RAIL RESTORATION LIFETIME ON HIGH SPEED LINE

Ph. Brédif[1], J.Plu[2], C. Royer[2], C. Poidevin[1] and Ph. Pouligny[2]

[1] CEA LIST, F-91191 Gif-sur-Yvette, France
[2] SNCF, Track Design Department, 6, avenue François Mitterrand 93574 La Plaine Saint Denis, France

Abstract. Electric arc welding process has been widely used by SNCF (French national railways) to repair rails which presents damage on running surface. Depending on the depth of the defect, rails can be more or less grounded and weld beads are deposited on one or more layers (2 to 15 mm) to restore the rail to its initial profile.
In-track observations show that this kind of restoration has a limited lifetime on high speed lines. Indeed, lots of rails are removed due to development of cracks in welding repair. Moreover this cause of removal has been increasing since the late 90s.
SNCF has initiated a study to improve knowledge about this phenomenon. This study is based on the idea that welding repair behaviour cannot be explained without considering its metallurgical quality. One of the main reasons of cracks development on welds is the presence of small gas inclusions spread among the whole repair, which could then cause crack initiation under mechanical stress. Until now, destructive methods were used to determine quantity and size information about porosities in welds. SNCF asked the CEA LIST to develop a non-destructive testing method to check weld integrity. CEA LIST was also asked to develop a specific instrumentation to detect, locate and classify by size gas inclusions bigger than 0.3 mm in the whole repair.
The principle of the method is based on the use of an ultrasonic contact phased-array transducer associated with a specific processing. The transducer is articulated to conform as much as possible to the nominal rail section. The use of a phased-array probe allows limitation of mechanical displacements to only one axis, along the longitudinal plane of the rail. Inspection in the plane perpendicular to the axis of the rail is performed through electronic commutation and beam steering. The data analysis is done using CIVA software. A processing based on ultrasonic field computation was developed. The method was experimentally tested on real repairs in laboratory conditions. A prototype was then designed and realised to carry out the method on rail track.
This device performs two functions:
- Inspection of a repair without any operator intervention thanks to an automatic displacement of the transducer.
- Transportation of the system between two repairs.
The system is autonomous; it has its own power generator and water supply for ultrasonic coupling.
A test campaign was achieved by SNCF on the railway network during which nearly 400 repairs were inspected. Once relationship between integrity and lifetime is established, new porosity thresholds should be considered.
This paper describes the method as well as the instrumentation designed for this study. Experimental results including ultrasonic images and associated analysis are shown. A first assessment of the general health of the repair from the high-speed lines is done.

1. INTRODUCTION

SNCF (French national railways) widely proceeds to restoration on rails which running table is damaged. Arc welding technique is used to deposit metal in layers on the surface of the rail. The depth of such repairs is between 2 and 15 mm and the length is less than 500 mm. Unfortunately, lifetime of such restorations can be limited, particularly on high speed lines, due to cracks development in the deposit metal. As a consequence, rails are removed, and this cause of removal has been increasing since the late 90s.
A study was initiated by SNCF to improve the understanding of crack initiation and growth behaviour. One of the main reasons of cracks development is the presence of small gas inclusions in the restoration, which could cause crack initiation under mechanical stress.

SNCF asked the CEA to develop a non-destructive testing method and its associated instrumentation to detect and characterize gas inclusions equal or bigger than 300 µm embedded in restorations.
The first part of this paper describes the method of inspection, the instrumentation and the method of analysis specifically developed for this application. The second part presents an inspection campaign carried out by SNCF on high speed line restorations.

2. Method of inspection

2.1. Principle of the method

The method of inspection is based on a UT-phased array technique. A linear phased array, including 128 active elements individually driven, was designed for this application. This technique offers the advantage of inspecting the whole restoration with only one mechanical displacement, along the rail axis. The scanning in the perpendicular plane is achieved by an electronic commutation combined with several delay laws defined by CIVA-Software [2] (Figure 1).

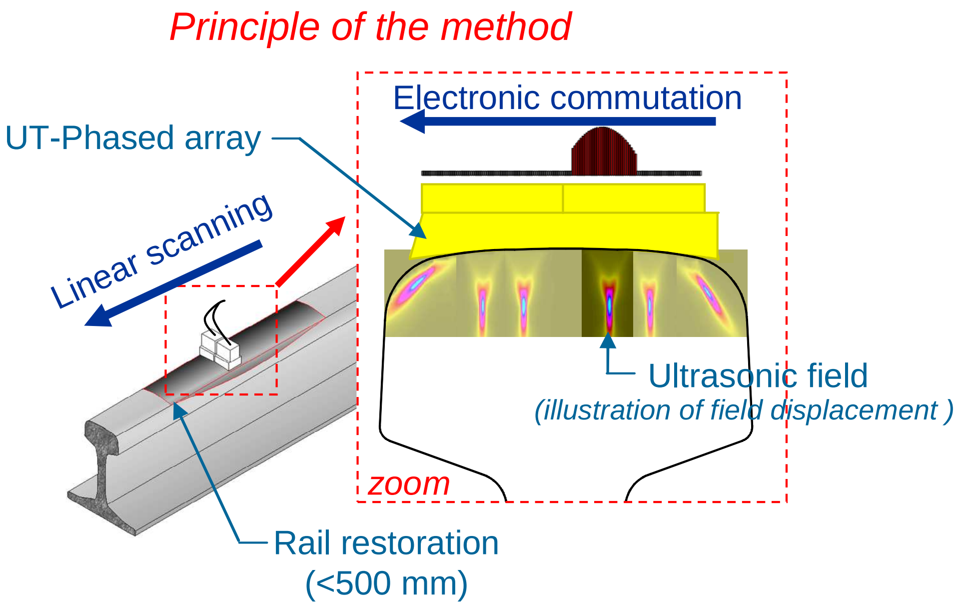


Figure 1. Illustration of the method of inspection

This specific UT-phased array is shown in Figure 2. The shape of the probe is cylindrically curved to focus naturally the ultrasonic beam in the cross section of the rail; focusing in the incident plane is done by applying electronic delay laws. Some head rails can present a profile different from the nominal one. Considering these cases, the contact between the wedge and the surface of the rail is improved thanks to a central articulation which provides a partial flexibility to the probe.

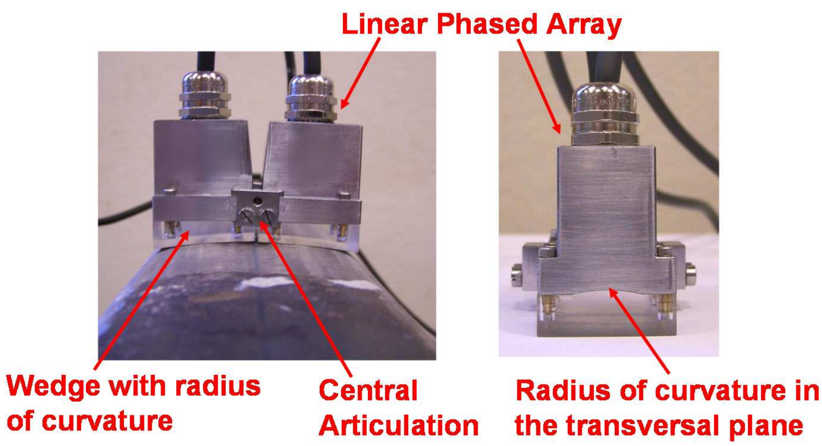


Figure 2. UT-Phased array probe

2.2. Instrumentation

The method of inspection was developed in laboratory and validated on railroads. A prototype was consequently designed to carry out the validation on tracks. This device performs two functions:

- Inspection of a repair without any operator intervention thanks to an automatic displacement of the transducer,
- Transportation of the system between two repairs.

The system is mainly made up of the UT-phased array, a Pulser/Receiver (M2M system), a motorized linear guide and a generator. The ultrasonic coupling between the probe and the rail is ensured by a film of water.

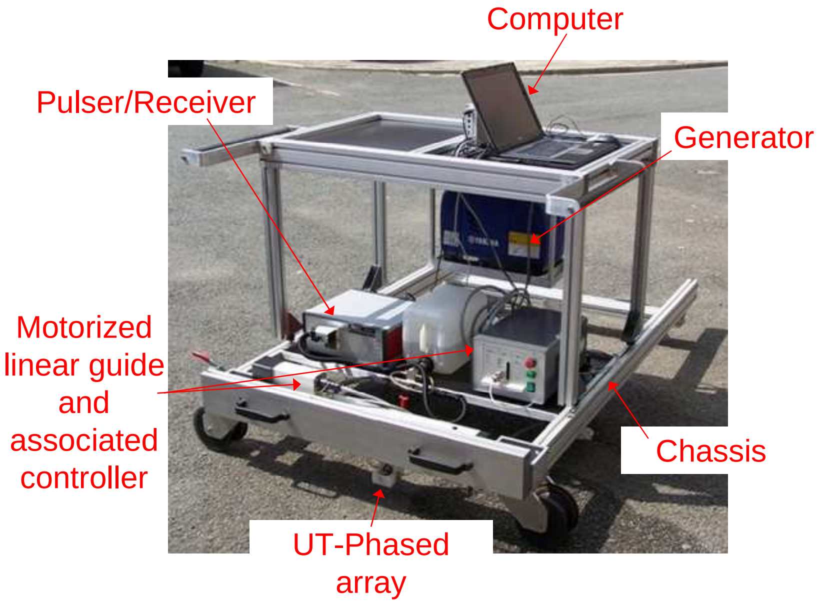


Figure 3. Prototype of inspection on track

2.3. Example of result

Figure 4 to Figure 6 show an example of inspection obtained on track with the prototype. These three figures illustrate the possibility to represent data in various views as C-scan (top view), B-scan along the rail axis and B-scan in the plane perpendicular to the rail.

One can observes that gas inclusions are detected in the whole volume of the repair. On Figure 5, alignment of several defects marks the boundary between restoration and base metal. Moreover, a difference of structural noise between the HAZ (heat-affected zone) and the base metal allows separating the limit between both areas.

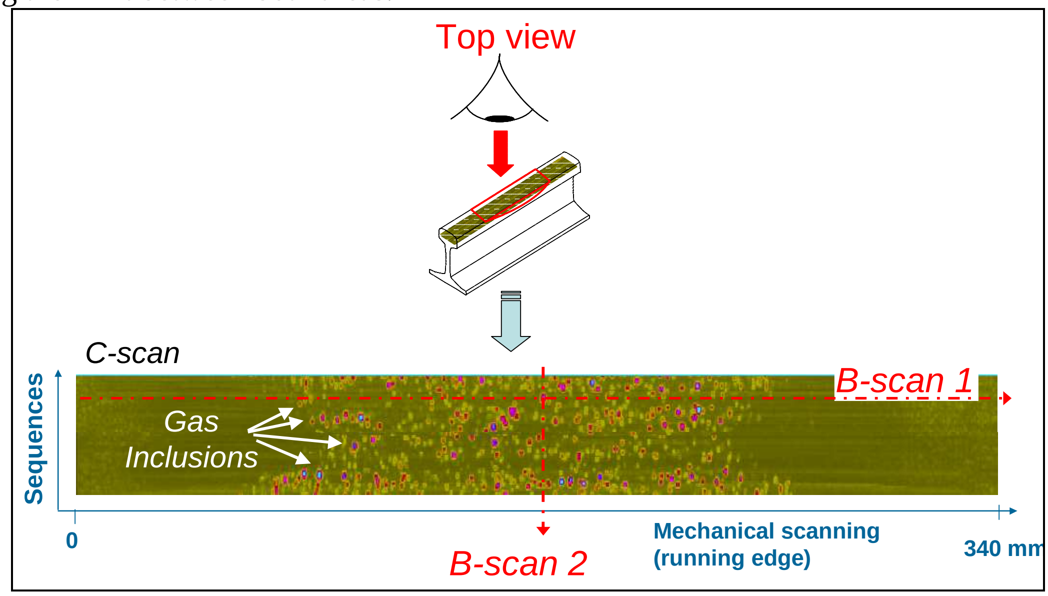


Figure 4. Example of inspection on track – Top view (C-scan)

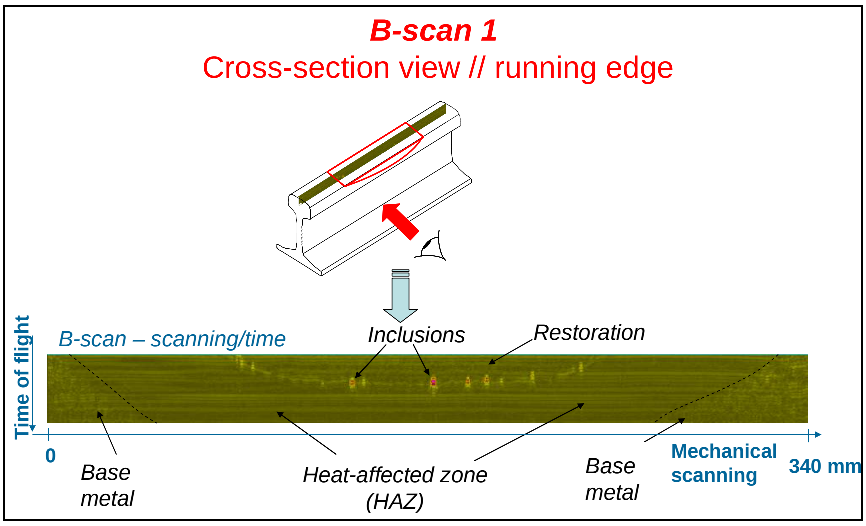


Figure 5. Example of inspection on track – Cross-section view // to the running edge (B-scan)

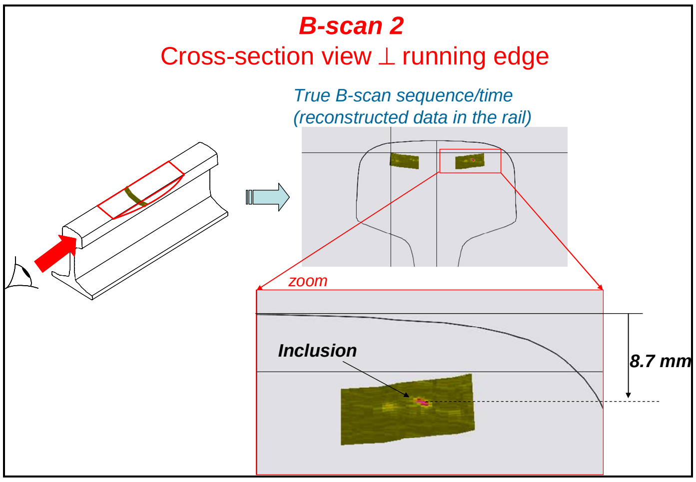


Figure 6. Example of inspection on track – Cross-section view ⊥ to the running edge (B-scan)

3. Method of analysis

Data analysis aims at characterizing gas inclusions in terms of size, position and number. This analysis is achieved using several tools already available in CIVA-software or specifically developed in the framework of this study.

3.1. Analysis tools

3.1.1. Equalization

Gas inclusion sizing is based on their reflected amplitude; which is supposed to increase according to the size of the defect assuming that the geometry of the flaw is approximately spherical. The link between size and amplitude can be calibrated using defects with known dimensions.
This method can be used if the amplitude variations due to the size of the defects can be separated from the amplitude variations caused by the field effects. We use a data-processing technique to compensate for the latter. First a DAC (Depth Amplitude Compensation) is applied to each shoot in order to compensate for the variations of sensitivity in depth. A second step takes into account the variations of sensitivity between all shoots. The processing then consists in performing normalization between the shots.

<u>Principle of the processing:</u>
Considering the number of shots and the geometry of the rail, it is impossible to determine a DAC and a normalization procedure from experimental results. For this reason, simulation was used.

The principle of the method to define the DAC curve is as follow: for each shot, we simulate the ultrasonic field along the ultrasonic path. We obtain amplitude versus time curve that allows determining the associated DAC. Figure 7 shows three examples of field computation (curves) along the main path of the beam (line).
In addition, variations of sensitivity between shots are automatically calculated. It is thus possible to deduce the normalization factor to apply for each shot.

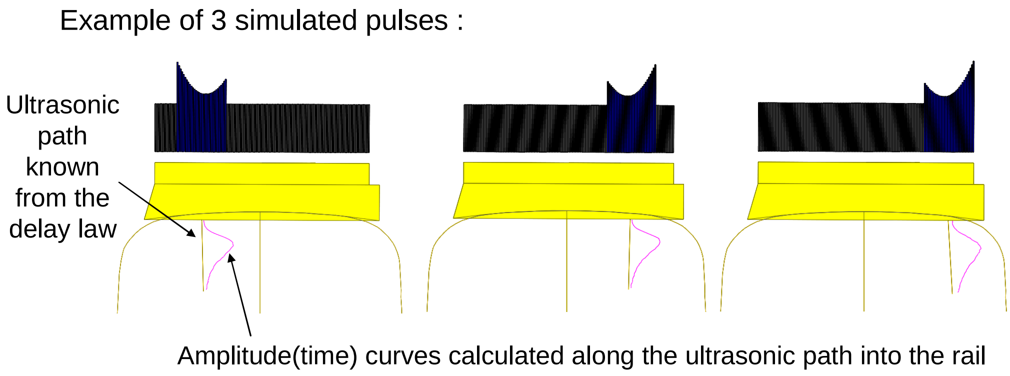


Figure 7. Example of field simulated with CIVA

Figure 8 shows an acquisition before and after applying data processing. Before processing, there is a 6 dB difference in amplitude between the holes located at 9 and 12 mm in depth. Using the processing, this difference is lowered to about 1 dB.

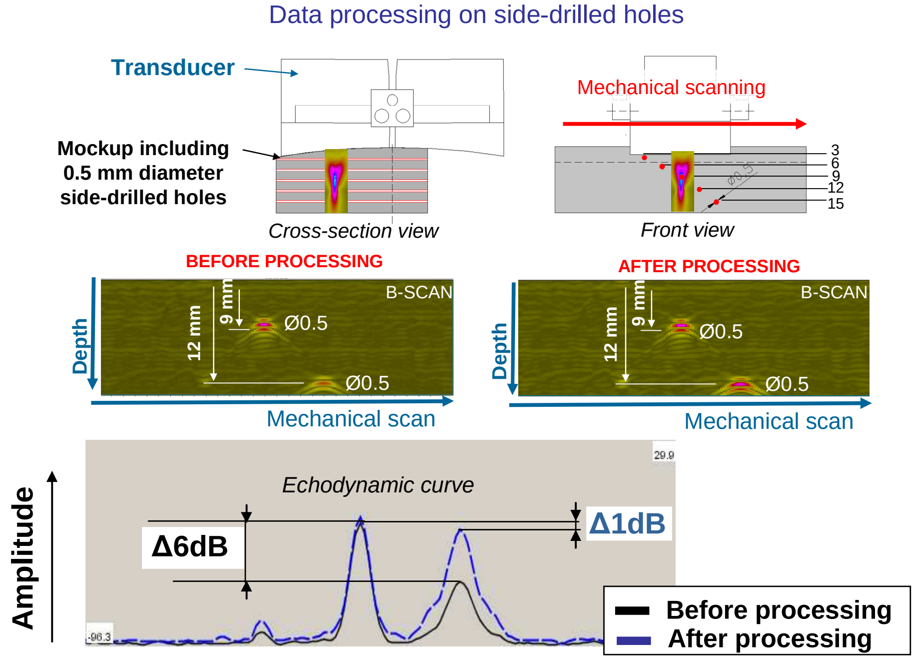


Figure 8. Procedure of equalization

3.1.3. Sizing method

The sizing method aims at sorting inclusions in size categories.
The connection between amplitude and defect size can be determined using equalization processing and spherical defects of known size. In that way, experiments were carried out on a mock-up that contains calibrated hemispherical bottom holes (HBH). Figure 9 shows a mock-up containing three HBH; 0.3, 0.6 and 0.9 mm in diameter. This mock-up was used to adjust detection threshold for the inspection of the area under the running band. The echodynamic curve shows the amplitude of the echoes during the mechanical scanning.

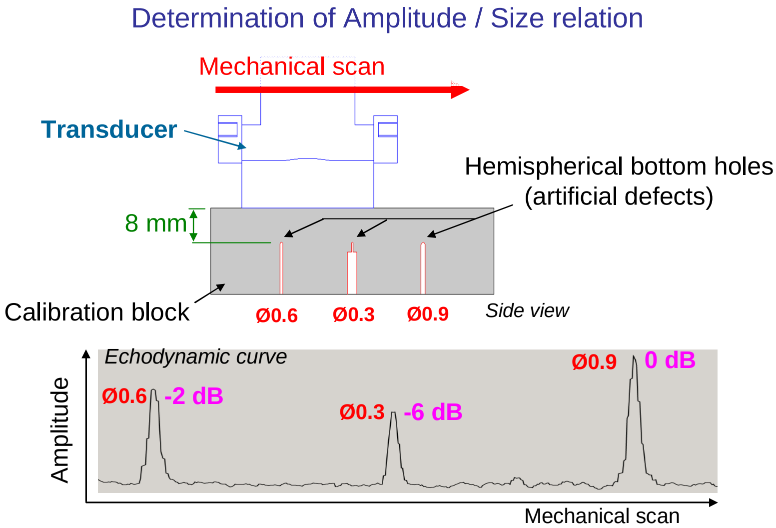


Figure 9. Establishment of the Amplitude/Size relation

Amplitude values are reported in the table 1.

Size (mm)	∅0.3	∅0.6	∅0.9
Amplitude	-6 dB	-2 dB	0 dB

Table 1. Amplitude / Size connection

From this acquisition, two thresholds are defined at -2 dB and -6 dB allowing defects to be sorted in three categories:

- Amplitude ≥ -2 dB for defects bigger or equal to 0.6 mm,
- -6 dB ≤ Amplitude < -2 dB for defects of size ranging from 0.3 to 0.5 mm,
- Amplitude < -6 dB for defects strictly smaller than 0.3 mm.

These values were validated by Radiographic Testing on real repairs including gas inclusions. Moreover, several simulation and experimental acquisitions were done to confirm the validity of these thresholds on worn rails.

3.1.2. Segmentation

The “Segmentation” tool of CIVA Software provides information such as the number of defects, the position for each one, their maximum amplitude and it makes also possible to classify the defects according to these criteria. The principle of segmentation is based on the search for coherences between consecutive signals of the same acquisition to gather them into segments (2D) then into groups (3D). Each group corresponds finally to a defect in the repair (Figure 10).

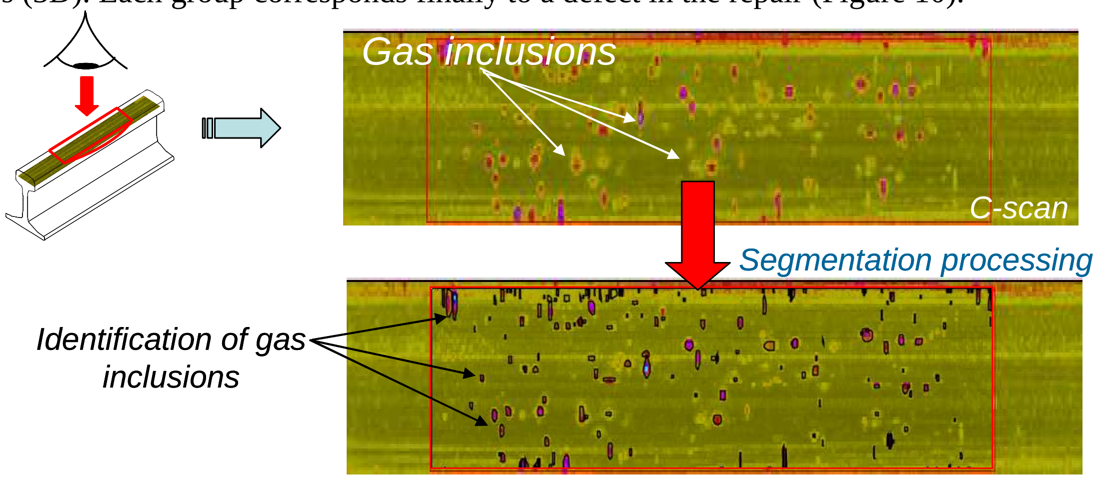


Figure 10. Procedure of segmentation

3.2. Automation tools

A new automation module was specifically developed to make the analysis of inspection easier. This module automatically performs the processing described above and provides a report containing the number of inclusions, their position and their amplitude which can be connected to the size. Moreover, this automation module can be carried out by a non-specialist operator.

4. Test campaign on tracks and first analysis

4.1. On track tests

There is no national register of all restoration carried-out on track. There is only local information about the working area but not a precise location. That is why it was decided to determine an area where it is known that rail restoration has been realised (1 or 2 kilometres area) and find precise location directly on track. Each rail restoration found has been inspected with the prototype.

In order to have a representative sample of network, 38 areas of high speed lines were inspected. One night of inspection per area (tracks are available only by night on high speed lines) was organised, so the whole campaign represents 38 nights between June and September 2008.
One night represents 5 hours of work, conducted according to this process:

- prototype set up,
- first acquisition for signal checking,
- rail restoration searching,

for each rail restoration:

- realisation date on hallmark is noted
- rail repair is carried-out as described above
- last acquisition to check that there is no drift of signal.

Nine rail restorations were inspected on average per night, so around 370 results.

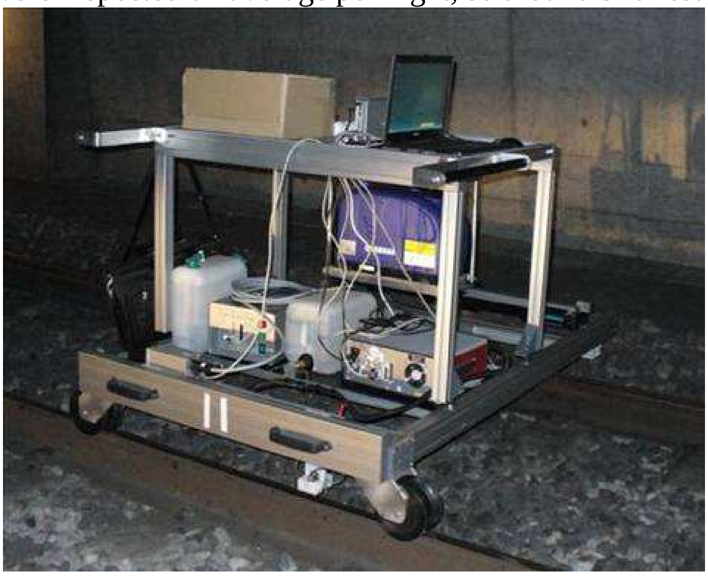


Figure 11 : On track inspection

4.2. First analysis

A first laboratory study was realised in 2000 on ten samples of broken and non broken rails, to understand crack initiation and development on rail restoration. It concludes that cracks seem to initiate on internal small porosities, more often located at the rail metal/deposit metal limit, and progress from depth to surface.
The localisation of porosities has a metallurgic explanation: welding operation involves fusion of the surface of the rail, and apparition of gas. UT observations show this alignment of gas inclusion.

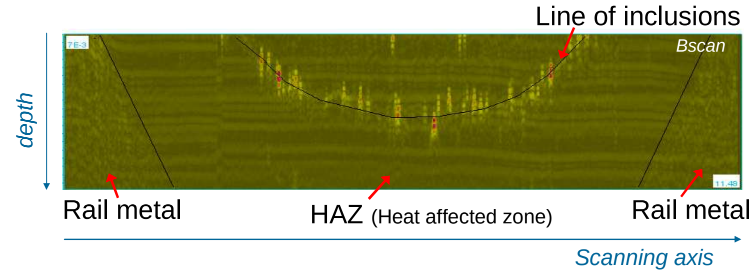


Figure 12. Line of inclusions

The first part of the analysis consists in validating the hypothesis of crack initiation and development cycle (from depth to surface). For that, recorded data of rail presenting crack will be analysed to confirm location of crack initiation (surface or not).

To make a statistic analysis of recorded data, we have to propose a representative parameter of rail damage. Thanks to conclusions of a laboratory study, we can consider that there is a link between location of inclusions and risk of crack initiation. That's why the first criterion of the analysis is the position of the porosity in the deposit.

For each recorded file, two kind of information are considered:

- Depth of the deposit: It is possible to estimate the depth thanks to the visibly limit of rail metal/deposit metal by UT.

Figure 13: Limit of metals

  It is important to note that metal deposit thickness depends on age of restoration. Indeed, metal is removed by wear and grinding, especially on high speed line. After some years, metal deposit is totally removed. A first analysis made on the 370 restorations inspected during the campaign shows that only 20% are deeper than 5 mm.

- Location of the porosities. As for depth, it is important to take into account rail age. Indeed, with metal removed relative position of inclusions from surface changes. Inclusions, located in-depth at the realisation of rail restoration, are closer to surface after some years.

The aim of statistic analysis is to try to determine an area in the depth of deposit metal, where inclusion progress as crack, maybe due to special solicitations.
Then, two kind of standard rail restoration evolution can be defined:

- There is no porosities apparition during welding process: with time, metal is removed by wear or grinding and deposit metal disappears,
- There is porosities apparition during welding process: metal is removed by wear or grinding and porosities climb up to the surface; cracks are initiated from porosities when they are at a well defined depth.

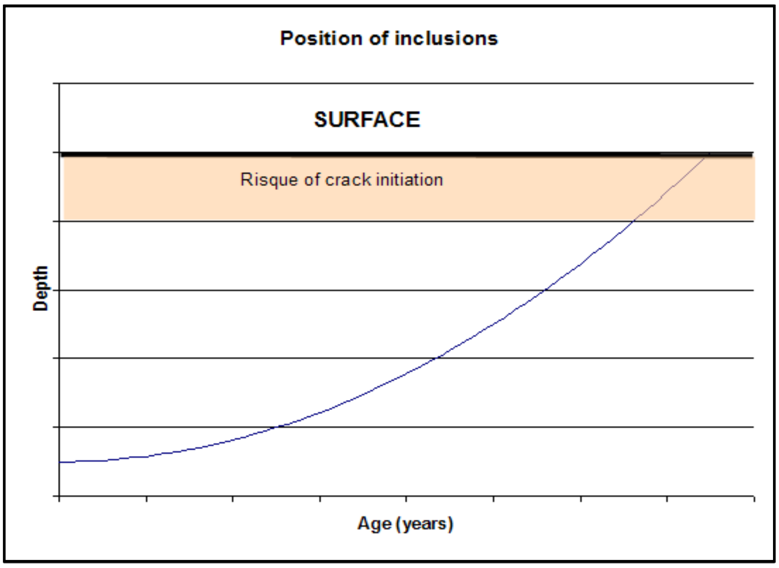
The analysis of old rail restoration already on track could be very interesting. Indeed, two categories can be determined:

- rail restoration where metal deposit near to elimination by wear ; the process of welding can be consider as well-done
- rail restoration presenting porosities, the associated question is : is there any chance that a crack could initiate on one of these porosities?

A third fictive category is rail restoration where there was crack development and rail break, and which are not yet on track.

With this statistic analysis, we could estimate:

- Location of inclusions in the metal deposit where risk of crack development exists



-

Figure 14: Risk area for crack initiation

- risk of damage of rail restoration with initial metallurgic quality

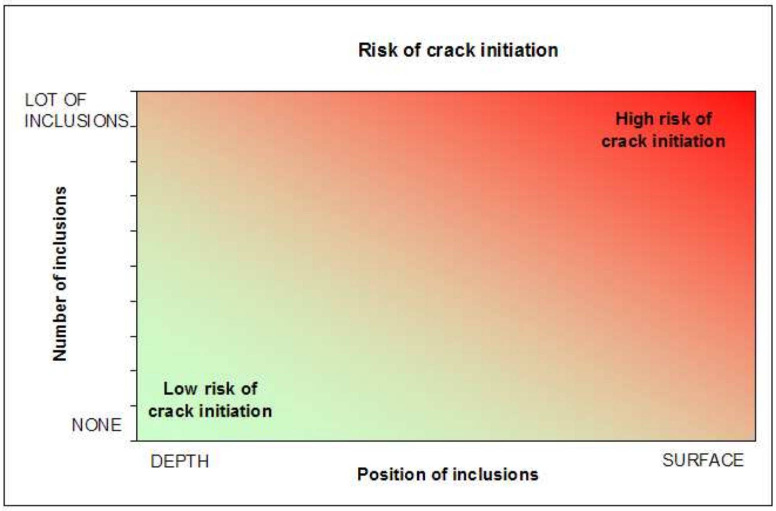


Figure 15: Risk of crack initiation

This analyse will aim at establishing a correlation between lifetime restoration and probabilities of crack initiation.

5. CONCLUSIONS

Operations of restoration are widely made on rail presenting damaged running band. Several layers of weld metal are deposited by arc-welding technique. Unfortunately, this kind of restoration can have limited lifetime, particularly on high speed lines, due to cracks initiation in welding layers. One of the main reasons of cracks development on welds is the presence of small gas inclusions

spread among the whole repair, which could then cause crack initiation under mechanical stress.
SNCF asked CEA to develop a non-destructive method and an associated instrumentation to detect gas inclusions in restorations; this method is based on UT-phased array technique. An analysis method was also developed to characterize inclusions in terms of quantity, position and size.
The developed method of inspection has then been carried out by SNCF on high speed lines, and a total of around 370 restorations were inspected. Statistical analysis realized on these acquisitions will aim at assessing the general health of restorations, and enhancing the understanding of the crack initiation mechanism.

6. REFERENCES

1. P Brédif, J.Plu, P. Pouligny and C. Poidevin: *Phased-array method for the UT-inspection of French rail repairs*, Review of Progress in Quantitative NDE, Edited by Donald O. Thompson and Dale E. Chimenti, AIP Conference Proceedings, Vol. 27A, Golden Colorado, 2007, pp. 762-769.

2. P. Calmon, S. Mahaut, S. Chatillon and R. Raillon: *CIVA: an expertise platform for simulation and processing NDT data*, Ultrasonics 44, 2006, pp. 975-979.

3. EN 15594: 2006: *Railways applications – Track – Restoration of rails by electric arc welding*, European Standard