Advantages of Damage Tolerant Approach using Automated Eddy Current Nondestructive Inspection of Freight Car Axles

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Abstract:

Nondestructive testing of railway axles is an important step to ensure structural integrity by identifying surface and subsurface flaws from the manufacturing process or service-induced degradation. Traditionally, inspection for surface flaws in freight car axles has been by visual or magnetic particle techniques. These methods have the limitations of operator skill, lighting, surface condition, low productivity, and difficulty in quantifying results for data analysis. Eddy current inspection, however, has gained increasing interest and popularity with the improvement in signal processing and array development allowing for ease of testing with little operator skill, high productivity, and electronic data collection of size, location, and orientation of surface flaws. This information can be coupled with fracture mechanics determination of critical flaw size for a given axle design and anticipated loading spectra. In this case, surface flaws can be evaluated against specific, yet conservative criteria. This paper also describes testing conducted to demonstrate an automated axle eddy current inspection system to repeatedly resolve indications down to a length of 3-mm.

Keywords: Magnetic Particle, Eddy Current, Inspection

1. Introduction

In North American interchange service, railway axles are designed with the goal of infinite fatigue life (i.e., cycles to failure $\geq 10^7$ cycles). Even though they are designed and manufactured for this goal, imperfections from the manufacturing process and service-induced damage may still occur. Therefore, it is necessary to develop an approach that determines the maximum tolerable initial flaw size and orientation that will still provide the intended life given the following considerations: (1) the critical locations (e.g., fillets, dust guard, body) where stresses are greatest for a given axle design and loading (i.e., actual static and dynamic loads), (2) material properties (i.e., axle chemistry and heat treatment), and (3) residual stresses from thermal and/or surface treatments (i.e., quenching, induction hardening, etc.). Once the full details of fatigue crack growth are known, the initial permissible flaw characteristics can be established at every location along the length of the axle in terms of flaw size (i.e., length and depth) and orientation (i.e., longitudinal, circumferential, off-axis). Finally, a suitable non-destructive inspection (NDI) method must be used that is capable of detecting this flaw size, and larger, with a high degree of confidence. The primary focus of this paper will be on the available NDI methods for new, as-manufactured axles before entering service, but the same reasoning can be extended to used axles prior to re-entering service.

2. Review of Current Requirements for Manufactured Freight Car Axles

We will start with a review of current requirements of manufactured axles entering North American service. Current design and NDI are based on an experience-based approach. No formal method exists for railway axle design acceptance in North American freight car service as it does in the design of wheels (e.g., S-660 and S-669). This is likely due to the small number of designs and simple geometry. In addition, no rigorous periodic inspections of axles or service-related damage are required, except when they are received at a G-II repair facility.

Visual inspection is the accepted NDI method for detecting defects considered injurious in roller bearing freight car, as-manufactured axles [1]. Any transverse (i.e., circumferential) seam, crack, or lap of indeterminate depth on axle surfaces, regardless of location or size, are considered to be 'injurious' and cause for rejection. For longitudinal defects (i.e., seams, cracks, or laps), the maximum permissible sizes are specified by location. In journals and dust guards: 19-mm (0.75-inch) in the journal, 12.5-mm (0.5-inch) in the dust guard, and the total length of all indications over 6.5-mm (0.25-inch) in length must not exceed 51-mm (2-inches) in any one end of an axle. In wheel and gear seats: 51-mm (2-inch) individually and total length of all indications between 6.5-mm and 51-mm (0.25 and 2-inches) in length must not exceed 101.5-mm (4-inches) in any one end of an axle. For the body: any indications must not extend into the fillets, not exceed 12.5-mm (0.5-inch) individually, and total length of all indications between 6.5-mm and 12.5-mm (0.25 and 0.5-inches) in length must not exceed 38-mm (1.5-inches) in any 305-mm (12-inch) body section length.

This review of current requirements shows that an assessment of the anticipated service loads and stress concentrations have been, in effect, considered in their development. However, much has changed in the 25+ years since this approach has been adopted, both in service loads and inspection technology.

3. Reliability of Non-Destructive Inspection Methods

After it has been determined what the initial permissible flaw characteristics are based on a rigorous and accurate stress analysis, the focus shifts to the NDI method's reliability in detecting this flaw. NDI reliability has been defined as "the probability of detecting a flaw in a given size group under the inspection conditions and procedures specified" [2]. There also three important components of NDI reliability: (1) NDI method capability/performance, which is defined by the metric Probability of Detection (POD); (2) NDI method repeatability, which is established by a rigid procedure for the use of materials, equipment, and documentation; and (3) NDI method reproducibility, which is maintained by a calibration procedure that will reproduce the responses used in establishing and validating the NDI procedures [3].

NDI results are recorded in two different formats. In the first, results are only recorded as hit-or-miss data, i.e., if a defect/indication/crack is detected, or not. Examples of NDI methods that use this format include visual and magnetic particle inspection. In the second format, not only is the hit-or-miss data recorded, but also there is information on the size of the crack. For example, the peak voltage in eddy current inspection gives an indication of the size. In this case, a threshold value can be established to determine acceptance/rejection of the flaw. With array technology, location information can also be recorded.

Ultrasonic testing is universally used for the detection of internal defects in railway axles. However, a number of methods may be used for detecting surface cracks and flaws. These include visual, magnetic particle, dye penetrant, ultrasonic, and eddy current. Since visual and magnetic particle inspection methods are hit/miss methods, they are highly dependent on key human factors such as: skill of the operator, level of training and experience, the mental state of the operator (awareness, level of concentration, tolerance to environmental conditions), management supervision, and level of accountability [4].

In the following discussion, we will examine and compare two potential NDI methods for new, as-manufactured axles for North American service: Magnetic Particle Inspection (MPI) and Eddy Current Inspection (ECI), in lieu of the current visual inspection requirements.

4. MAGNETIC PARTICLE INSPECTION

MPI is an NDI method for detection of surface and near surface discontinuities in ferromagnetic materials. These discontinuities can include cracks, forging seams/laps, and deep scratches.

MPI uses the principle, that during the magnetization of a ferromagnetic material, magnetic lines of force, or flux lines, pass through the part under inspection. When a part is magnetized such that the direction of the magnetic flux lines is perpendicular, or nearly perpendicular, to the length of a surface-breaking discontinuity, a portion of the flux lines are diverted, or leak-out, and create a magnetic leakage field above the discontinuity as shown in Fig. 1. This bending is caused by the change in magnetic permeability of the part to that in the discontinuity (e.g., air in the gap of a crack has very low magnetic permeability). (Note: Magnetic Permeability is a material property that expresses how it responds to an applied magnetic field. If a material's internal dipoles become easily oriented by an applied magnetic field, that material is regarded as being a high-permeability material. If its internal dipoles do not become easily oriented to an applied magnetic field, it is a low-permeability magnetic material.) The leakage field spans the entire length of the discontinuity as long as it is remains nearly perpendicular to the applied magnetic field. To show this leakage field, colored, or fluorescent, finely-divided iron particles are sprayed onto the area under examination. The leakage field attracts and accumulates some of these iron powder particles that span the discontinuity, shorten and strengthen the leakage field, and creates an iron powder visual line indication for the human eye to detect. When the discontinuity is near, but not breaking, the surface, a broader and weaker leakage field may form in the air above the surface of the discontinuity creating a wide and fuzzy indication.

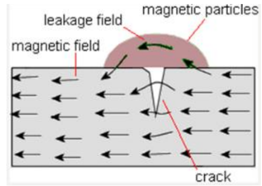

Fig. 1. THE PRINCIPLE OF MAGNETIC PARTICLE INSPECTION

MPI of railway axles in North America (currently only required in G-II shops for secondhand and converted axles) is carried out using the wet fluorescent magnetic particle method where the particles are bonded to a fluorescent chemical and are mixed in a water-based solution. These particles fluoresce and have excellent visibility when illuminated by Ultraviolet (UV) light.

This NDI method has the advantage of direct visualization of the indication produced directly on the surface of the part and above the discontinuity. All surface and near-surface discontinuities which produces a leakage field at the test surface can be detected such as cracks or nonmetallic indications. No elaborate precleaning is necessary.

For MPI to be a reliable NDI method, the angle between the applied magnetic field direction and the defect's length must not be greater than 45°. In addition, the discontinuity depth must be near perpendicular to the surface. Small discontinuity surface opening width is important, so that the gap created Is narrow and allows the magnetic particles to span the opening. In general, reliable detection requires that the width:depth:length dimensions of the discontinuities correspond to the ratio 1:5:10 [5].

There are several distinct disadvantages of MPI as it relates specifically to railway axle NDI. First, large amounts of electrical current are required to create the required longitudinal and circumferential magnetic fields. For the longitudinal inspection, the amperage must be 300 to 800-amps/inch of the wheel seat diameter. Thus, the system must be capable of producing a 6,000-amp, full-wave rectified DC current. The longitudinal inspection is performed first, followed by circumferential inspection, and finally demagnetization to a maximum 3-gauss magnetic field. It is necessary to demagnetize the component if residual magnetism is detected. Residual magnetic fields can: (1) affect machining by causing turnings to cling to the surface and (2) attract metallic particles/debris into bearings causing premature wear/reduced life. Finally, conventional MPI reliability depends on visual inspection by a technician under UV lighting in a darkroom. So, in addition to the aforementioned human factors, the working conditions are formidable. Some technical experience is needed in applying the suspension properly, but more errors are made by not using correct particle concentration and maintaining the proper state of cleanliness in the suspension. Problems that arise that effect the method's reproducibility and repeatability are: (1) magnetization level, (2) concentration, magnetic properties, and morphology of the iron particles, (3) method of particle application, and (4) method of illumination [6].

The process is time consuming: The solution must be applied to the entire axle length with magnetism applied. After thorough coverage with the solution, the solution is cut-off while the current remains on for a short time. The axle must then be inspected along the entire length while it is rotated slowly. The axle should be rotated at least two complete turns during this inspection. This inspection must be completed twice: once for the longitudinal test and once for the circumferential test.

Efforts have been taken to partially automate MPI, but the identification process still depends on a technician's visual inspection. Recently, there has been work to develop a machine vision-assisted system for wet fluorescent MPI of railway wheelsets. This system uses a vision system with complex algorithms to account for morphology, blur, and color to detect discontinuities in lieu of visual observation [7].

5. EDDY CURRENT INSPECTION

Magnetism, the underlying principle behind MPI, also enables eddy current inspection (ECI). ECI is a non-contact method for the inspection of metallic parts. Eddy currents are created through a process called electromagnetic induction. When alternating electric current is applied to a coiled conductor (or coils in a probe assembly), a magnetic field develops in and around the coil. This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero. If another electrical conductor is brought into the close proximity to this changing magnetic field, current will be induced in this second conductor. These induced electrical currents flow in a circular path in the second conductor (i.e., the inspected part) as shown in Fig. 2 and are called 'eddy currents.' They get their name from "eddies" that are formed when a liquid or gas flows in a circular path around obstacles in their path. The eddy current flowing through the metal in turn generates its own magnetic field, which interacts with the coil and its field through mutual inductance.

Eddy currents probes consist of one or more coils in an assembly. Discontinuities or property variations in the test part change the flow of the eddy current and are detected by the inspection probe as changes in electrical impedance amplitude and phase angle, enabling thickness measurements or the detection of discontinuities such as cracks, laps, or non-metallics (e.g., inclusions or corrosion products).

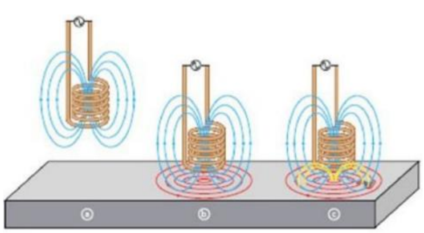

FIG. 2. THE PRINCIPLE OF EDDY CURRENT INSPECTION

Eddy current density is highest near the surface of the part, so this is the region of highest test resolution. Depth of penetration is determined by the test frequency and the magnetic permeability and conductivity of the test material. Depth of penetration decreases with increasing frequency and increasing conductivity and permeability of the material tested. For this reason, penetration into ferrous metals is very small at practical test frequencies. Thus, ECI of steel parts is limited to detecting surface-breaking discontinuities.

It is essential that an eddy current test procedure consist of calibration with the appropriate reference standards at the start of a test. In surface flaw detection applications, this calibration process involves the use of reference standards of the same material, shape, and size as the test piece that contains artificial defects of known size to simulate flaws.

6. EDDY CURRENT ARRAYS

Eddy current array (ECA) technology provides the ability to electronically drive multiple eddy current coils placed side by side in the same probe assembly. This concept is depicted schematically in Fig. 3.

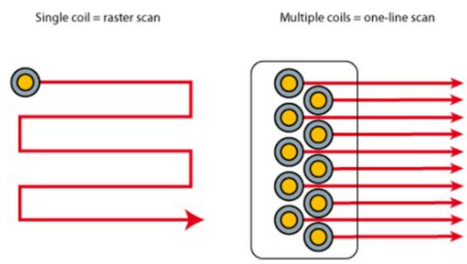

FIG. 3. COMPARISON OF MANUAL, SINGLE COIL INSPECTION WITH EDDY CURRENT ARRAY INSPECTION

Data acquisition is performed by multiplexing the eddy current coils in a special pattern to avoid mutual inductance between the individual coils. When multiplexed, the individual coils are excited at different times, allowing the system to excite all of the coils in the probe without ever exciting any two adjacent coils at the same time and allowing inspection overlap as shown in Fig. 4. While conductivity and permeability are properties of the test material, the test frequency, coil type, and coil size (d) can be chosen to provide the desired resolution (r) and sensitivity (see Fig. 4).

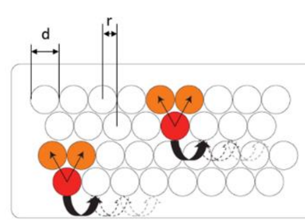

FIG. 4. CONCEPT OF MULTIPLEXING EDDY CURRENT COILS IN AN ARRAY

This data is reassembled and referenced to an encoded position and represented graphically as a C-scan image showing discontinuity data in a planar view. In addition to the enhanced imaging capabilities, multiplexing allows any individual coil (data) channel to be analyzed after inspection.

Multiplexing allows increased channel resolution, coil sensitivity (through the reduction of mutual inductance), coverage overlap, and a reduced noise level. In addition to providing visualization through C-scan imaging, ECA enables coverage of larger areas in a single pass while maintaining high resolution. As a result, multiplexed ECA inspection significantly improves the POD over manual, conventional ECI. Now, with flexible printed circuit board technology, flexible planar eddy current arrays have been developed for the inspection of curved and complex shapes. In these arrays, both exciting and sensing coils are etched on polyimide films.

Normalization is performed to standardize sensitivity for an ECA probe. To do this, a calibration standard containing a reference discontinuity (e.g., a long, transverse notch) is scanned in order to generate the same eddy current signal for each channel. In this procedure, the gain and rotation of each channel is adjusted so that they are the same in all channels.

7. Example Comparing MPI and ECI of a Freight Car Axle

To compare these two methods for the inspection of freight car axles, a 6.5 x 9 class K axle was prepared with artificial flaws produced by Electrical Discharge Machining (EDM). Both longitudinal and circumferential notches were produced in the body and dust collar radius for evaluation as shown in Fig. 5.

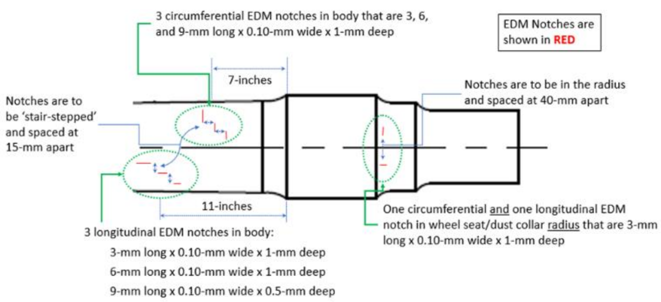

FIG. 5. CLASS K TEST AXLE WITH ARTIFICIAL SURFACE FLAWS

Per AAR Section G, Standard M-101, Appendix A, any circumferential defects of indeterminate depth on axle surfaces, regardless of location or size are considered to be 'injurious' and cause for rejection. This is limited to the probability of visual detection by the technician during the inspection of as-manufactured axles. For longitudinal defects, the smallest size required by detection (per Appendix A) is 6.5-mm. So, to be conservative in this specific test axle, 3-mm was chosen to be the smallest length defect.

7.1. Magnetic Particle Inspection Results

The axle was inspected using conventional MPI procedures specified in AAR Section G-II Section S-659 [8]. The results are shown pictorially in Fig. 6. While the flaws from 3 to 9-mm long in both orientations were easily detected, the actual lengths were not able to be measured since MPI is a hit-or-miss method, and measuring lengths of indications under UV lighting is inherently difficult without the use of calibrated comparison features.

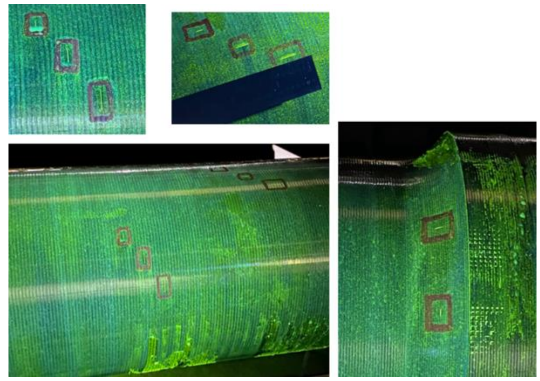

FIG. 6. RESULTS FROM MAGNETIC PARTICLE INSPECTION

7.2. Eddy Current Array Inspection Results

Inspection of the same axle was performed using two different ECA probes as shown in Fig. 7: one for the flat sections and another for the curved fillets of the axle. The requirements include the complete inspection of all flat areas and radii within 3-minutes along with concurrent UT inspection for internal indications.

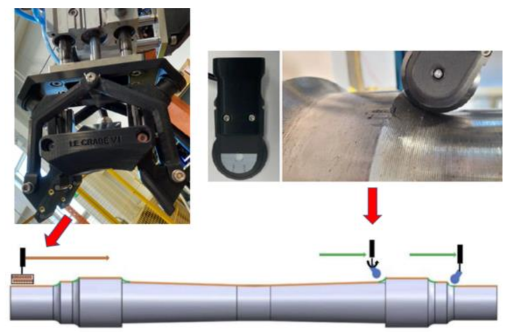

FIG. 7. EDDY CURRENT ARRAY PROBES AND INSPECTION COVERAGE OF FREIGHT CAR AXLE

The probes were moved in the longitudinal direction while the axle was rotated on a roller bed. The flat areas of the axle were scanned with a multi-coil ECA probe offering 20-mm coverage. The radii were scanned with a 50-mm housing allowing inspection of radii ≥ 25-mm. This radii probe was composed of a 5-coil flexible array capable of rotating 180° to accommodate different radii orientations.

The ECA inspection results are shown Figs. 8-11. C-scan imaging shows both the circumferential and longitudinal indications in this axle as well as position information.

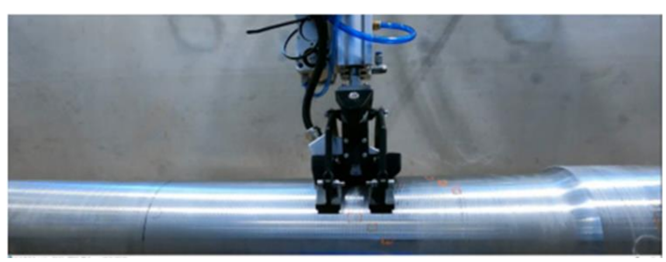

FIG. 8. AXLE BODY INSPECTION USING MULTI-COIL ECA PROBE

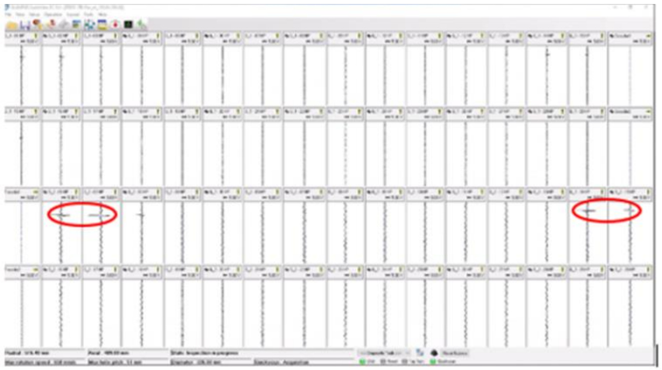

FIG. 9. 'LIVE' DATA DURING BODY INSPECTION WITH DATA FROM INDICATIONS CIRCLED.

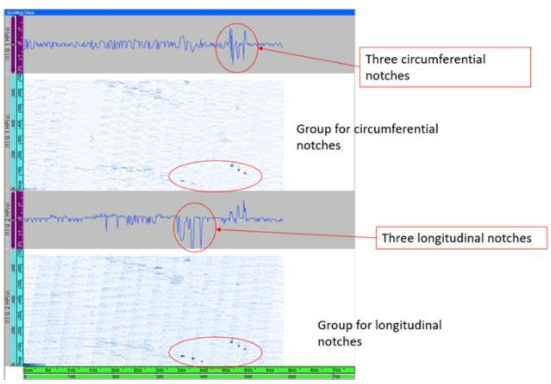

FIG. 10. AXLE BODY C-SCAN IMAGES OF 3, 6, AND 9-MM LONG CIRCUMFERENTIAL AND LONGITUDINAL INDICATIONS

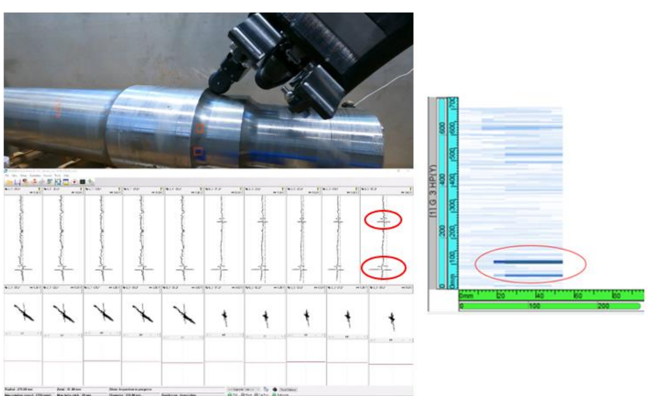

FIG. 11. AXLE DUST COLLAR/WHEEL SEAT RADIUS INSPECTION WITH C-SCAN IMAGE

7.3. Discussion

Detection and location information of 3, 6, and 9-mm longitudinal and circumferential artificial flaws in a Class K freight car axle was demonstrated by MPI and ECA inspection methods. Analysis of ECA data easily conforms to the sizing requirements of AAR M-101, Appendix A, while the hit-or-miss approach of visual and MPI methods are inherently more difficult to quantify. Thresholds for maximum allowable individual indication size and total size of all indications within a specified range in each zone of the axle (i.e., journal, dust collar, wheel seat, body, radii) can be established and executed using ECA inspection. In addition, ECA inspection and data analysis can be automated and performed in a relatively short amount of time in comparison to visual and MPI methods.

8. SUMMARY

While North American freight car axles are designed and manufactured with the goal of infinite fatigue life, imperfections from the manufacturing process and service-induced damage may still occur. Once the full details of fatigue crack growth and initial permissible flaw characteristics are established, a suitable NDI method must be used that is capable of detecting this flaw size, and larger, with a high degree of confidence. While only visual inspection is required for as-manufactured railway axles, this study examined and compared the methods of MPI and ECA inspection. It was shown that ECA inspection offers the advantages of fewer human factor errors and improved reliability over visual inspection and MPI hit-or-miss methods. Multiplexed ECA inspection significantly improves the POD over manual, conventional ECI and allows for automation and high productivity. In addition, data from ECA inspection provides information on the size and location of the discontinuities and thresholds can be established. Finally, ECA inspection data can be stored for archiving, reporting, and post-process analysis.

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