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Development of an ultrasonic technique, sensors and systems for the volumetric examination of alumino-thermic rail welds

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RAILECT

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Final ReportSummary - RAILECT (Development of an ultrasonic technique, sensors and systems for the volumetric examination of alumino-thermic rail welds)

RAILECT is a collaboration between EU SMEs and research organisations with the objective to develop and produce a novel 'clamp-on' ultrasonic testing device for the volumetric examination of aluminothermic rail welds. The RAILECT device was developed to fit the UIC 60 European standard rail profile and it uses phased array ultrasonic technology to assess integrity of rail welds.

To date, only a few techniques of inspection have had some limited success to control the quality of aluminothermic welds. Manual ultrasonic and radiography techniques are sometimes carried out on the welds but this is not common practice in the railway industry. Generally, only visual inspection is performed because it is presented as a rapid and simple technique to control weld quality; however it remains a very subjective and superficial technique since only the weld geometry and surface defects are examined. Visual inspection does not provide a volumetric inspection of the weld and therefore critical welding defects can be easily missed. Also, visual inspection results in very high rejection rates due to the limited performance of the technique which is only based on the assessment of the weld geometry, profile and surface defects. Very often, as a precautionary measure, welds are rejected due to a geometry or profile fault although they might be internally sound. This high rejection rate can be very costly for the railway industry and can raise concerns about the validity of the acceptance criteria and therefore the suitability of the technique. The railway industry is in need of an advanced and efficient system of inspection that could overcome these issues and this is why the RAILECT system was developed and produced. It will increase safety on railways whilst reducing costs by having a more genuine rejection rate.

The RAILECT system is a reliable high performance device that can give full coverage of the rail weld and assess its integrity in a very short time. To date, the inspection can be performed in less than 20 minutes with the current prototype design. However, it is a first prototype and there is room for improvement; with further developments, a target of 5 minutes inspection time could be easily achieved.

Phased array technology is relatively new to the railway industry and therefore many developments were required to build an operator friendly and high performance system. These developments involved specifically the following:

(1) Modelling the ultrasonic beams through the weld. This was carried out using the CIVA software and validated against calibration flaws in a rail weld section.
(2) Developing acceptance criteria validated by fatigue tests of defective welds. These former were then implemented into the analysis software.
(3) Designing and manufacturing phased array probes and also defining appropriate focal laws parameters to provide optimum coverage of the rail weld.
(4) Designing and manufacturing a deployment mechanism that allows a simple clamp-on application.
(5) Developing automatic defect recognition (ADR) software that could provide a rapid sentence on the weld integrity.

The field trials carried out on Network Rail's test track confirmed that the RAILECT device is a high performance and effective product that is of considerable interest for the railway industry. It will give early identification to allow prevention or effective planned repair rather than urgent intervention, immediate fix or failure. Therefore, it will improve passenger safety whilst reducing costs for railway companies. On this basis, the RAILECT device could save millions to the railway industry and if a high number of units are sold, additional employment will be created to manufacture, assemble, distribute and operate the system. A training course and certification scheme will also have to be established and this will also generate employment. The SMEs will benefit from sales of both the equipment and the training and certifications.

After the successful outcome of the final demonstration of the RAILECT device, three of the four SMEs (Vermon, Spree, KCC) gathered under the name of exploitation committee and decided to focus all their efforts and resources towards the exploitation of the RAILECT system.

Videos of the final demonstration are available and will be accessible from the project website at http://www.railect.com The project was completed very successfully and it received very positive feedback from the end-user Network Rail. Following the final demonstration, interest from the industry has kept growing and as a result the SMEs are now in the process of finalising a patent application that will protect the RAILECT mechanical system design and methodology.

Project context and objectives:

There are an estimated 11 million site aluminothermic welds on the European rail network with thousands of new welds (estimated at 300 000 to 400 000 annually) being made daily throughout Europe. These welds form the basis of 'continuous welded rail' (CWR) that is a common feature of the European rail system. Although the aluminothermic welding technique is well proven, it is, nonetheless, a critical safety component of the rail infrastructure. An increase in rail speeds, density of rail traffic and freight train weights can now cause an increasing number of rail breaks across the European rail network.

The types of volumetric defects found in aluminothermic welds are those normally associated with gravity feed castings. They include shrinkage, hot tears, 'lack of fusion' slag inclusions, cracks and porosity. The consequences of a single failure could result in derailment causing loss of life and millions of Euros of cost.

However these welds are not volumetrically examined in any of the countries in the European Union as there is currently no suitable NDT technique due to the complex structure, geometry and thickness of the aluminothermic welds. The need for this project arises from the fact that breakages at rail welded joints occur when there are flaws in the weld. Hence, the RAILECT project is designed to deliver solutions for volumetric inspection of aluminothermic welds.

The concept of the project is to produce a 'clamp-on' ultrasonic testing device allowing to obtain a full coverage of the weld by the ultrasonic beam which will test the weld, and classifies it according to pre-determined quality criteria. A number of strategic technical objectives were determined to achieve these developments:

- to establish system specifications and industrial requirements (WP1);
- to determine performance of aluminothermic welds in presence of defect and to define acceptance criteria (WP2);
- to develop and validate ultrasonic models determining the ultrasonic beams interaction with defects and the weld metal (WP3);
- to identify the ultrasonic probe arrangement allowing full volumetric coverage of the rail weld and to design the ultrasonic system. This was carried out through modelling experiments (WP3) and experimental testing to validate the modelling results (WP4);
- to produce a prototype system consisting of:
i. a number of ultrasonic probes designed and manufactured according to the specifications given by the models (WP5);
ii. a manipulator that will position the ultrasonic probes to operate on complex geometry of the rail weld (WP5);
iii. an electronic instrument capable of driving the ultrasonic probes and performing data acquisition and recording (WP5);
iv. automatic sizing of flaws by means of the combined time domain analysis of ultrasonic signals;
v. an automatic defect recognition (ADR) software (WP6) that compares sizing with ECA results and give an output to sentence the weld;
- to validate the final prototype by carrying out laboratory and field trials (WP7);
- to produce promotional material (WP7) and a plan for use and dissemination of knowledge (WP8).

To accomplish the strategic objectives, the work activities have been organised into a number of discrete work packages. Those were divided into a data acquisition and design phase (WPs 1 to 4) and the implementation phase (WPs 5 to 8).

Besides technical objectives, economic, social and environmental objectives were also targeted in the RAILECT project.

The economic objective was to improve the competitiveness of a group of European SMEs by exploiting the technology developed within the project through companies in the rail sector. The project also helped to ensure that the aluminothermic welding carried out will not fail prematurely and will therefore reduce delays and the potential for accidents caused by rail weld failures and therefore all the costs associated to these will be considerably reduced.

The social objective was to reduce the number of rail failure resulting in accidents, injuries, and fatalities to the public and rail workers; caused by the increase in rail speeds and density of rail traffic. Improving safety and reliability of railways was one of main driving forces of the RAILECT project.

The environmental objective was to increase public confidence in an environmental friendly transport mode by reducing derailment and delays due to track faults.

In order to perform the volumetric examination of in service and new aluminothermic rail welds, it was planned within the work programme to develop an advanced ultrasonic technique, sensors and systems. The RAILECT device was to provide the only means of detecting significant defects, including lack of fusion, shrinkage, in the welded joints. The work undertaken in the project aimed to develop the following features:

- a rapid clamp on system;
- automatic deployment of the probes;
- quick interpretation of data and rapid analysis;
- classification of welds with criteria for a go / no go decision.

The main objective was to provide the SMEs in the European manufacture / inspection / maintenance industry with the ability to supply services and equipments for the transport sector, using advanced phased array inspection techniques, developed in this project. The project would therefore open up new application areas for theses SMEs.

Project results:

The first year of the project concentrated mainly on the three first work packages (WPs). In the first six months of the project, the majority of the activity focused on work packages 1 and 2. At the six month meeting, work package 1 was mostly completed and work package 2 was in good progress. At this date, the progress and achievements of the project were satisfactory. Although the work package 3 related to the modelling started slightly later than the start date targeted, the deliverables have still been completed by the 12 month meeting. Towards the end of the first year, work package 4 started also with a slight delay due to delays experienced in previous work packages. Work package 4 concerned the design of the UT system and was highly dependent on the results obtained in work packages 1, 2 and 3.

The second period of the project focused on the remaining five work packages. Work package 4 related to the ultrasonic system design was the critical path of the project plan. A lot of effort, resources and time were spent on this work package. 7 months were required to identify, select and agree the design of the ultrasonic system. Completion of the system specification (milestone 1) was only achieved month 20. The programme scheduled for the project was therefore delayed considerably. Besides these technical delays, the consortium faced multiple changes of partnership and this led the project being unable to be completed within the two year period. Due to these exceptional circumstances, the project was allocated a four month extension to achieve all the strategic technical objectives. Due to the delays caused by the establishment of the system design, system manufacture corresponding to work package 5 and software and system integration related to work package 6 were also overdue. Whilst completion of the manufacturing system design (milestone 2), was achieved month 22, the entire system was fully integrated and functioning month 26 (milestone 3).

Completion of the field trials (milestone 4) had a significant positive impact on the project outcome and success towards the end of the second year period. The final demonstration was very well received by Network Rail and as a result, the consortium and more specifically the SMEs participating to the project were very motivated for exploiting the project results (WP8). A number of dissemination activities were also carried out during the course of the second year period due to the number of developments and advancements made during this time.

Below is presented a more detailed description of the technical and scientific results for each work package.

Work Package 1: Review, system specification and sample acquisition

Review EU standard and literature (task 1.1) and System specification (task 1.2) consisted mainly of desk-based studies and discussions with the end users. The aims were to establish the industrial requirements for the system to be developed and to give an overview of the international standards and literature available for the ultrasonic examination of welded joints.

An interim meeting was scheduled at the three month period at the end user facilities with some of the partners. Discussions about the industrial requirement and the inspection system were carried out prior to a demonstration of the welding process in real conditions. This meeting helped establish the needs and constrains of the end user in using inspection tools as the one to be developed within this work programme. The final conceptual product obtained at the end of this project has to respond to industrial needs which had to be clearly identified.

Review EU standard and literature (Task 1.1) consisted of ensuring that any relevant information on EU wide specific requirements for ultrasonic inspection (including regulations and safety instructions) that existed already were incorporated into the system specification. The literature review gave an overview of the different ultrasonic methods available on the market and relevant for the inspection of aluminothermic welds. The review grouped the following methods:

- a list of relevant standards related to ultrasonic inspections adopted by the industry in the EU;
- a list of requirements for the traditional ultrasonic inspection, extracted from standards;
- an overview of the time of flight diffraction (ToFD), extracted from standards;
- an overview of the phased array technique, extracted from standards;
- a review of the beam scanning and beam coverage techniques;
- a review of the most common defects in the rails (location, size, cause, etc);
- an overview of the type of stresses that can be found in rails.

According to the literature review, three ultrasonic testing (UT) methods could be investigated for the development of the inspection system of rail welds: conventional UT, ToFD and phased array. Each of the

UT techniques was described as potential inspection method for the rail weld. The choice of the most appropriate technique was dependent on many parameters such as the type of weld, the weld geometry, the size and location of the defects, the system requirements, etc.

Besides inspection methods, the literature review also helped to determine the main critical areas in the rail weld and the type of defects relative to these areas. Five main locations in the weld were susceptible to fatigue failures. It was agreed that three types of defects in three different locations would be investigated for the rest of the work programme. Those were:

- porosity in the head area
- shrinkage defect in the web area
- lack of fusion in the foot area.

Establishment of the system specification (task 1.2) consisted of producing a document specifying the expected performance of the overall device and of the individual components. Although this task benefited from the input of all the partners, the involvement of Jarvis and Spree was essential and critical for the success of the project at this stage.

Based on discussion during the kick off meeting, it was highlighted that there were many types (i.e. size and shape) of rail. Because the scope of this work programme was to demonstrate the principle of volumetric inspection of aluminothermic welds, it was decided that the project should concentrate on one rail design. Indeed the development of the inspection technique is dependent on the rail geometry. The rail profile selected was the CEN60E1 as it is the most common and recent profile to all high speed rail networks in Europe.

It was agreed that the RAILECT device should follow the following criteria:

- be portable, the weight of the device should ideally not exceed 5 kg;
- be weatherproof and functional in inclement weather;
- be easy to operate;
- give clear indications of defective welds;
- be an integrated system with no separate laptop if possible.

Besides the industrial requirements, other specific parameters also had to be taken into account for the establishment of the system specifications. Those specific parameters were the rail configurations and geometries involved in the aluminothermic welding process. It was imperative to take those into account when designing the RAILECT device to ensure perfect fitting when deployed on site.

Task 1.3 consisted in designing and manufacturing test samples. Initially, a total of 20 samples were prepared. It should be noted that the aluminothermic welding process is a casting process and therefore it was difficult to predict the exact location and size of intended defects. The five 'non defective' samples were manufactured by Jarvis following current welding practices and procedures. Those samples were considered as reference samples for the duration of the project. The lack of fusion and porosity defective samples were also prepared by the project end-users based on their experience. The porosity defects were created by introducing water into the welding mix and the lack of fusion defects by using unaligned rails.

All samples manufactured were assessed using non destructive means, such as radiographic and conventional manual ultrasonic inspection in order to confirm the presence and/or the absence of defect. Also, it allowed comparisons between the performance of the techniques. The manual ultrasonic inspection was carried out based on the standard BS EN 14730-1:2006.

Samples with lack of fusion in the foot of the rail weld were not successfully manufactured in the first period of the project. In the second period of the project, several attempts were made to produce samples with lack of fusion defects but they all failed. The project end-users prepared another three samples later on during the project and the samples did not show any lack of fusion.

Shrinkage or hot tear defect is known in the industry to be an important problem. In rail welds, shape of the defect is known to manifest itself as a teardrop shape. Experiments were carried out by the end-user to produce this type of defect but most of them were unsuccessful. Therefore, the consortium decided that they would formulate an experimental plan to reproduce rail welds with centreline defects using artificial means. After multiple trials, a similar defect to the shrinkage defect was successfully reproduced by introducing a very small ceramic insert in the central weld line. Although this technique reproduced a very similar defective area as it would be for a real shrinkage defect, it remained an artififcial defect and the ultrasonic response for a real shrinkage defect might be different. However, given this limitation, the RAILECT system was shown to work with flaws available to represent these flaw types.

Unlike lack of fusion and shrinkage defects, porosity was relatively easy to reproduce. As a result, all the testing done during the course of the project was performed on samples containing porosity, shrinkage defect and on samples with artificial flaws such as notched and side drilled holes of various sizes and located at different depths.

The production of samples with known defects proved to be very difficult and this was a significant issue encountered in the RAILECT project. It had a considerable impact on the project advancement and results. The lack of defective samples made the developments of the ultrasonic system difficult and artificial defects such as side drilled holes and notches had to be manufactured so that the system performance could be evaluated and tested.

Three samples of each type were kept for fatigue testing whilst the two remaining were used for the validation of the inspection device (laboratory trials).

Work package 2: Determine acceptance criteria

The objective of WP2 was to produce acceptance criteria for the volumetric defects in different areas of the weld. The engineering critical assessment (ECA) were used to give information on the critical size of defects and to evaluate the severity of a detected crack. This work was then compared with the results obtained from the fatigue testing of the samples. This comparison aimed to understand which defect was critical enough for the sample to be rejected. This study was planned to be used later on in the project for the elaboration of the software.

Task 2.1 consisted of carrying out hardness measurements, tensile and fracture toughness tests for the purpose of the acceptance criteria calculations. These mechanical test results were then implemented into the ECA calculations.

The objective of the ECA (task 2.2) was to provide the theoretical defect size criteria for the different parts of the rail. Equations describing the stress intensity factors around the front of a number of crack configurations in a finite plate which are representative of the types of cracks encountered in rails were used. The crack configurations include an embedded elliptical crack, a semi-elliptical surface crack and a quarter elliptical corner cracks. These equations were derived from three-dimensional finite element analysis (FEA). The equations were used to make the ECA of the severity of a detected crack (i.e. shape and size) by having knowledge of the applied load and the fracture toughness of the rail material. In addition, having knowledge of the load history and the Paris law parameters, predictions of the remaining life of a cracked rail was made.

It was concluded that the accuracy in the fatigue crack propagation prediction depends on accurate determination of the initial size of the flaw, the fatigue crack growth coefficients and the stress range (service load). Hence, provided all these parameters are known the prediction of the crack propagation is facilitated. It was found that using the equations provided in the study combined with loading patterns on rails allowed for an assessment of the criticality of a flaw in a rail. Knowledge of the rail material mechanical properties should also provide a reasonable estimate of the remaining life of a rail when a flaw is detected.

Task 2.3 was related to the fatigue endurance tests to verify the acceptance criteria determined in Task 2.2. In parallel to the ECA study, fatigue testing on the designated samples was carried out by TWI. The type of fatigue test carried out was a four point bend and it followed the standard BS EN 14730-1:2006.

The testing started with the samples manufactured in ideal conditions (following good practice, reference samples) and then it carried on with the other samples containing defects. As expected, the samples with no defects performed well and it was agreed that the testing would be stopped after two million cycles. It was agreed that if the sample passes two millions cycles it was a 'good sample'.

As expected porosity and shrinkage defects reduced considerably the life of the weld. Moreover, high level of porosity caused the rail weld to fail very prematurely.

The time allocated for the fatigue testing was significantly underestimated. Depending on the type of defect located in the weld, some of the samples were tested for several months which delayed all the testing plans. All the tests were completed by month 23 which was very close to the initial end date of the project. Additional issues were encountered with the fatigue testing, two machines broke down and there had been a period with a lack of samples due to the difficulty to make defective samples (see work package 1). All these issues contributed to the delay of a number of deliverables since ECA and software developments were relying on the results of the fatigue testing.

Work package 3: Ultrasonic modelling

The aims of this work package were to model the output signals from a range of ultrasonic probes and defects and to provide the number and types of probes and their theoretical output signals from a range of defects. The conclusion of this work package was to define most of the parameters for the preparation of the ultrasonic system design. This work package involved inspection trials and modelling experiments. At this stage of the project, the consortium agreed that the most appropriate ultrasonic technique to deploy for the examination of aluminothermic rail welds was the phased array technique.

Task 3.1 was related to the ultrasonic measurements parameters. The ultrasonic measurements parameters of the parent and weld metals were determined. The aim of the experimental work was to determine the velocity of the waves in the rail material (ASTM E494) as well as the attenuation for both weld and parental material. The rail profile CEN60E1 had a complex shape. Therefore, both velocity and attenuation were determined using the rail height as reference.

The measurements consisted of generating either longitudinal or transverse waves in the rail and to determine the time needed for the pulse of ultrasound to travel from one transducer return to it (pulse-echo technique) after bouncing on the far side. Two phased array probes were used to determine the characteristic of the longitudinal and transverse ultrasonic waves in the rail. The transducers were both: 2.25 MHz, 0 degrees contact probes, one generating compression waves and the other one generating shear waves. It should be noted that the rail height is known and constant along the rail (i.e. 172 mm) except at the weld location. Therefore, measurements of the rail height were taken where the ultrasonic tests were carried out.

In both cases, the time elapsed between the ultrasonic pulse and the reception of the signal from the rail foot was established and the velocity calculated. Moreover, as the ultrasonic wave propagation is influenced by the microstructure of the material through which it propagates, the damping and scattering from the grain boundary of the material attenuate the wave. The attenuation was determined by examining the exponential decay of multiple back surface reflections.

Measurements were taken on various samples and at various locations. These results were essential for the development of the models in task 3.2. The aim of this task was to find the optimal configuration of ultrasonic phased array transducers for the RAILECT device. The concept of the system to be modelled was inspired from the various European and British standards for railway applications. Hence, it was agreed that a system of probes would be modelled for three specific areas of the weld: the head zone, the middle zone (named web) and the ankle zone of the foot of the weld. The standards concerned conventional single element probes and not array but because of the geometry of the rail it was agreed that phased array would be the most suitable ultrasonic technique for the inspection of the rail weld. Also, the use of the phased array method enables an ultrasonic test of the weld without mechanical scanning which agrees with the concept of the project: an automated system device allowing less qualified personal to carry out the inspection of aluminothermic rail welds for defect detection.

All the models were developed using transverse waves at 2 MHz and 5 MHz. The possible positions of the array were calculated, keeping in mind the industrial requirements on defect locations in specific areas of the rail weld. Four cases were investigated:

- position of the array for inspecting the area of the rail head;
- position of the array for inspecting the middle zone (web) of the rail weld;
- position of the array for inspecting the foot of the weld.

The results showed that the coverage by the beam depends on parameters such as the weld width and the number of probes used (one probe on one side of the weld or two transducers at opposite side of the weld). In the four cases, it was demonstrated that the coverage of the rail weld area by the ultrasonic beam was better for a weld width of 35 mm compared to a rail width of 90 mm and also when two probes (placed at opposite side of the weld) were used instead of one.

The modelling results showed that the head zone cannot fully be inspected using the configuration chosen. The top surface of the rail head was not covered by the beam. This issue was discussed at the 12 month meeting and it was agreed that this problem could be easily solved by using a probe situated on top of the rail head (at the weld location). The idea was to add a spacer, acting as a wedge, between the probe and the top of the rail weld made of Perspex or Rexolite. Then, by using a linear scan at normal incidence, defects close to the surface should be detectable. Consequently, a combination of probes will allow a full coverage of the head zone.

To find optimum configuration of the phased arrays, along with the Civa modelling, the phased array was also modelled using the finite element analysis (FEA). The FEA analysis showed that small defects were more difficult to detect using the phased array technique. The Civa and FEA modelling analysis were both done using 2 MHz transducers mainly because the FEA modelling could not be run using transducers with frequencies higher than 2 MHz.

The model validation (task 3.3) consisted of checking the capability of phased array ultrasonic testing (PAUT) for the inspection of aluminothermic welds and validating the modelling work. Various configurations of probes and inspection techniques were investigated with the NDT simulation.

The main objective was to be able to generate and propagate focused ultrasonic beams and to detect flaws selected for the project (porosity and shrinkage). For these trials, 5 MHz and 2 MHz phased array transducers were used. Moreover, a test block specifically designed for the manual ultrasonic inspection carried out in task 1.3 (based on the standard BS EN 14730-1:2006) was used for the calibration of the technique. The test block was taken from a piece of rail (400 mm long) corresponding to the appropriate rail profile (i.e. CEN60E1). Six flat bottom holes (FBH) were manufactured; five on face 1 and one on face 2.

The phased array technique was successfully deployed at both 2 and 5 MHz on manufactured samples. The full weld body from head to foot excluding the ankle and toe of the rail foot could be inspected using conventional 32 element linear array transducers located at various positions on the head of the rail. The inspection of the ankle and toe of the rail foot was not possible from the head location. Therefore, an additional ultrasonic inspection needed to be developed for this specific area of the weld. This was discussed at the 12 month meeting and it was agreed that the partners would have to decide an adequate solution in order to define the design of the system. A number of ideas were discussed, such as the use of a 2D matrix array probe located at the foot. It was decided that the various designs possibilities will be reviewed by the entire Consortium and after deliberation the most appropriate technique of inspection for all areas of the weld will be selected.

The ankle of the rail foot proved to be more complex to inspect than the weld body. Probes and laws to be used for the inspection of the ankle of the rail foot had more specific requirements than the ones used for the inspection of the head and web. The geometry and dimensions of the ankle and toe of the rail foot were responsible for the difficulty of both modelling work and experimental trials.

Because of the very small surface area accessible on the rail foot, small footprint phased array transducers had to be used to fit on top of the foot profile. Three probes (1 x 16 elements and 2 x 8 elements) were necessary for the inspection of each side of the rail weld. This configuration was validated experimentally and relatively good results were achieved.

The 2 MHz sectorial scans appeared less sharp than the ones performed at 5 MHz. This is due to the longer wavelength of the 2 MHz probe which leads to a lesser sensitivity to small discontinuities, meaning that it will be more difficult to separate a group of small discontinuities close to each other with a 2 MHz probe. Moreover, the noise levels in the 2 MHz inspection (comparing the heat affected zone in particular), made it harder to interpret the flaw signals. The modelling analysis using the 5 MHz probe showed some loss of amplitude of the foot signal, therefore the attenuation of the signal at this frequency was relatively high and this is why it was first advised to work with 2 MHz frequency probe. However, although theoretically the 2 MHz frequency should have been more appropriate to use in the final system, the experimental trials showed that better results were achieved with the 5 MHz frequency transducer. These results could not have been predicted using the modelling work and this is why carrying out an experimental validation was essential. The partners discussed this issue at the 17 month meeting and reviewing the results from the experimental study, it was agreed that the 5 MHz probe would be used for the RAILECT prototype.

Work package 4:Ultrasonic system design

The aim of this work package was to deliver a detailed design of the ultrasonic system to be developed given the results achieved in work package 3.

In order to choose the most appropriate design, the consortium had to consider a design that could provide the most effective coverage of the weld area and where data acquisition and analysis could be feasible and relatively fast. Coverage of the weld area was investigated using both modelling and experimental tests carried out in work package 3. The delivery of the system electronic instrumentation was delayed considerably and as a temporary solution of replacement, a commercial instrument named OmniScan was used. This instrument was selected because it was already owned by more than two beneficiaries of the project. This instrument was able to drive the phased array probes and perform data acquisition and recording. The OmniScan; is a portable and modular phased array instrument that can be used for manual and automated inspections.

Work package 3 showed that the inspection of the head and web of the weld could be done using two 32 element phased array transducers respectively located on top of the head of the rail weld and on top of the rail with a known offset from the weld centreline. Regarding the inspection of the rail foot, three phased array probes (with small footprint) on each side of the foot were necessary. Hence, a height phased array transducer system was found to provide optimum coverage of the rail weld from one side. In total, 16 phased array probes would have been necessary to inspect the weld from both sides of the centreline, however such as system would not be affordable but also not compatible with the electronic instrumentation which is a 128 channel system. As a result, the consortium agreed to build a half automated system that would be comprised of height phased array transducer system which would have to be deployed twice (on either side of the weld) to complete the inspection.

Optimisation of probe positions and equipment design for carrying out procedures (tasks 4.1 and 4.2) were established correlating information resulting from the modelling experiments with the results of the model validation done through experimental trials. The system had no scanning probes, the probes remained on a fixed position, and it was decided that couplant such as Ultragel II could be applied manually, dispensing with the need for a couplant delivery system (task 4.3).

Design of the mechanical clamping system and probe holder for this height phased array probe system was not trivial. Moreover, the mechanical system design had to satisfy the requirements specified in work package 1:

- rapid positioning of the scanning frame; ideally a one man clamping operation;
- use of the correct amount of pressure onto the probes to enable good contact between top surface inspected and the system wedge of the phased array probe (essential for the propagation of the ultrasonic beam in the material);
- light and portable instrument so that it can be transported easily by a single man.

Two iterations of the mechanical clamping system were produced during the course of the project. The first one was tested at the Barrow Hill Railway Centre in the UK and this demonstration showed that the first design was not well adapted for field testing. The design needed major improvements to offer a more practical clamping mechanism and probe deployment system. A second iteration was made a few months later. The clamping jig was enhanced significantly and the probe deployment was made easier. The second prototype version could be placed on the rail in a few seconds only compared to the 2 min for the initial design. This second version of the RAILECT prototype was presented for the final field trials and it was very well received by the end-user of the project.

Work package 5:Design system manufacture

Work package 5 delivered the mechanical and electronic parts of the prototype.

No major issues were encountered in this work package. The phased array probes were manufactured according to the design and specifications given in the previous work packages (task 5.1).

The electronic instrumentation that was developed specifically for the RAILECT system was not provided on time and therefore the manufacture of the instrument was delayed (task 5.2). It could not be integrated on time in the final ultrasonic system for the laboratory and field trials. Instead, as specified in work package 4, it was temporarily replaced by a commercial instrument. Note that the ultrasonic system has been designed so that when the dedicated phased array instrumentation was made available it could be easily integrated in the RAILECT device.

The deployment system, probe holders and couplant delivery for each probe was built and tested successfully (task 5.3).

Preliminary field trials were carried out at the Barrow Hill Railway Centre in the UK. The software was not developed yet at this stage; therefore, interpretation of the results had to be done by the operator directly on site. Although the ultrasonic system showed that it needed improvements in terms of the design of the clamping mechanism and probe deployment, the concept of using phased array technology to inspect the weld volumetrically was successively validated.

Work package 6: Software and system integration

The software and system integration were completed in this work package. A first version of the RAILECT software although very basic was made available and integrated on time in the RAILECT system (task 6.1) for the final demonstration held at the Rail Innovation and Development Centre.

The C Sharp programming language development environment was selected to support this software initiative as C Sharp was a widely accepted development language that was supported by many third party software vendors, and in this instance the Olympus Tomoview; software associated to the OmniScan; instrument supported C Sharp development.

The first stage of image analysis focused on separating areas of potential defect from the image background where there was no anomaly. As the rail weld was precisely located within the scan, the region of interest (ROI) could be precisely defined, and further analysis could be tailored to process just this region. The phased array ultrasonic instrument generates data using a phased array probe, and this data can be used to produce linear or azimuthal plots. After the initial requirement of import and display, the next step was to provide additional analysis. With the aim to identify and locate various types of defects, image processing methods were researched to identify porosity and shrinkage defects. An averaging filter was developed and a golden image subtraction filter was created to assist this task. The software successfully identified both defect types and automatically sentenced defects correctly.

Although functioning on the defective and non defective samples, it was recognised that the software could still benefit from additional improvements. The end user highlighted the fact that the interface would need to be more user-friendly and intuitive. The software development activities (task 6.2) have been underestimated and additional time and resources would be needed for the construction of more stable and sophisticated software.

The system integration (task 6.3) required:

(1) focal laws for the probes to be written in a convenient location for access on the laptop;
(2) installation of the probes into the mechanical system;
(3) installation of the software;
(4) construction of a housing for the system.

These three points were achieved successfully and were demonstrated during the final demonstration at the Railway Innovation and Development Centre which is also Network Rail's test track. The only system component missing was the in house electronic instrumentation which was replaced by a commercial instrument until it became available.

Work package 7: Laboratory and field trials

Laboratory (task 7.1) and field trials (task 7.2) were carried out in accordance with the planned activities. The final field demonstration took place at the Rail Innovation and Development Centre in High Marnham, United Kingdom (UK). A preliminary field trial was also carried out at Barrow Hill Railway Centre and this led to modifications of the system for the field trials at High Marnham. The final demonstration was a real success and very positive feedback was received from the end-user who was very interested in the product developed during the course of the project. Network Rail's technical team was impressed by the capabilities of the equipment. Software developments, packaging and industrial validation were the three main points that they wished the consortium could focus their future efforts on.

A lot of efforts were put into the preparation of promotional material. For this purpose, the RAILECT website, a flyer, a video of the field trials and an article for the Railway Gazette (international journal) were produced. In addition, a 3 min promotional video was also prepared for the closure of the project. This video was planned to be used as a marketing tool for the device developed. It was intentionally made a lot shorter than the first video of the final demonstration so that it could be broadcasted easily on the internet.

The final demonstration was attended by all the partners. Network Rail's involvement in this work package was significant since they were responsible for the organisation of the testing of the RAILECT system on their test track

Work package 8: Exploitation, dissemination and training

After the event of the final field trials, Network Rail expressed true interest in the RAILECT system and the decision was taken by the SMEs to:

(a) apply for a patent;
(b) write an exploitation agreement;
(c) establish an exploitation strategy;
(d) draft a business plan (task 8.1).

Although the RAILECT system was very well received by the entire consortium, it was also recognised that the prototype would benefit from further improvements before being implemented in the market (software developments, packaging, industrial validation, etc.). These improvements were considered as potential opportunities for further demonstration and research projects by the SMEs.

Dissemination of the project (task 8.2) continued although care had to be taken to avoid pre-publication of sensitive information that could jeopardise the patent application. A paper was presented at the British Institute of NDT Annual Conference and at the Institute of Rail Welding Annual Seminar. An article was published in an International Journal named the Railway Gazette and two scientific publications were published by KTU.

Training material for a pilot course (task 8.3) started being produced but unfortunately due to the overlap of a number of activities could not be finalised for the end of the project. A procedure for the RAILECT system was developed and it will be available once the patent application has been made. Also, the training was not performed mainly due to unavailability of personnel to receive the course but also because of the number of other critical activities occurring in the same period i.e. preparation of the exploitation agreement and strategy and establishment of a draft business plan.

Network Rail was really valuable in terms of networking. A lot of efforts were made by the RTDs to disseminate the project results (TWI and KTU published and presented a number of papers), the SMEs spent a lot of their resources defining the exploitation agreement and exploitation strategy to define routes to market for the RAILECT system. They also started drafting a business plan to prepare the entry to market of the system.

Potential impact:

The RAILECT project has been very successful and Network Rail's enrolment towards the end of the project has been extremely valuable and beneficial for the exposure of the RAILECT product. The field trials carried out on Network Rail's test track confirmed that the RAILECT device is a high performance and effective product that is of considerable interest for the railway industry. It is a unique system that can perform quick and simple inspection of aluminothermic rail welds. Although the system is not fully automated, it can provide volumetric inspection of the rail weld in less than 20 min (delay in the inspection time mostly due to the electronics). Moreover, it is believed that the inspection time (examination and data interpretation) can be reduced to 5 minutes with further developments.

The future of the RAILECT system is thought to be dependent at this stage on the demand and price for the device. The investment cost for such a system remains very high but this is mainly due to the electronic instrumentation that can be easily replaced by a more simple and affordable instrument. For instance, if Optel's instrument is fully compatible and validated with the rest of the RAILECT components, it could then replace the commercial instrument currently used in the RAILECT system and as a result the price will be reduced considerably.

In terms of benefits, this project will benefit the SMEs but it will also increase passenger safety whilst reducing costs for railway companies. There is currently no technique available that can perform a simple and rapid volumeric examination and give an interpretation of the weld integrity. The technique currently used is visual inspection and this, giving only an external assessment of the weld, cannot compete with the phased array system developed. Therefore, the device will hopefully save costs by reducing considerably the rejection rates (resulting from the visual inspection). It will also facilitate early identification to allow prevention or effective planned repair rather than urgent intervention, immediate fix or failure. On this basis, the RAILECT device could save millions of Euros for railway companies and if a high number of units are sold, additional staff will be required to manufacture, assemble, distribute and operate the system. A training course and certification scheme will also have to be established and this will also generate employment. The SMEs will benefit from sales of both the equipment and the training and certifications.

After the successful outcome of the final demonstration of the RAILECT device, three of the four SMEs (Vermon, Spree, KCC) gathered under the name of Exploitation Committee and decided to focus all their efforts and resources towards the exploitation of the RAILECT system. They very quickly decided to:

(a) apply for a patent;
(b) write an exploitation agreement;
(c) establish an exploitation strategy;
(d) draft a business plan.

The patent that will be applied for will protect both methodology and mechanical design of the RAILECT system. Video and other promotional materials disclosing sensitive information have been put on hold due to the patent application pending. This slowed down dissemination activities in the last period of the project. Any information about the RAILECT system, even after completion of the project, will have to be very rigorously controlled by the Exploitation Committee to protect the Intellectual Property gained during the project.

The project being completed, the RAILECT exploitation committee will make sure that rapid progress is achieved regarding the submission of the patent so that further actions could be taken for the dissemination of the promotional materials. Once the patent is applied for, further promotional material such as the video will be released in the public domain and it is expected to have a significant impact on the demand for the RAILECT system. Meanwhile, whilst the patent has not been applied for, it is very difficult to forecast the reaction, interest and demand for the RAILECT product since it has not been fully exposed to the outside world. Nevertheless, the project end-user's views (Network Rail) were already very encouraging and promising for the future of the device.

Besides the patent application, a detailed exploitation agreement was discussed and defined by the four SMEs. This agreement states the involvement of each party in the exploitation of the RAILECT project results. This document was signed between all the parties concerned so that a clear strategy could be adopted to use and develop further the RAILECT device. The RAILECT project being so successful, the SMEs saw a real benefit in establishing an agreement, especially because three of them were very keen to carry on the research on this topic and to push the RAILECT product to market. To achieve this goal, the SMEs knew that they had to seek for further funding so that the RAILECT product could be optimised and tailored to make it more marketable. The exploitation agreement clarified the situation of the intellectual property between the various SMEs and stated that the exploitation committee constituted of Vermon, KCC and Spree Engineering could go forward with any types of exploitation of the RAILECT project results.

A first draft of the exploitation strategy was defined towards the end of the RAILECT project by the exploitation committee along with the support of the end-user Network Rail. Several meetings were planned between Network Rail and the SMEs to discuss the future of the RAILECT system. The objectives were to understand where to focus the efforts once the project was completed and also to quantify the business opportunities for such a device. All the information collected was then fed into a draft business plan which was part of the exploitation strategy to establish the preparation of the RAILECT device commercialisation. The aim of the exploitation plan was to define a strategy to prepare, enhance and optimise the integration of the RAILECT device into the railway industry to ensure its successful commercialisation.

A strengths / weaknesses / opportunities / threats (SWOT) analysis was carried out to identify the main assets and limitations of the RAILECT system. This analysis was performed with a view to help the creation of a business plan. The strengths of the RAILECT system have already been identified as very valuable to the railway industry; however, in order to increase interest and need in the device, the exploitation committee will have to overcome the product weaknesses and this can only be done through additional product developments and enhancements.

Threats for the system are not very critical and they depend on the way the information resulting from the RAILECT project will be disseminated and exploited. Although dissemination activities until the patent is released will be kept minimal, the device competitiveness will have to be protected and the exploitation committee will have to have a clear strategy to keep the exclusivity on such an advanced system.

Most of the weaknesses can be solved with additional resources and time to enhance the system. The price of the RAILECT device remains very high and this is one of the major concerns. A considerable part of the final cost is due to the electronic instrumentation currently used with the system. There are already alternative equipments with simpler functionalities that have already been found on the market and these latter could lower down the final price of the system considerably.

The SWOT analysis shows that the system opens the door to many other opportunities. With further improvements, additional features can be brought to the RAILECT device and this will contribute to increase the device competitiveness.

After consulting the project end-user, the exploitation committee came to the conclusion that there were two ways the RAILECT product could be brought to market depending on the end-user requirements.

Level 1 RAILECT system:

This level 1 system will be adapted for railway companies who want to perform welds inspection in house. The inspection will be performed by existing personnel who will receive basic training on the use of the RAILECT system (level 1 only) and will follow a written procedure. In this case, the RAILECT system will have to be designed so that there is limited access to the inspection parameters and no access to data analysis. The ADR software will have to be significantly improved to show high reliability, consistency and stability since the operator will have no knowledge about data interpretation. However, all the data collected would be recorded and stored to allow a more experienced and qualified personnel to review the data if necessary.

Level 2 RAILECT system

This level 2 system will be adapted for more specialist NDT operators. These can be NDT service companies that are subcontracted by railway companies to inspect rail welds. In this case, the operators should be qualified of at least a level 2 training course on phased array ultrasonic testing and on the RAILECT system. The operator would therefore be able to access and change the inspection parameters if required to and he would also have access to acceptance criteria within the software to adapt the inspection parameters to specific procedures. Data analysis would also be done by the level 2 operators through root images or the ADR software. The RAILECT system is in this case a lot more flexible than the level 1 RAILECT system. The RAILECT prototype as it states after completion of the project is not far from the level 2 RAILECT system. With minor improvements, it could very rapidly be commercialised as the level 2 RAILECT system.

Incomes will be generated from two kinds of revenue: sales of equipment (level 1 and 2 RAILECT systems) and sales of training and certification. Note that level 1 system will need to benefit from significant improvements (software developments especially) to enhance the system automation.

In the final stage of the RAILECT project, the price of the prototype was discussed but not totally defined due to the necessary replacement of the electronic instrumentation and the additional developments needed. Many alternatives are currently being investigated and this will reduce the price of the system considerably. The objective is to be able to sell the RAILECT system for a price comprised between EUR 60 000 and EUR 80 000.

In order to prepare the entry to market of the RAILECT system, various funding schemes have been investigated depending on the type of work to be carried out. These projects will hopefully facilitate the implementation of the RAILECT product in the railway industry. The prototype has only been tested once on rail track during the course of the RAILECT project and it is essential for the commercialisation of the product to go through a validation stage and product enhancement. Among applications for other funding schemes, there is a plan to demonstrate the product in workshop and conference in Europe and worldwide so that the information can be broadly disseminated. The objective is to generate interest and increase the demand for this product.

Various worldwide, European and UK events are listed and hopefully most of them will be attended by one of the member of the exploitation committee so that the RAILECT product can be demonstrated and promoted. In parallel, various collaborative projects have been planned to be applied for so that the further validation work can be carried out. The objective of this programme is to have a marketable product in phase with the industry technical and financial requirements.

A number of dissemination activities were performed during the course of the project to expose the project results and to make the developments visible to the industry. Conferences and seminars related to rail or NDT technology were attended by the project partners and several publications and presentations were given. Articles in international journals such as the Railway Gazette, the Welding Lines or the UIC Newsletter were published. In addition, a large quantity of promotional materials was also created to circulate and advertise the project achievements to a wide audience. A website was made within the first year of the RAILECT project and t was decided that it would remain the principal internet platform where information, contact, news and developments about the RAILECT system would remain and be accessible to the public during but also after the project completion. Flyers, posters and two videos were made available as marketing tools for the project.

Dissemination activities after completion of the project were considered critical for the successful implementation and commercialisation of the product and this is why a very intensive dissemination exercise was also planned after the project completion. The objective was to use large amount and variety of promotional materials so that the RAILECT product could be exposed to a broad European but also worldwide audience.

Most of the exploitation will focus on improving the RAILECT product technically but also financially by reducing the price of the system. It has currently a relatively high investment cost product for a railway company and a more affordable price would increase the demand significantly. Reducing the cost of the product is achievable and the SMEs will work together on the necessary developments and modifications required by the actual system to become more attractive financially. In order to achieve these objectives, the next stage for the exploitation committee will be to establish a strong business plan and plan the developments required for the system to be marketable.

Project website:

The public website address for the project is http://www.railect.com/ , this website will be kept as the main platform for any communications related to the RAILECT project even after project completion.

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