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TECHNIQUES USED IN THE INSPECTION OF DEFECTS IN RAILS: A REVIEW

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Abstract. *The inspection techniques used in the detection of defects are applied in all areas of engineering in order to predict through monitoring, failures that may cause the partial or total loss of the required function of a machine or material in service. The new challenges imposed by the new technologies, coupled with a globalized economy scenario, contribute to a more effective demand for materials inspection in the maintenance activity and in the production process. In the railroad, the inspection techniques are basically focused on the monitoring of wheels and rails, seeking to increase the reliability of these assets. In order to contribute to the evolution in the railway sector, this article proposes a literature review of the inspection techniques in the market and its applications in the field of engineering. In the first stage, a survey will be made of non-destructive conventional techniques in the inspection of various materials. In the second stage, several nonconventional inspection techniques will be explored. Finally, in the third stage, the inspection techniques used to the detection of defects in railway rails. Thus, it is hoped that the results obtained will achieve consistent and reliable information regarding the various inspection techniques currently used.*

Keywords: *Non-Destructive Testing Techniques (NDT), Rail defects*

1. INTRODUCTION

Defects in various types of materials occur when type and loading modes associated with environmental contour conditions partially affect their required function by reducing their capacity in service. The efforts made in the materials result in the generation of tensions in which exceeding the capacity to withstand these tensions, the materials begin to present wear or collapse by ruptures, the so-called failures.

On railways, contact between the train wheel and the rail in conjunction with the speed of traffic generates contact stress in a very small area, causing wear and defects. These defects originate from the phenomenon of contact fatigue that, according to Magalhães (2002), exceeds the limit of steel flow, as this limit is almost equal to the limit of crushing or contact, the wheel and the rail deform, appearing state plastic.

According to Zarembski (2005), the defects or anomalies appear in the surface of the billet of the rails and are found in any type of railroad. These superficial defects can be classified into periodicals and not periodic ones, causing a reduction in the useful life of the rail. The removal of these defects occurs through the grinding process that was introduced in the operational routines of the railroads in the early 20th century and that for 50 years was limited to a tool for removal of imperfections only.

From the 70's onwards, there was a change in the practices of this process, which began to be implemented as a preventive measure allied to concepts of direct costs, indirect costs and loss of production, and thus the grinding process evolved from corrective action to control action in the search for the development of practical and quick solutions in the correction of superficial defects.

At the beginning of the 80's, several topics began to be approached with the need to perform a reliable rail grinding and within technical-metallurgical parameters, such as control of grinding motors, mechanical tests for the definition of fatigue limits, study of wheel-rail contact are examples of applications aimed at increasing the reliability of this rail asset that has a very high cost. Currently, to detect the occurrence of defects and potential failures, railway engineering relies on an inspection technique that provides for monitoring the presence of unwanted discontinuities in the material. The techniques of inspections used are classified as conventional and unconventional, whereas conventional non-destructive testing (NDT) techniques are the most used in the production and manufacturing processes.

In railways, the detection of surface defects in rails is done by ultrasound, an apparatus equipped with angular heads that emit high frequency sound waves capable of detecting discontinuity in the medium where the wave propagates. According to Kalousek (2004), it is essential to obtain reliable information from the ultrasound equipment that the surface of the rail is linear and smooth, favoring the propagation of the waves without interference. However, in practice, the propagation of superficial defects behaves in a non-linear manner, which results in the decoupling of the head, making it difficult to perform the ultrasound in detecting discontinuity in the surface of the billet. This condition limits the recognition of faults only at a level of greater depth as cracks, which ends up being a disadvantage in the technique and that leads the railwayers to assume a posture of practical character during the inspection which is not very reliable.

In order to contribute to the evolution in the railway sector, this article proposes a literature review of the inspection techniques in the market and its applications in the field of engineering. In the first stage, a survey will be made of non-destructive conventional techniques in the inspection of various materials. In the second stage, several nonconventional inspection techniques will be explored. Finally, in the third stage, the inspection techniques used to the detection of defects in railway rails. Thus, it is hoped that the results obtained will achieve consistent and reliable information regarding the various inspection techniques currently used.

2. INSPECTION TECHNICS

Inspection techniques are widely used in the manufacturing process in the areas of preventive and predictive maintenance. They are powerful tools to help technicians and engineers to detect defects and prevent material failures that could compromise safety and the environment. Inspection techniques are used to measure, detect properties or verify the performance of metallic materials (ferrous or non-ferrous) and non-metallic materials. These techniques are characterized by NDT techniques.

According to Hellier, (2003) NDT techniques that can be used to inspect various types of materials, equipment or even to perform measurements are large and continue to grow, as researchers continue to find new ways of applying physics and other disciplines to develop sophisticated inspection techniques. Sandeep et al., (2017) corroborate by emphasizing that there is a wide variety of non-destructive techniques or methods. These methods can be performed on metals, plastics, ceramics, composites and coatings in order to identify cracks, internal voids, surface cavities, delamination, incomplete defective welds and any type of failure that would lead to premature failure. The commonly used NDT test methods can be seen in Table 1

Table 1. Commonly used NDT techniques – Adapted from Web.Itu.Edu.Tr/~Arana/Ndt.Pdf.

Technique	Application	Limitation	Objective/Procedure
Visual Inspection	Macroscopic surface flaws	Small flaws are difficult to detect, no subsurface flaws	inspection only visually used in the detection of defects of the type: different dimensions, connection faults, kneading, corrosion principle, large cracks, improper finishing of surface defects in welds
Industrial Radiology	Subsurface flaws	Smallest defect detectable is 2% of the thickness; radiation protection. No subsurface flaws for porous materials	Detect volumetric defects with good sensitivity such as cracks. This means that the ability of the process to detect these defects perpendicular to the beam will depend on the test technique performed.
Ultrasonic	Subsurface flaws	Material must be good conductor of sound	Detection of internal defects or discontinuities present in the most varied types or forms of ferrous or non-ferrous materials. The technique is characterized by the emission of an electric signal applied to a piezoelectric crystal that vibrates by emitting sound waves over a long period and a short period at a frequency related to the thickness of the crystal.
Dye penetrate	Surface flaws	No subsurface flaws for porous materials	Used for the detection of open surface discontinuities of solid and non-porous materials. They are usually inspected using DPT or Penetrate Liquid Inspection (LPI). Inspection is performed under ultraviolet or white light, depending on the type of dye used (fluorescent or non-fluorescent).
Magnetic Particle	Surface / near surface and layer flaws	Limited subsurface capability, only for ferromagnetic materials	Used in locating surface and subsurface discontinuities in ferromagnetic materials. It consists in subjecting the structure, or part of it, to a magnetic field with the application of ferromagnetic particles. The agglomeration of the particles will indicate the shape and extent of the discontinuity.
Eddy Current for metals	Surface and near surface flaws	Difficult to interpret in some applications; only for metals	Detection of cracks, thickness measurement of fine parts. It is an excellent method for detecting superficial and subsurface defects, as they interrupt the passage of the parasitic current, weakening its intensity. Defects like cracks are easily detected.
Acoustic emission	Can analyze entire structure	Difficult to interpret, expensive equipaments	(AE) is the technique based on the detection of transient waves generated by the process of degradation of the material. Acoustic emission (AE) is capable of detecting leaks in equipment subject to internal pressure and detecting premature failure in the structures.

The Brazilian Association of Non Destructive Testing (ABENDI), complements pointing out that in addition to conventional inspection techniques, there are other non conventional techniques such as: Thermal Inspection, Internal Rotary Inspection System (IRIS), Metalographic Replication, Neutron Radiography, Optical Holography.

Thermal Inspection - Thermal Inspection comprises all methods in which heat sensing devices are used to measure temperature variations in physical components, structures, systems or processes. Thermal methods may be useful in detecting subsurface voids or voids provided that the depth of failure is not large compared to its diameter. Thermal inspection becomes less effective in detecting subsurface failures as the thickness of an object increases because the depth of defects increases, ASM Handbook (1992). It is applicable to complex shapes or sets of similar or different materials and can be used in the inspection of objects on one side. In addition, because of the availability of infrared detection systems, thermal inspection can also provide rapid contactless scanning of surfaces, components, or assemblies.
Thermal inspection does not include methods that use thermal excitation of a test object and a non-thermal sensor device for inspection. For example, thermally induced voltage in holography or the thermal excitation technique with ultrasonic or acoustic methods do not constitute thermal inspection.

Internal Rotary Inspection System (IRIS) - The Internal Rotational Inspection System (IRIS) is a non-destructive ultrasonic testing method. This advanced technology is generally used for the measurement of thinning and corrosion of walls due to corrosion and erosion of small diameter pipes. IRIS uses ultrasonic technology that enables the inspection of a wide variety of materials. The Internal Rotating Inspection System probe is inserted into a tube that is flooded with water, and the probe is removed as the data is displayed and recorded. The rotating ultrasonic beam allows the detection of metal loss both inside and outside the tube wall. The IRIS probe produces very accurate and detailed results. The data can be safely used in integrity assessment studies and in the calculation of remaining lifetime. ABENDI (2014).

Metalographic Replication - Replication metallography is a nondestructive test method used to visualize the microstructure of a component while it is still in place. It can provide detailed metallographic information, such as evidence of spheroidization, creep damage, cracking, and particle size. A replica of the component is made in the workplace and then seen in our laboratory by a team of engineers. The quality of in-situ metallographic replicas is comparable to that obtained destructively in laboratories. The great advantage of this method is that it provides information about the component's thermal history, approximate high temperature range and cooling rates. It is also cover to identify mechanical properties and morphology of the defect. The material, shape and size of the object are not limiting factors for the inspection.
However, for the execution of the method, adequate access to the component is required, it is more difficult to paleness at temperatures above 70 ° C or below -10 ° C and is also a highly dependent method of the skill and experience of the technician performing the inspection. ABENDI (2014).

Neutron Radiography - is a form of nondestructive inspection that uses a specific type of particulate radiation, called neutrons, to form a radiographic image of a testpiece. The geometric principles of shadow formation, the variation of attenuation with the thickness of the sample and many other factors that govern the exposure and processing of a nêutron radiographs are similar to those for radiography using x-rays or x-rays the difference being in the neutrons that are subatomic particles that are characterized by relatively large mass and neutral electric charge in which the attenuation of neutrons differs from the attenuation of x-rays because the processes of attenuation are nuclear instead of those that depend on the interaction with the electron layers around the nucleus. ABENDI (2014)

Optical Holography - Holography is a process for creating an entire image - that is, a three-dimensional image - of a diffusely reflecting object having some arbitrary shape. More precisely, it is a means of recording and subsequently reconstructing the wave fronts that have been reflected or transmitted through an object of interest. As the entire wavefront and not just a two-dimensional image is reconstructed, an image of the original object can be viewed with full depth of field, location, and parallax. The process involves two steps. In the first step, both the amplitude and phase of any kind of coherent wave motion emanating from the object are recorded by encoding this information in a suitable medium. This recording is called a hologram. Subsequently, the wave motion is reconstructed from the hologram by a coherent beam in a process that results in the regeneration (reconstruction) of an image that has the true shape of the object. The usefulness of holography for The non-destructive inspection of materials, components and structures resides in the fact that this reconstructed image can then be used as a kind of three-dimensional model, against which any deviation in the shape or dimensions of the object can be observed and measured. ABENDI (2014)

2.1 Inspection Tchnique in Rails: state-of-the-art

The rail is the most important asset of the railway superstructure, it is considered the main support and guide element of rail vehicles and is also the most costly component of the permanent track. Thus, it is essential to use this material properly and rationally so that its operational performance is reliable. In passenger and freight railways, the most commonly used rail type is VIGNOLE, which has its own format divided into three parts: Billet, Soul and Skate.

The billet is the part that is in contact with the wheel of the rail vehicle receiving direct load and through the dynamic action results in wear evolving later to internal and superficial defects that compromise the safety of vehicles and passengers. Rail defects are changes expected or not in the characteristics of the rail constituent material, which give rise to failures that may influence its performance. Preventing these defects provides a reliability gain in the rail network and for that, use of fault analysis, an engineering area that consists of systematically and standardized evaluation of the ways in which rail failures occur. The analysis must be conducted until it reaches the basic events or causes and whose analysis can not be detailed or deepened. the following table classifies the types of defects occurring in railway rails..

Table 2. Defects in rails – Own author

INTERNAL DEFECTS	TYPES	DEVELOPMENT
Caused by failure to manufacture or end of life due to constant load and are caused by contact stresses, thermal tensions and residual stresses	VERTICAL SPLIT HEAD - VSH	It develops in a progressive way very quickly longitudinally to the center of the billet and can reach up to 2 meters along the rail.
	HORIZONTAL SPLIT HEAD – HSH	It is a fracture in the horizontal plane that develops progressively, longitudinally and parallel to the top of the billet, distancing itself from the rolling surface in at least 1/3 of the height of the billet.
	ENGINE BURN FRACTURE – EBF	It develops in the transverse plane caused by the skidding of the wheel. She spreads toward rail soul and towards the outside of the billet.
	HEAD & WEB SEPARATION – HWS	It develops initially in the horizontal plane of progressive way, being able to reach 25 cm of extension and propagates down towards the foot.
	HORIZONTAL SPLIT WEB – HSW	It develops in the horizontal plane progressively and longitudinally in the middle of the soul.
	TRANSVERSE DEFECT – TD	It develops progressively only in the cross section of the rail. It starts from a point, nucleus or imperfection inside the billet or the foot its growth and relatively slow until reaching 20 to 25% of the billet then evolves quickly
	TRANSVERSE DEFECT – TDX	It develops only in the transverse section in a progressive way and are considered multiple when they are within the same bar of 12 meters
	BOLD HOLE CRACK - BHC	They propagate from the hole, diagonally to the billet, or to the other hole
	DEFECTIVE WELD PLANT CRACKS OUT	It develops in the transverse or horizontal plane, from some internal defect of the weld (inclusion, incrustation and or collapse of material)
	DEFECTIVE WELD FIELD PLANT CRACKS OUT - DFCO	It develops in the transverse or horizontal plane, from some internal defect of the weld (inclusion, incrustation and or collapse of material)
	WEB & FOOT SEPARATION – WFS	It develops in the horizontal plane of progressive way, being able to reach 25 cm of extension and then to progress up towards the soul.
SURFACE DEFECTS	**TYPES**	**DEVELOPMENT**
These are defects caused by contact fatigue from the contact dynamics of the wheel with the rail	CRACKING	Small cracks in the surface of the rail (crack's)
	HEAD-CHECKS	Cracking in the corner of the gauge
	FLAKING	Flaking billet
	SPALLING	Grit corner chipping
	SHELLING	Gutter corner smash

The application of non-destructive techniques can be used to inspect the types of defects mentioned in the table above, the correct application of these methods reduces the cost of operating the permanent track and maintains an excellent level of quality. The most commonly used method is the ultrasonic test that uses sound wave beams to detect faults in rails. Despite the efficiency of the method in many applications, in the case of the rail there is a limiter related to surface measurement in the billet that compromises the validation of the obtained results. Today, researchers continue to study new ways of applying physics and other scientific disciplines to develop sophisticated NDT methods on railroad tracks.

2.2 New Techniques of Non-Destructive Tests in Rails

M.E. Turan et al. (2019) studied the comparison between destructive and non-destructive residual stress measurement techniques and investigated the influence of billet geometry on residual stress through the use of two different grade rails. One of the rails is of type R260 and the other is of type R260. In addition to the residual stress measurement with strain gauge and X-ray diffraction method, microstructures of the specimens were examined. The results show that the grooved rail has higher residual stress and different types of stress were observed for samples that are supported by the X-ray and strain gauge method.

P.W. Loveday et al. (2018) It studied the precise calculation of the dispersion characteristics of the guided waves in the rails, for the development of the inspection and monitoring systems. The wave-versus-frequency number curves calculated by the semi-analytical finite element method exhibit mode repulsion and crossover so that it can be difficult to distinguish. Derivatives of their own value, relative to the wave number, are used to investigate these regions. A term that causes repulsion between two modes is identified and a condition for two crossover modes is established. In symmetrical rail profiles, mode shapes are symmetrical or antisymmetric. Symmetric and antisymmetric modes may intersect while modes within symmetric and antisymmetric families do not appear to cross. The modes can therefore be numbered in the same way that the Lamb waves in plates are numbered, facilitating the communication of the results. The derivative of the eigenvectors in relation to the wave number contains the same repulsion term and shows how the mode models the swop during a repulsion. The introduction of a small asymmetry seems to lead to repulsive forces that prevent any mode crossing. Measurements on a continuously welded rail have been performed to illustrate a mode of repulsion.

M. Evans et al. (2018) They discussed current UK standard practices for the periodic inspection of level crossing rails using conventional (VT) and conventional ultrasonic (UT) methods. They have assessed that the limitations of these methods are discussed and how these limitations affect the general maintenance program for level crossings. They proposed a new method of inspection, Guided Wave Test (GWT), described with particular emphasis on its advantages for level crossing inspection. GWT was first used commercially for pipe inspection around 1999 (Alleyne et al., 2001) and has now gained widespread use. Finally, a review of the current GWT network rail test at level crossings using G-Scan is done.

A. Sabato, C. Niezrecki (2017) They presented a structural health monitoring (SHM) study of old railroads focused on safety, to avoid catastrophic failures and to reduce maintenance costs. Rails and foundations are complex systems that may contain defects or damages, including internal cracks in rails, pitting or surface corrosion, ballast support degradation, or rail ballast failure. In recent years, interest in SHM has been growing by measuring structural deformation, total field deformation and geometry profiles using three-dimensional (3D) Digital Image Correlation (DIC) systems. In this study, a new approach to using DIC and projecting patterns to evaluate deformation of rail rails is proposed. The proposed sensing approach should enable a wagon-mounted sensor system to perform inspection while moving at typical operating speeds (eg 60 mph). The feasibility of the proposed 3D DIC system is evaluated through extensive laboratory tests. The ability of the approach to measure the total field displacement of the back and shape (i.e. at levels similar to those found in the field) as different loading conditions are applied is demonstrated. The influence of movement similar to what can be found in a rail service environment in the accuracy of measurements is also quantified.

Naeime et al. (2017) Developed a computerized tomography (CT) technique to reconstruct the three-dimensional geometry of cracks in railroads. Sample rails with squats of different severities were removed from the Dutch rail network. Four specimens of different sizes were prepared and investigated with the tomograph. The detailed procedures of the The CT experiment and the post-processing work were described. A sequence of high-quality X-ray images was collected during each sweep. These 2D images were combined to construct the 3D view of the sample. Image processing tools were applied to extract and reconstruct the internal cracking geometries, thus allowing cracking differentiated from bulk steel. For validation, the results of the CT were compared with the observations of the rail surface for all defects and vertical section when needed. Discussions were made in relation to the appropriate size of the rails samples and the severity of the cracks. According to the results, CT allows for a 3D view of Rolling Contact

Fatigue (RCF) defects, providing high quality data in the internal cracking geometry. Per to choose appropriate settings and sample size, CT could accurately reconstruct squat cracks in diferente phases of growth. This research shows the potential of the CT technique as intermediate detection and characterization between microchannel cracking and micro / nano cracking methods. Finally, a practical specimen design and a detailed scanning procedure are proposed, based on the CT experiments carried out in this research.

Liu, (2017) Related the ultrasonic inspection and the frequency of defects in the railroad during transportation of hazardous materials. A Pareto optimization model was developed to determine inspection frequencies in different road segments with different levels of risk. The model provides an assessment of the risk of transport of hazardous materials specific to the segment due to rail failures, as well as an assessment of risk-based prioritization of rail defect inspection. The model can be adapted to other types of hazardous materials or account for other causes of accidents in the future.

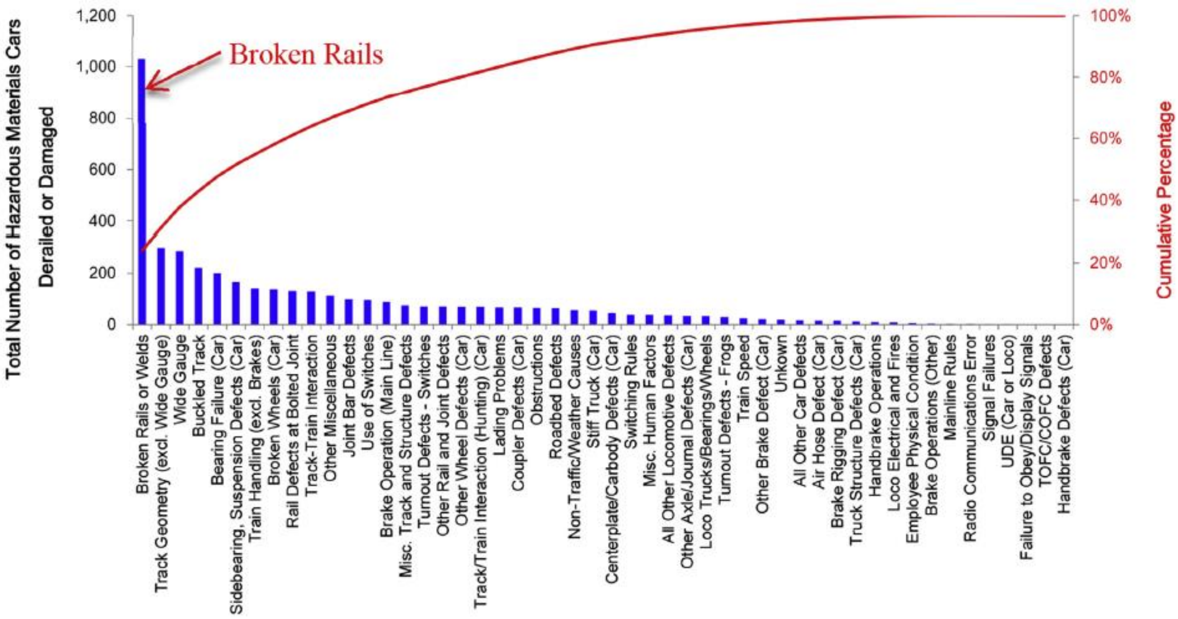

Figure 1. Dangerous material cars derailed because of major road accidents in the US, from 2000 to 2014

Trofimov, (2016) Developed a multi-structural instrument to identify surface defects in rails. The instrument operates on the basis of intelligent analysis of video data, and opens a wide range of possibilities to analyze of real-time neural network images. The instrument can transform a color image into a Zero-Contrast image and convert them to binary format. It distinguishes itself by its real time noise suppression, assessment of indicators that provide information on defects and automatic neural networks classification of defects. The instrument is used in conjunction with a dynamic expert system that employs a production model of knowledge representation.

M. Guerrieri et al. (2012) He studied a new procedure to reconstruct the transversal profile of rails in operation through the technique of image processing. This methodological approach is based on the "information" contained in high-resolution photographic lane images and on specific algorithms that allow to obtain the exact geometric profile of the rails and, therefore, to measure the state of extruded wear of the rail head. The analyzes and results relate to rails removed from railway lines under improvement by mono and stereoscopic methods which are suitable for use in laboratory applications or in high efficiency surveys.

I. Bartoli et al. (2005) Demonstrated the use of a commercial finite element package, ABAQUS EXPLICIT, to model waves in structural components. The particular application of interest is to model the interaction of a vertical broadband fold mode with transverse type defects on train rails. This topic is part of a broader project on high speed defect detection in long range rails of ultrasonic inspections. The spectra of the reflection coefficient in the range of 20 to 45 kHz are obtained for four different sizes and three orientations of transverse failures of the vessel. A preliminary study of waves on a free board helps to design modeling guidelines for the rail.

R. Pohl et al. (2004) Developed a destructive (NDT) for rail service inspection and rail ticket corners, was the main activity of Division VIII of the END. 4 in BAM in the last 2 years. For these different components, two different inspection techniques were fundamentally chosen to meet end-user requirements. First, inspection of the wheels - rim and disc - should be performed without dismounting the wheels and using ultrasonic techniques. On the other hand, the inspection of the surface of the railway at a train speed of about 70 km / h should be guaranteed using parasitic current techniques. The above mentioned tasks were a challenge for the laboratory staff.The accessibility for the wheel inspection was limited due to several impassable barriers such as sand tubes, etc. Eddy current application focused mainly on the detection of head check defects occurring at the gauge corner of the rail. Investigations carried out also showed, that other types of surface defects (e.g. Belgrospis, wheel burns, short-pitch corrugations, etc.) could easily be detected. Some aspects of the inspection system as well as an overview of test results are presented in the current contribution.

F.L. Di Scalea (2000) He presented two methods of rail inspection that use new developments in ultrasonic contact and high frequency laser to provide more efficient and potent UT in railing inspection than previously achievable. Both methods employ laser ultrasound generation that is coupled to laser detection in the first system and with pneumatic coupling detection in the second system, respectively. In fact, it is important to note that in the case of an open access test, a direct response to the test can not be obtained.

3. CONCLUSION

In the present review, several non-destructive testing techniques available for application in the industrial sector as a whole and for application in the railway sector were addressed with a focus on detecting surface defects as well as internal rail defects. The techniques used have advanced in the last 20 years, several authors have awakened to the advantage of applying the technique and are demonstrating through bi-biographical research the reliability of the ultrasonic and light (laser) methods. We also conclude that the researches look for alternatives that are not commonly used in the railroad, but which show a positive result mainly in the detection of superficial faults such as imaging techniques, x - rays, thermography and parasitic currents and are intended to provide testing options where there are limitations of conventional techniques.

Finally, the NDT surveys for the rail section show that no test method provides sufficient results in the characterization of rail defects because they have their own limitation and therefore the combination of two or more techniques is used to obtain a better result and increase the research effectiveness, thus allowing more studies in the field opening a series of interdisciplinary opportunities with other areas of engineering. Finally, it is believed that the future that presents itself in relation to new inspection techniques applied to the railroad, is possible new test methods incorporated to tools of the industry 4.0 thus allowing a change in the dynamics of maintenance of the permanent way.

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