A MAPOD approach for phased array ultrasonic inspections applied to aluminothermic welds in rails

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Abstract

Nowadays, long welded railway rails are achieved by means of aluminothermic and flush-butt welding processes. Compared to bolted joints, welds proved to be effective in terms of reduced wheel damage, ride comfort and maintenance. In rails, surface cracks often initiate within the welded and the heat affected regions of the foot, leading to brittle failure. On the subject, a recent work developed a probabilistic methodology for determining day-by-day failure probability. However, apart from this structural integrity study and few others, a complete damage tolerance approach should also consider the capability of non-destructive inspections. The latter is recognized as an essential input to define maintenance inspection intervals. The present work is focused on the capability assessment of Phased Array ultrasonic inspection applied to aluminothermic-welded joints by means of Probability of Detection curves, as a result of experimental and Model Assisted data samples.

1. Introduction

The so called "long welded rail" (Fig. 1) is gradually substituting traditional bolted joints because it proves to be more effective in terms of reduced wheel damage, ride comfort and maintenance. Two manufacturing processes can be applied for manufacturing the welds: aluminothermic and flush-butt. The present research considers the former (1), which is manufactured by an on-site foundry process (Fig. 1).

Figure 1. The "long welded rail".

Aluminothermic welded rails can fail during service, most often, by surface cracks initiating, due to defects and/or stress concentrations, within the welded and the heat affected regions of the foot and causing brittle failure after short propagation (Fig. 2). Inexplicably, this event is not fully considered in relevant standards, such as (2), even if periodic maintenance NDT inspections are prescribed by conventional ultrasonic testing and only considering centred cracks inspected from the rolling surface. This means the lateral tips of the foot are never inspected during service.


Figure 2. Typical in-service failure of the long welded rail.

The right approach, then, requires optimized inspection intervals defined by the application of the "Damage Tolerance" concept (3), which implies the availability, along with other "ingredients", of reliable POD curves (4)-(6) for the adopted UT technique.

The present research proposes to substitute the conventional UT approach with Phased Array Ultrasonic Testing (PAUT) and tries to evaluate its reliability for aluminothermic welded rails, as a result of experimental and Model Assisted data samples realizing, de facto, a Model Assisted Probability of Detection approach (7)-(8). Moreover, an inspection procedure for the lateral tips of the foot is set up and evaluated for reliability, as well.

2. Experiments

Artificial semi-elliptical notches were introduced (Fig. 3) into two samples of welded rails, taken from service, at the location of the maximum stress concentration. The considered material is a R260 steel grade and the profile type is 60E1, both according to (2). Two sets of notches, one at the symmetrical axis of the section and the other at the foot lateral tip, were manufactured by milling, using a spherical tip tool, and were all characterized by an aspect ratio equal to 0.4. Notches depth varied from 0.5 mm to 2 mm, with a few intermediate values, by a progressive increase by machining between inspections.

An Olympus Omniscan phased array unit was used to carry out all inspections. In particular, central notches were inspected (Fig. 4) from the rolling surface by a 2L64-A2 linear probe (2.25 MHz, 64 elements, S-Scan: 40°- 60°), while lateral ones from the foot upper surface by a 2L8-DGS1 linear probe (2.25 MHz, 8 elements, S-Scan: 50°- 70°).

Moreover, each notch was inspected from both its side with respect to the weld (approach here named “SX”) and the other side (approach here named “DX”). The latter implies the full interaction of the sound beam with the weld and the heat affected zones. Figure 5 shows some examples of S-Scans obtained, during inspections, adopting the SX approach. As can be seen, both the inherent geometry and the artificial notch can be clearly detected by the chosen operative parameters. In particular, the reported S-Scan ranges are those optimized for the application after several trials based on the best the trade-off between the needs of the inspections and accessibility due to the geometry of the welded rail, especially considering the lateral tips of the foot.

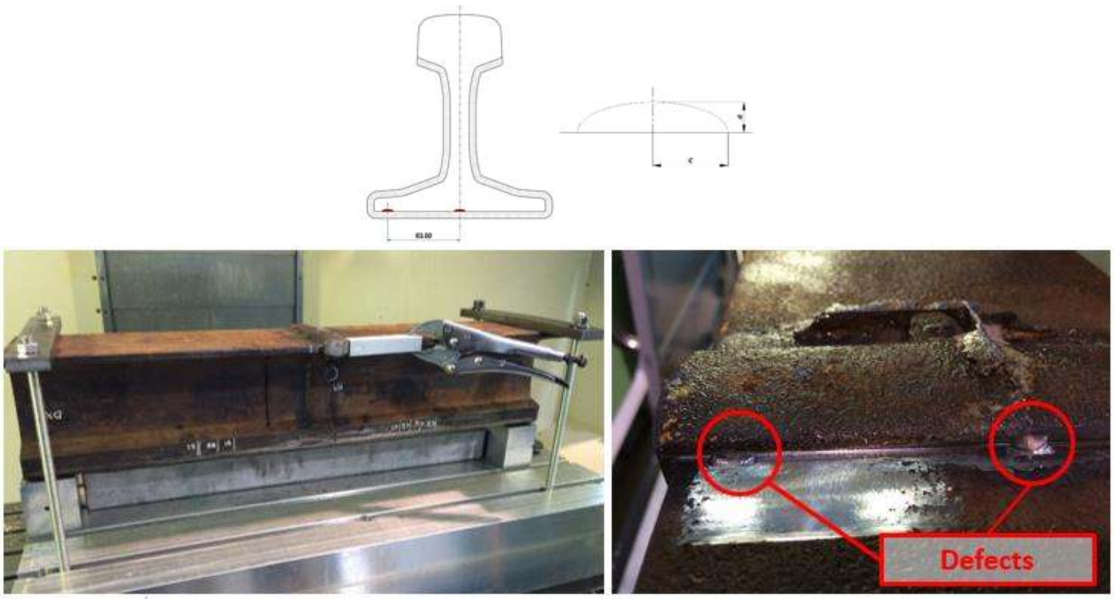


Figure 3. Manufacturing of artificial notches in welded rails.

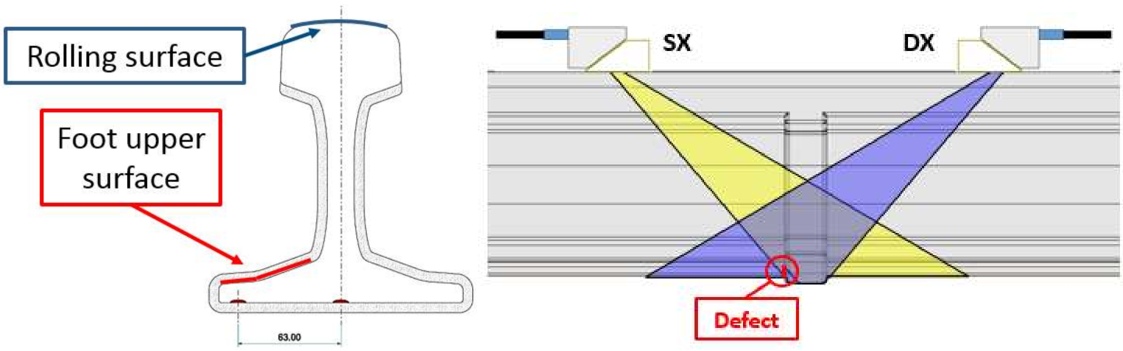
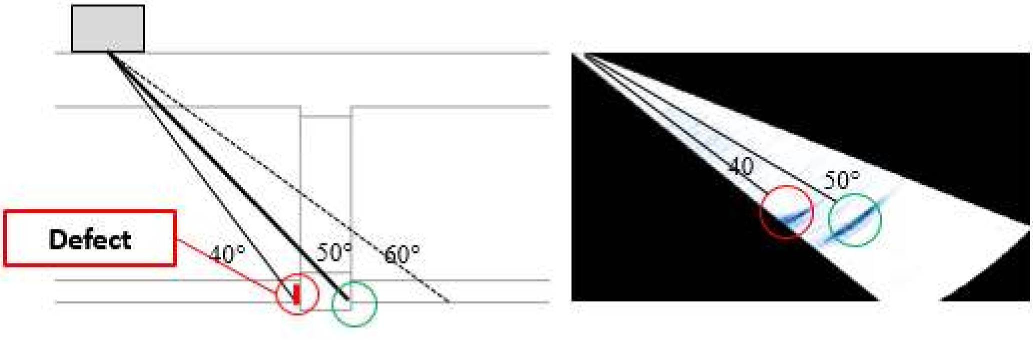


Figure 4. Approaches to inspections.

Figure 6 summarizes the obtained a vs. â responses. As can be seen, the DX approach is not acceptable and not consistent. It is difficult to think to the possibility to derive meaningful POD curves by the DX approach. The reason can be ascribed to the heterogeneous and coarse microstructure usually characterizing this type of weld and heat affected zones. On the other hand, the SX approach seems to provide, from the two inspected samples, good, consistent and comparable data, allowing for the determination of POD curves. The conclusion, which can be drawn, is that inspections should be carried out from both sides of the weld to maximize reliability.



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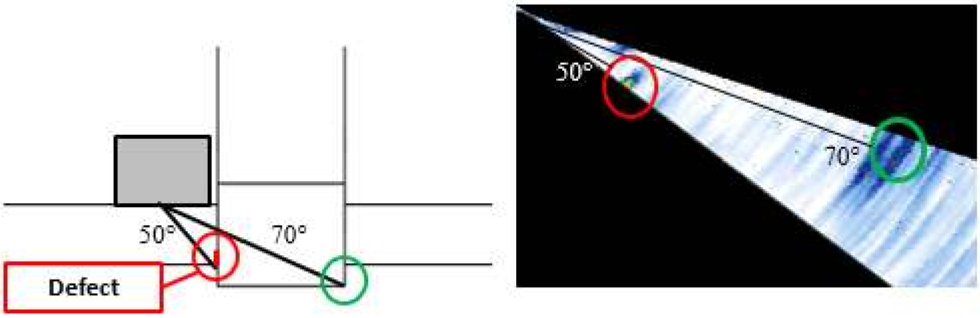
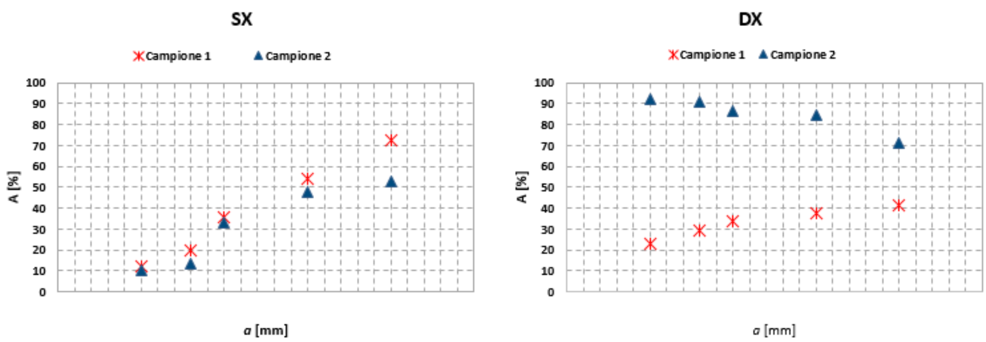


(b)

Figure 5. Examples of S-Scans from welded rails: a) from rolling surface; b) from foot upper surface.



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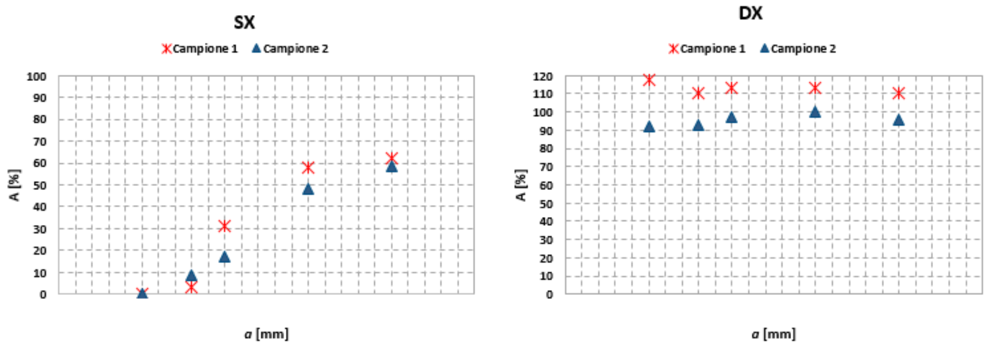


(b)

Figure 6. Summary of the obtained a vs. â responses: a) from rolling surface; b) from foot upper surface.

The final experimental activity dealt with the characterization of structural attenuation for both to clarify the just described behaviour of DX inspection and to implement it into the following numerical models. Both longitudinal and shear waves were characterized. Figure 7 shows the experimental set-up and the obtained results in the case of longitudinal waves inspected by two different normal probes characterized by a different diameter of the crystal (DP20: Ø=20 mm, DP10: Ø=10 mm). The sample block was machined from a real welded joint and allowed characterizing the structural attenuation for the base material (BM), heat affected zones (HAZ) and weld (W). Indeed, results showed a significantly higher structural attenuation of the welded material with respect to the heat affect zones and the base material.

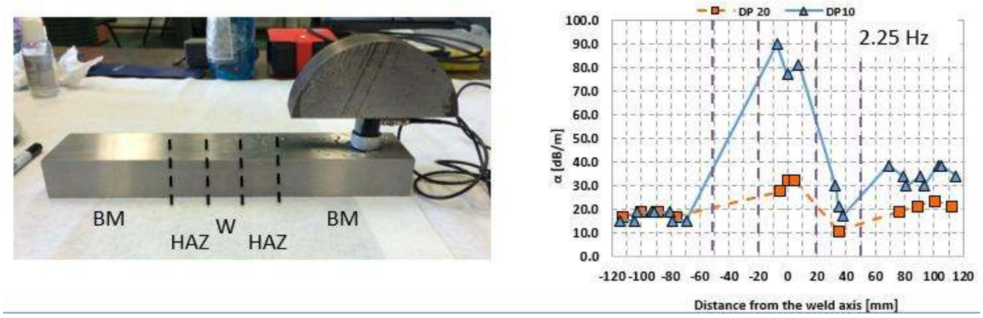


Figure 7. Experimental characterization of structural attenuation.

3. Set-up of the Numerical Model

The available experimental data are too few to provide a reliable determination of POD curves, so a MAPOD approach (7)-(8) was adopted. The numerical simulations reported in the present paper were carried out by means of CIVA^{nde} 11.0 dedicated software package (9). First, the calibration of the model was achieved by simulating the real calibration procedure used for in-service inspections: it is based on two rails, without any weld, with six SDH (diameter = 5 mm) located at different depths. PAUT responses were obtained in terms of dBs needed to get 80% screen amplitude. Analyses were carried out both with and without structural attenuation in order to check the sensitivity to this parameter. Figure 8 shows the results obtained for both the rolling surface and the foot upper surface. As can be seen, in the case of the rolling surface, it seems mandatory to keep into account for the structural attenuation in order to get a good calibration, while, in the case of the foot upper surface, it does not seem to be necessary, likely due to the much shorter sound path into the material.

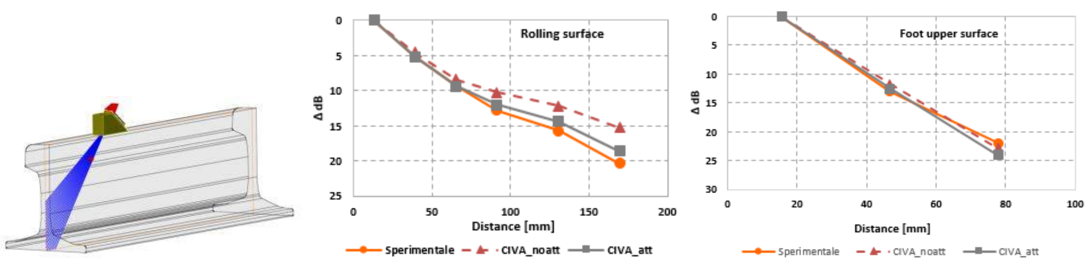


Figure 8. Calibration of the numerical model.

The calibrated model was, then, validated by simulating all the experimental inspections carried out on the welded samples and keeping into account for structural attenuation. Figure 9 shows the successful results of the validation.

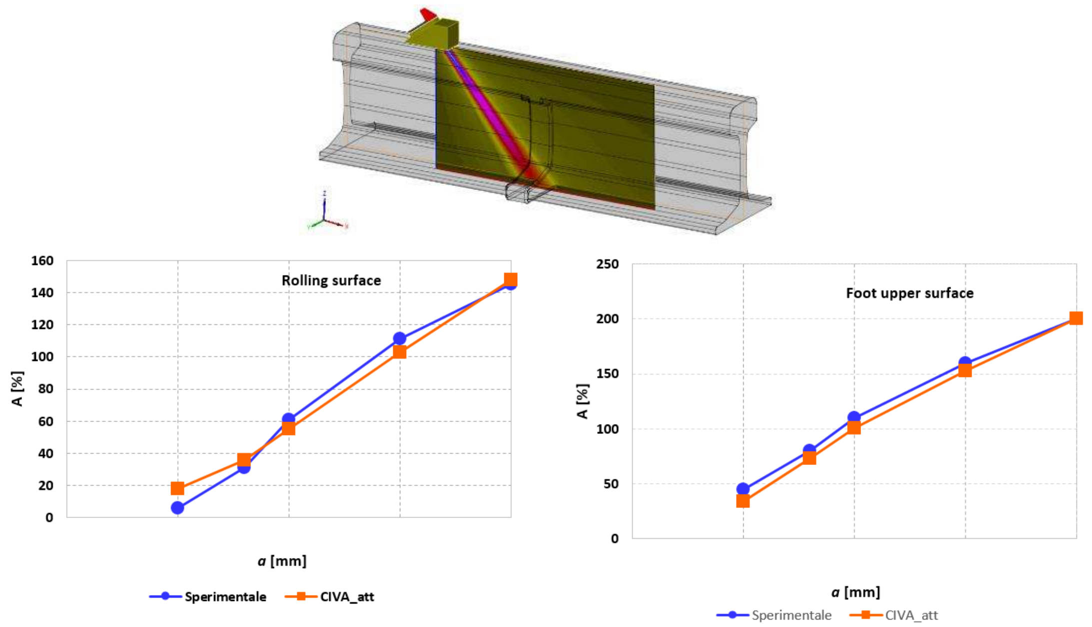


Figure 9. Validation of the numerical model.

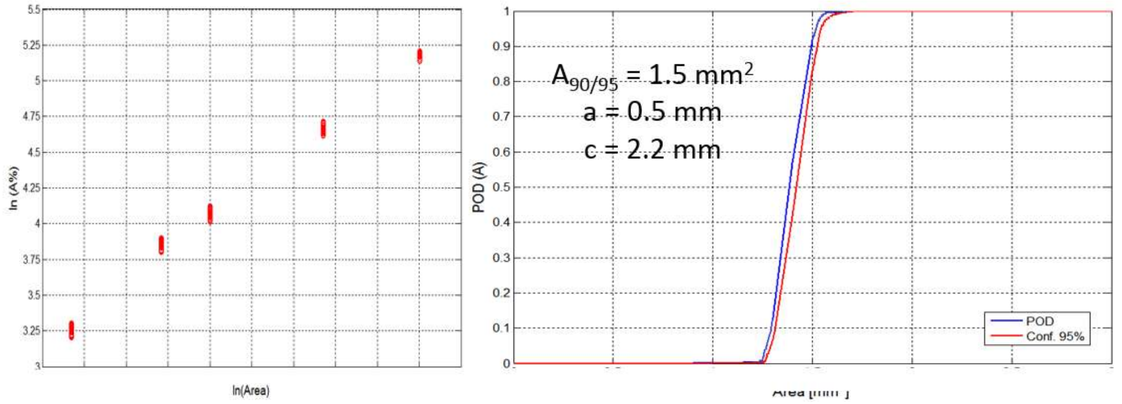
4. Derivation of Model-Assisted Probability of Detection Curves

MAPOD curves were derived, by means of Montecarlo extractions, stochastically varying two parameters: crack size and its position in the foot. It is worth remarking that, actually, more parameters should be accounted for, but that is still ongoing research and the presented results have to be considered as preliminary. 29 extractions of crack location, from a uniform distribution, were considered for each crack size so to guarantee the minimum sample size needed to derive, as for the classical statistical theory, the 95% confidence level of the mean. Data were collected as a function of the reflecting area (10) of the inspected defects. Finally, the background noise observed during experimental trials resulted to be equal to 6% screen height, so the decision threshold for POD determination was set to 20% screen height.

Figure 10 reports the obtained MAPOD curves. As can be seen, the performance of inspections from the rolling surface seems a bit better than that from the foot upper surface. This can be expected because the foot upper surface is not parallel to the foot base and because, contrarily to the rolling surface, it is not machined after the manufacturing of the weld and, consequently, its roughness is much worse.

5. Concluding remarks

Regarding the long welded rail obtained by the aluminothermic welding process, a reliability study of phased array ultrasonic inspections was carried out in order to substitute the traditional approach by conventional UT. Results seems reasonable and encouraging, but to be considered as preliminary, as well. More research work is being done in order to refine the approach and define a tool for the optimization of inspection intervals.



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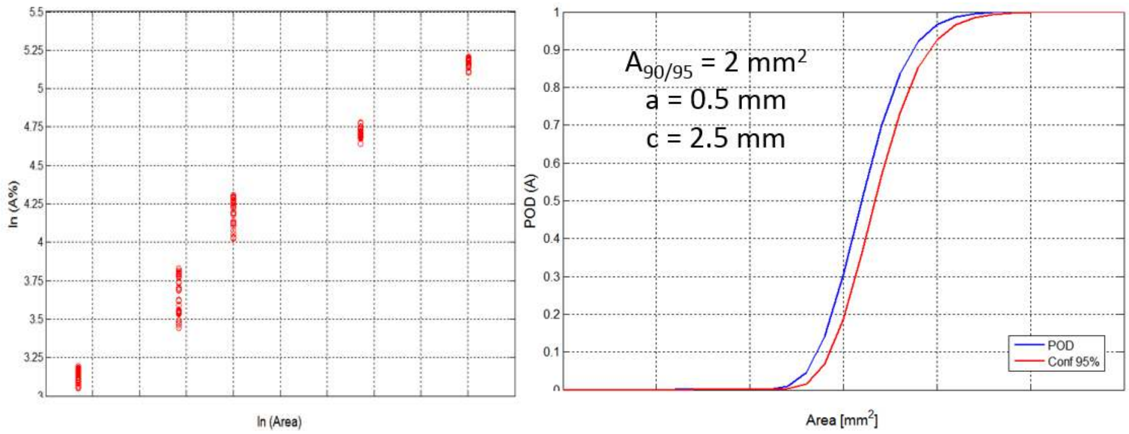

(b)

Figure 10. MAPOD curves: a) from rolling surface; b) from foot upper surface.

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