <4 mm as well as internal defects particularly at the rail foot
Magnetic flux leakage	High-speed systems (up to 35 km/h)	Surface defects and near surface internal rail head defects	Reliable in detecting surface defects and shallow internal rail head defects although cannot detect cracks smaller than <4 mm. MFL performance deteriorates at higher speeds
PEC (including FGI)	Manual and high-speed systems (up to 70 km/h)	Surface and near-surface internal defects	Reliable in detecting surface breaking defects. Adversely affected by grinding marks and lift-off variations
Automated visual inspection	Manual and high speed systems (up to 320 km/h)	Surface breaking defects, rail head profile, corrugation, missing parts, defective ballast	Reliable in detecting corrugation, rail head profile missing parts and defective ballast at high speeds. Cannot reliably detect surface breaking defects at speeds >4 km/h. Cannot assess the rail for internal defects
Radiography	Manual systems for static tests	Welds and known defects	Reliable in detecting internal defects in welds difficult to inspect by other means. Can miss certain transverse defects
EMAT	Low speed hi-rail vehicle (<10 km/h)	Surface defects, rail head, web and foot internal defects	Reliable for surface and internal defects. Can miss rail foot defects. Adversely affected by lift-off variations
Long range ultrasonics	Manual systems and low-speed hi-rail vehicle systems (<10 km/h)	Surface defects, rail head internal defects, rail web and foot defects	Reliable in detecting large transverse defects (>5 per cent of the overall cross-section)
Laser ultrasonics	Manual and low-speed hi-rail vehicle systems (<15 km/h)	Rail head, web and foot defects	Reliable in detecting internal defects. Can be affected by lift-off variations of the sensors, difficult to deploy at high speeds
ACFM	Manual systems (hi-speed system under development)	Surface breaking defects	Reliable in detecting and quantifying surface breaking defects. Cannot detect sub-surface defects. Very good tolerance to lift-off variations
AE	Experimental manual and high-speed systems	Rail breaks, wheel burns, squats, wet spots, worn rail profiles	Limited experiments. Cannot detect any internal defects
AEP	Experimental static tests	Surface defects, rail head internal defects, rail web and foot defects	Limited experiments. Can only be applied at predefined areas. Can miss non-transverse defects or small transverse defects
MAD	Experimental static tests	Broken rails, rail gaps	Limited experiments. Possibly capable of detecting large internal or surface-breaking defects (i.e. >50 per cent of the cross sectional area)

ultrasonic probes being integrated with MFL and PEC sensors with a considerable degree of success. Table 1 provides a brief summary of the techniques that are available today or currently being investigated for application in the rail industry.

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