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# Ionising Radiation in Non-Destructive Testing. Part 2 – Selected Issues Related to the Implementation of Radiographic Testing for the Diagnosis of Rail Joints on PKP PLK S.A. Infrastructure

Małgorzata OSTROMĘCKA[1]

**Summary**

The article presents the main issues and challenges associated with the implementation of radiographic testing for the diagnosis of rail joints conducted in field conditions on the infrastructure of PKP PLK. It outlines the range of guidelines that need to be created or modified in relation to the necessity of using ionising radiation, and identifies possible areas for reducing the time taken to perform the tests.

**Keywords:** non-destructive testing, industrial radiography, welded joint, rail joints

## 1. Introduction

Non-destructive testing methods do not alter the service properties of the component, do not disrupt its continuity, nor do they cause changes in its micro- and macrostructure. These methods enable the acquisition of information about the location and nature of material discrepancies within the material or on its surface. It is possible to determine the type of discontinuity, its location, and direction of propagation. Additionally, non-destructive testing can be used to detect areas of stress or locations affected by intergranular corrosion. This set of information makes it possible to classify the component into the correct quality class and to estimate its lifespan and assess its continued serviceability. In the case of welded joints, the following non-destructive testing methods are used:

- visual testing,
- penetrant testing,
- magnetic particle inspection,
- eddy current testing,
- radiographic testing,
- ultrasonic testing.

Appropriate standards have been developed for all these testing methods, which organise and standardise acceptance regulations based on the results of these tests [1–9]. In the case of rail welding, radiographic testing is not employed, and the standard volumetric test is ultrasonic testing The procedures (for infrastructure managed by PKP PLK S.A.) permitting contractors to perform termite welds, as well as welds performed in the welding shop or with welders on the track, do not provide for tests involving ionising radiation in Poland [10–12]. Such tests are not carried out on tracks, and there are no guidelines that would enable them.

The scientific literature concerning issues related to non-destructive testing of rails also most often omits this option [13–16], though it sometimes mentions that the radiographic method is used to confirm defects in thermite welds or in crossings and switches, previously detected by another non-destructive method [17].

However, replacing radiographic tests with ultrasonic tests is not always advantageous. Some discrepancies are more easily identified by the radiographic method, and considering passenger safety, which is a priority in rail transport, one should not completely abandon this form of diagnostics of rail joints performed by welding techniques.

Current development trends in non-destructive testing in the world railway industry are primarily focused on automating the testing process, using remote solutions, and artificial intelligence [18–20], and do

[1] Ph.D.Eng.; Railway Research Institute, Materials & Structure Laboratory; e-mail: mostromecka@ikolej.pl.

not encompass significant development towards radiographic testing. However, radiography is offering increasingly convenient solutions in the form of digital detectors, eliminating the lengthy photochemical processing of films, in favour of using phosphor plates or flat panels. Digital radiography also makes it possible to reduce radiation energy while simultaneously shortening the exposure time. This enables obtaining a result in a relatively short time, which is recorded in electronic form and can be subjected to multiple verifications (in case of doubts in interpretation).

## 2. Non-Destructive Volumetric Testing of Rails and Rail Joints

Volumetric (volume-based) testing enables the detection of internal material discrepancies. Volumetric methods of weld testing include ultrasonic and radiographic testing. There are numerous studies describing the advantages and disadvantages of both types of tests, as well as articles presenting their practical applications [21–26]. Unfortunately, publications on radiographic testing methods for rails are scarce [23].

In most studies, radiographic and ultrasonic testing are considered complementary. The authors [21] conclude that (…) *There is no universal testing method, and examining a welded joint with different methods can provide different information about its properties and quality* (…). They also present a comparison of radiographic and ultrasonic methods with indications for their use. On the basis of these studies, assuming digital radiography as an option, a comparison of methods emerges that justifies the desirability of using radiography in the diagnosis of rail joints (Table 1).

A separate issue, not covered in Table 2, is the impact of the material's microstructure – for example, grain size on the choice of testing method. In railway welding, the most widespread techniques for connecting rails are thermite welding and flash butt welding. Flash butt welding typically results in fine-grained structures, while thermite welding tends to produce coarse-grained structures. During ultrasonic testing, large grain sizes cause scattering of waves at the grain boundaries, resulting in both a significant increase in the attenuation coefficient and an elevated level of structural noise. As a result, in addition to the general deterioration of the signal-to-noise ratio (SNR), interference from scattered waves can sometimes lead to false indications [27].

Table 1

**Comparison of radiographic and ultrasonic methods**

| Radiographic Method (RT) | Ultrasonic Method (UT) |
|---|---|
| **Low detectability of flat defects located perpendicularly to the direction of the emitted radiation** | Very high detectability of flat defects located perpendicularly to the direction of the emitted ultrasonic wave |
| **Relatively high detectability of flat defects located parallel to the direction of the emitted radiation** | Zero detectability of flat defects located parallel to the direction of the emitted ultrasonic wave |
| **No possibility of indicating the location of defects located parallel to the direction of the emitted radiation (unless more than one direction of radiation is utilised)** | Complete possibility of indicating the location of defects |
| **Testing requires access from both sides of the test surface** | Testing requires access from only one side of the test surface – in the case of echo and TOFD methods |
| **Contact surface practically does not affect the quality of the test** | Contact surface affects the quality of the test – surface roughness significantly hinders or even completely prevents its execution |
| **Possibility of testing large surfaces in a relatively short time** | Very labour- and time-intensive when testing large surfaces |
| **Ease of testing joints of complex shapes and circumferential joints of pipes of small and large diameters** | Difficulty in testing joints of complex shapes and circumferential joints of pipes of small and large diameters |
| **Possibility of testing metals and their alloys as well as non-metals, additionally possibility of detecting objects embedded within other objects** | Possibility of testing metals and their alloys as well as non-metals |
| **Health risk associated with the test agent** | No health risk associated |

Authors' own elaboration based on [21].

Currently, guidelines for volumetric diagnostic testing of rails, namely ultrasonic tests, are based on the requirements outlined in Instructions Id-10 [28] and Id-17 [29], which were developed in 2005 by PKP Polskie Linie Kolejowe S.A. These instructions foresee the possibility of performing ultrasonic testing manually or automatically. During manual testing of the rail, single and dual probes are used for longitudinal waves at 0° and transverse waves at 45° and 70°, with frequencies of 2–3 MHz. For thermite welded rail joints, the tandem method is also used with two probes at a 45° angle. The time-consuming manual method makes it possible to test the rolling surface and the side of the rail head, as well as both sides of the base (Fig. 1) [30]. Due to the time and precision required for the test, such diagnostics require a team of operators, especially if it is conducted without closing down train traffic.

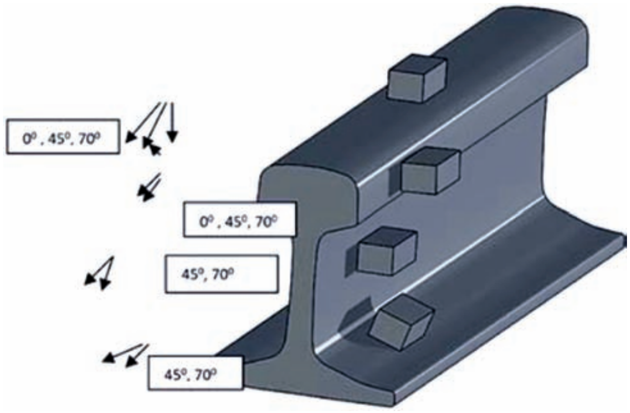


Fig. 1. Probe positioning during UT testing of rails [30]

The automatic method used on railway tracks in Poland requires the use of a multi-channel flaw detector and single and dual probes with various angles of ultrasonic wave emission into the rail material, mounted in the slides of the diagnostic vehicle. Such testing is currently performed at speeds up to 50 km/h (although work is underway to increase the speed to 120 km/h) and only on the rolling surface of the rail.

Radiographic testing, which as a volumetric method could provide valuable information during the diagnostics of rails and rail joints, is not used in Poland, although it is very widespread in other industries and is considered a basic testing method. A rail, as an element with a complex shape, variable thickness, and relatively large surface area (see Table 1 and Fig. 2), can be examined more quickly using the radiographic method than the ultrasonic method, particularly when using digital detectors. For this purpose, it is necessary to develop guidelines for conducting such tests, as the use of ionising radiation requires special regulations both for the test personnel and the organisation of the tests themselves.

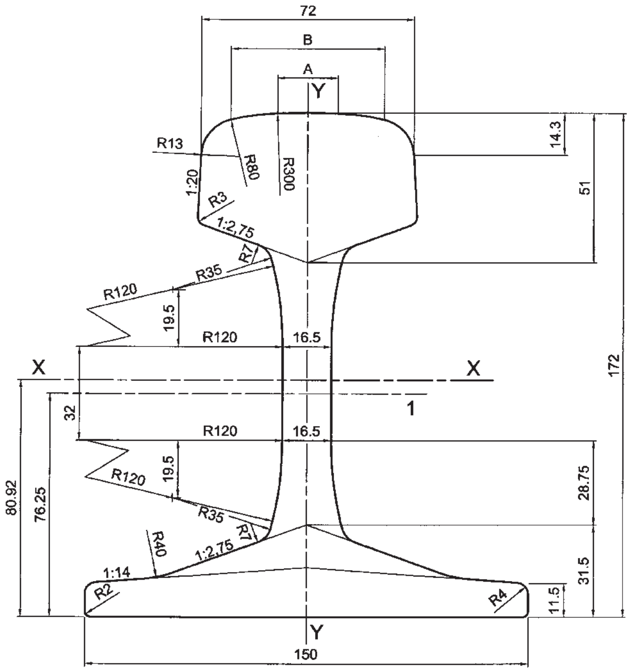


Fig. 2. Vignoles rail with a 60E1 profile; dimensions in millimetres [31]

## 3. Defects in Rail Joints and Welding Imperfections – Reference Documents for the Development of Guidelines for the Quality Assessment of Rail Joints

The classification scheme for rail defects, as listed in the UIC 712 catalogue (2002) [32] and IRS 70712 (2018) [33], presents a division according to a numeric code, where the first digit determines the type and location of the defect:

- defects at the ends of the rails,
- defects outside the ends of the rails,
- defects caused by damage to the rails during production or transport,
- defects in welded and fusion-welded joints and padding welds.

Rail joint defects marked with the number 4 are further classified by three additional digits according to the diagram (Fig. 3).

The (welded) joint area (Figure 4) covers a distance of 10 cm on either side of the joint axis. Any defect that originates within this area is classified as a joint defect [34].

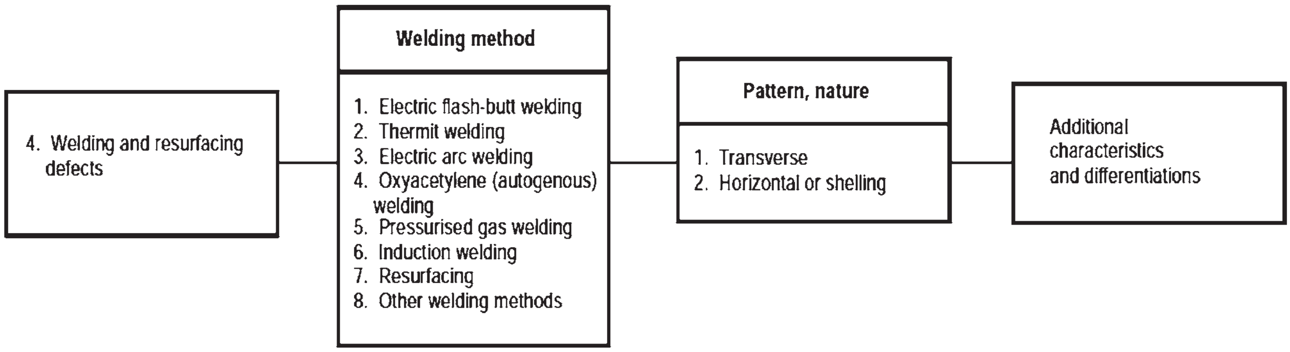


Fig. 3. Diagram of rail joint defects; author's own elaboration based on [32]

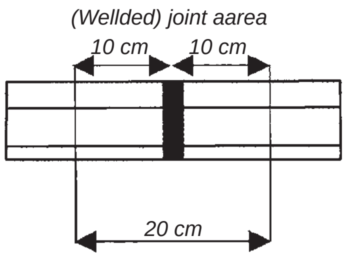


Fig. 4. Rail joint area [35]

However, in welding terminology, the term 'defect' is not used, but rather 'unacceptable' or 'acceptable' non-conformities. According to the standard PN-EN ISO 6520-1 [8], non-conformities occurring in welded joints are classified, regardless of the materials used, into six groups:

1) cracks – discontinuities in the metal of the weld or the heat-affected zone in the form of a rupture created by stress,
2) cavities – spaces filled with gas,
3) solid inclusions – solid foreign substances entrapped in the weld metal – slag, flux, foreign metal,
4) lack of fusion and penetration – lack of union between the weld metal and the parent metal or between the successive layers of weld metal,
5) imperfect shape and dimensions – undercuts, excess weld metal, incorrect weld toe, angular misalignment, incorrect joint geometry,
6) miscellaneous imperfections – other than those in points 1–5, e.g., stray arc, discolouration, slag or flux residues, grinding.

According to the first part of the standard PN-EN ISO 6520-1 [8], the designations for groups 1–6 apply to arc welding, electron beam welding, and laser welding processes. In the second part of this standard [9], pertaining to welding, the designations for groups 1–6 are preceded by the letter P. Acceptance criteria and threshold values for various welding non-conformities are provided by the standard PN-EN ISO 5817 [7] in relation to quality levels B, C, D (respectively: stringent, moderate, and lenient requirements). In assessing non-conformities using any non-destructive method, technicians usually refer to specified threshold values of non-conformities for a particular quality class. In the case of non-destructive testing in Polish railways, acceptance criteria are imposed by the guidelines of PKP PLK S.A. [36–38]. In the guidelines [36, 37], apart from defects related to vertical and horizontal linearity, defects in rail joints are distinguished depending on the welding method used (Table 2).

This list includes selected types of defects related to welding non-conformities, referring to the old standard EN 26520:1997, which used letter designations for non-conformities. In the current version of the standard [8, 9], number-based designations are used. Implementing radiography for use on the PKP PLK infrastructure poses a choice for the creators of new guidelines concerning the acceptance criteria of test results in terms of reference documents. On the one hand, the alignment of the acceptance criteria with the PN-EN ISO 5817 standard [7] relating to specific quality levels would enable the method to be adapted to universal requirements, and staff training in radiographic testing would have full knowledge of the principles of joint quality assessment after the course. On the other hand, the infrastructure manager's guidelines are the predominant reference, which is justified by the specificity of the welding methods used in rail joining and makes it possible to compile the necessary requirements in fewer documents adapted to the needs of the railway industry. Therefore, it may be more appropriate to adapt the assessment of radiographic test results to the current PKP PLK guidelines, which will involve developing instructions for radiographic testing of rail joints modelled on existing ones for ultrasonic testing, as well as modifying existing guidelines related to thermite welding and rail welding [36, 37], and other normative documents.

Table 2

**List of selected defects in rail joints based on PKP PLK guidelines [36, 37]**

| **Thermite joint defects according to Id-5 [36]** | **Flash-welded joint defects [37]** |
|---|---|
| Execution defects | |
| **Fa – leakage (lack of metal)**<br>**Fe – porosity of the weld**<br>**Db – lack of fusion**<br>**Fk – excessive sprue**<br>**Ba – compacted slag**<br>**Bb – band slag;**<br>**Bc – foreign metal inclusions**<br>**Bd – sand inclusions** | Db – lack of fusion<br>Fk – excessive flash<br>Bc – foreign metal inclusions<br>Sc – improper grinding of the jaw contact areas |
| Weld/Join cracks | |
| **Ea – longitudinal**<br>**Eb – transverse**<br>**Ec – radial** | Ea – longitudinal<br>Eb – transverse<br>Ec – radial |
| Treatment defects | |
| **Pt – rolling surface**<br>**Pb – side surface**<br>**Ns – uncleaned weld** | Pt – rolling surface<br>Pb – side surface<br>Nw – uncut flash |

## 4. Safety of Radiographic Testing

The main challenge in implementing the radiographic method for railway rail testing is the need to create procedures and instructions to organise these tests in a way that is safe for operators and the environment. Such guidelines must address issues that include, in technical terms, the following procedures for performing radiographic testing:

- choosing between X-ray or gamma radiographic equipment,
- determining test parameters – exposure time, source-object distance, radiation voltage (intensity),
- Selecting the appropriate digital detection technique – phosphor plates or flat panels,
- sequence of actions in conducting the tests.

Procedures for evaluating radiograms and developing and documenting results:

- marking radiograms and indicating and identifying welds on radiograms,
- personnel qualifications (certificate according to the PN-EN ISO 9712: 2012 standard [39] at least level 2 in radiographic testing and having the authorisation to perform tests),
- placement of Image Quality Indicators (in accordance with PN-EN ISO 17636-2 [1]),
- standardized Signal-to-Noise Ratio (SNR) [1],
- developing methods for documenting interpreted results e.g.: model radiography protocol.

Organisational procedures:

- employment of a Radiation Protection Officer [40],
- preparatory activities: planning radiographic tests and a system for informing the surroundings about conducting radiological tests [41],
- requirements related to securing the area: designating and marking the boundary of the area where radiographic tests are conducted (day and night options), using collimators and lead screens to protect against scattered radiation [41],
- regulations for working with X-ray or gamma radiation,
- instructions for the transport of hazardous materials [42],
- procedures in the event of a radiological incident [43],
- procedures for purchasing and storing gamma radiation sources and monitoring their suitability for testing (half-life),
- procedures related to ensuring the safety of individuals during radiographic testing – using dosimeters [44].

All these issues must be taken into account when creating conditions for performing radiographic testing on tracks, and cases and places where such tests are absolutely prohibited should also be indicated.


Fig. 5. Work in a refinery with a portable Digital Radiography (DR) system [45]

## 5. Opportunities to Accelerate the Diagnostic Process

One of the advantages of radiographic testing, which constitutes a certain superiority over ultrasonic testing, is the ability to examine a larger area with relatively high accuracy in a shorter amount of time. The area inspected by radiography is practically limited to the dimensions of the digital detector plate, whereas in ultrasonic testing, it is limited to the size of the probe or probe assembly. The use of traditional radiography using photographic films requires photochemical processing, which prolongs the time needed to obtain a result. However, currently, portable radiographic devices with digital detectors are available in the product range of specialist companies, eliminating the need for photographic films [45, 46]. Figure 5 shows a gammagraphy device for obtaining digital image recordings in a convenient form.

The use of flat panels (DR, *Direct Digital Radiography*) has an advantage over tests using phosphor plates (CR, *Computed Radiography*), which are relatively expensive and sensitive to damage Above all, it provides the opportunity to immediately view the radiograph taken and, if necessary, retake the image if it does not meet the quality requirements. To achieve a specific SNR (*Simplified Noise Level Reduction*), much shorter exposure times are used. Unfortunately, flat panels also have their limitations, such as the inability to conform the panel to the curvature of the tested element. In addition, different types of flat panels are available on the market, which means that they are not universally applicable, but require specific selection based on the performed tests. Proper implementation of DR radiography will therefore require thorough preparation at the stage of purchasing the digital detector, where not only the resolution and matrix size are important but also the type of scintillator, the range of radiation energy, and the maximum accumulated dose. These issues have been addressed in publication [47]. The use of DR radiography is undoubtedly the best way to shorten the testing time and the most optimal solution for implementing this non-destructive method in railway infrastructure testing.

Another issue is the consideration of the possibility of mechanising the process. The most common mechanised or automated applications of the radiographic method in the industry include computed tomography. Mobile CT scanners have been developed for industrial objects such as bridges, pipelines, and aircraft, which cannot be brought into a laboratory due to their size [48, 49]. CT reconstruction allows for three-dimensional (3D) mapping of the material structure and its defects, comparable to micrography.

Mechanised solutions for radiographic field testing of circumferential pipeline welds are used in the industry (Fig. 6). Similar solutions are used in the TOFT+PE ultrasonic method [50]. It is important to emphasise that in such tests, continuous verification of the settings of mechanised systems on reference samples (scope and sensitivity of the test) is very important.

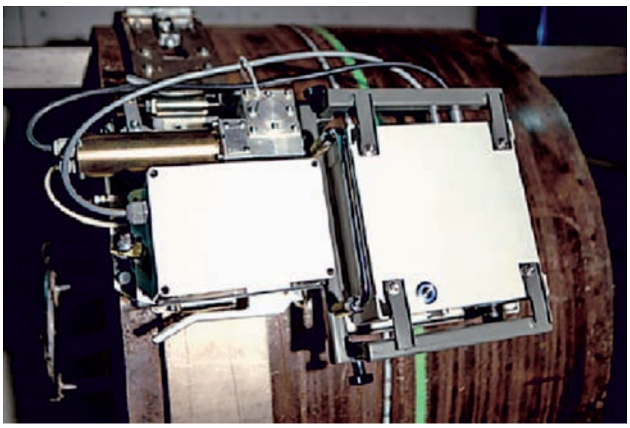

Fig. 6. Scanner together with a DR detector guided on a Cross tape during the testing of peripheral joints [50]

Regardless of whether the testing will be carried out in a mechanised or manual manner, the question arises to what extent this will be possible between train runs. The organisation of the tests themselves, the necessity to secure the area and notify people who may be nearby about the hazards associated with conducting tests using ionising radiation, assumes that radiological testing must be carefully planned and subject to a much stricter regime than ultrasonic testing.

## 6. Conclusion

Conducting radiographic testing requires the training of competent personnel and the preparation of a number of regulations that ensure safety in working with ionising radiation for both the specialists conducting these tests and those whose presence during the tests is necessary. For PKP PLK infrastructure, there are no guidelines stipulating the application of this testing method for the evaluation of rail joints made using welding methods. At the same time, radiography is often used in many industries as a method to obtain valuable information about the quality of the component under examination and to identify defects that are not detectable by ultrasonic methods. Considering the possibility of developing a special, rail-adapted, mobile solution for radiographic testing of rail welds and seams located in the track, it will be an immensely labour-intensive challenge to create procedures, instructions and other guidelines that take into account all aspects of working with ionising radiation.

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