Universidad
de Oviedo

ACERALIA
Corporación Siderúrgica

Centro Sviluppo Materiali S.p.A.

INGENIERÍA DE SISTEMAS Y AUTOMÁTICA

NOVEL ON-LINE SURFACE QUALITY CONTROL FOR HOT SLABS IN CONTINUOUS CASTING

ECSC Project Number 7215 - « SURFIN 'CC »

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The work presented in this session is the result of an ECSC funded project, SURFIN'CC (On-line slab surface inspection in continuous casting using novel conoscopic holography).

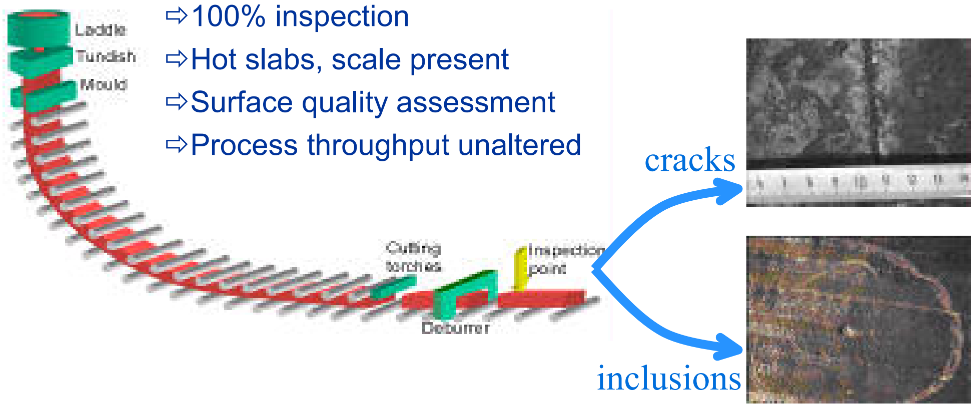
Index of the presentation

- Objectives and specifications
- Solution overview and technologies involved
- Inclusion inspection subsystem results
- Crack inspection subsystem results
- Conclusions

The presentation begins describing the problem aimed in this project. Then, we will see the solution chosen and the technologies involved, the actual results obtained so far, and the conclusions that can be derived from the progress achieved to date.

Objectives of the project

- Automatic on-line inspection of surface defects in slabs
  - ⇨100% inspection
  - ⇨Hot slabs, scale present
  - ⇨Surface quality assessment
  - ⇨Process throughput unaltered



Aceralia, according with its policy of continuous research and innovation has developed this project that, as you will see along this presentation, represents a quite new, innovative and technological breakthrough way in the field of automatic inspection.

The partners in this project - Aceralia, University of Oviedo and Centro Sviluppo Materiali - using the sensing technology provided by our subcontractor CDO, have developed a novel system for on-line detection of surface defects in hot slabs at the final stages of the continuous casting facility.

The prototype developed is able to detect, automatically, two different kinds of defects: surface cracks and inclusions/pores.

Cracks bigger than 100 mm in length (longitudinal and transversal) are detected on the entire surface of the slab without removing scale.

Inclusions and pores with diameters bigger than 1 mm are detected in a small strip, 70 mm wide, after removing the skin with a specially developed tool.

Benefits of the project

- Automatic on-line inspection of 100% of production
  - Saves storage resources and inspection operations
  - Saves energy (increments hot charge ratio)
  - Reduces surface cleaning operations
  - Improvement of process parameters and production practices
  - Possible reduction of defects due to feedback
  - Uniformity of inspection
  - Improves quality assessment

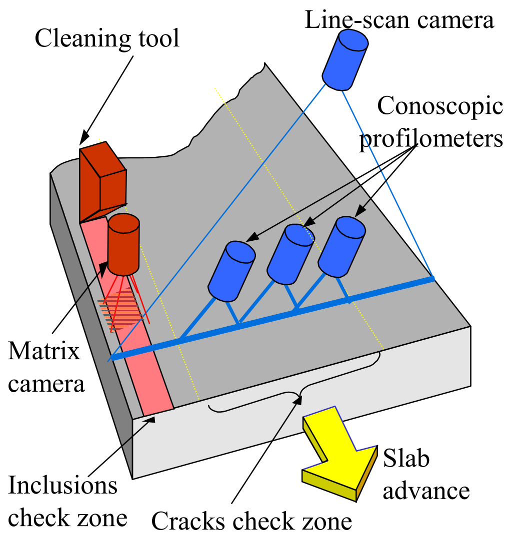
The benefits of the prototype developed are very important for the steel industry. On-line quality control of the production permits 100% objective inspection, reducing or eliminating expensive off-line manual inspection operations, and ensuring that only defect-free slabs are directly sent to the following downstream process: the hot strip mill.

This project mainly yields significant economic savings in several areas: energy, storage, and surface repair resources, as not all suspicious slabs but only the actually defective ones need to be cooled, repaired and then reheated in the following process. The economic impact can be easily calculated when the ratio between the actually defective slabs and the total number of suspicious slabs is known.

There are other additional benefits which cannot be directly quantified in economic terms, but which may become as important as the ones previously mentioned. This prototype offers the possibility of improving the process knowledge with a fast feed-back, resulting in the improvement of process parameters and production practices and, consequently, in a reduction in the presence of defects. Other important benefits to be noted are the homogeneity of the inspection, the automatic storage of the results for process traceability, and the improvement of quality assessment.

Adopted solution: two different inspection subsystems

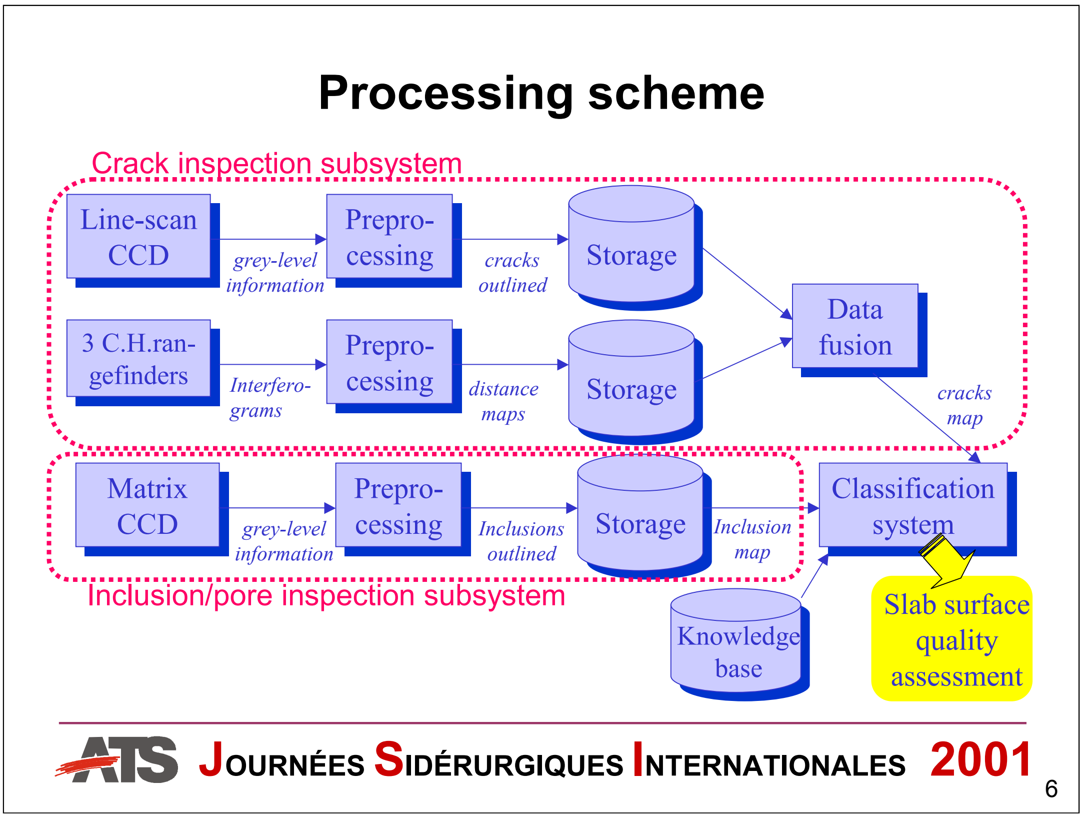
- Crack inspection
  - Full width
  - Scale present
  - Two technologies involved
    - Conventional imaging
    - Conoscopic Holography
- Inclusion pore inspection
  - Narrow strip
  - Extrapolation of results
  - Surface cleaning needed
  - Conventional imaging detection



The figure shows the set-up of the solution adopted. Two different systems have been developed for the two kinds of defects to be detected. In both cases, the system takes advantage of the normal slab forward movement for scanning the full length.

For crack detection without scale removal, a double detector system is used (indicated with blue elements in the figure). A conventional line-scan CCD camera provides a grey-level image of the slab, while several conoscopic holography based profilometers give a topographic map of the surface. The data from both sources are combined in order to produce a single indication of the position and size of surface cracks.

On the other hand, red elements in the figure concern the inclusion and pore inspection subsystem. Inclusions and pores are only scanned in a narrow strip along the slab, on which the skin is removed by means of a specially developed shaping tool. The detection is performed with a CCD matrix camera. The results obtained in this strip are a good estimate of the presence of this kind of defects over the whole width.

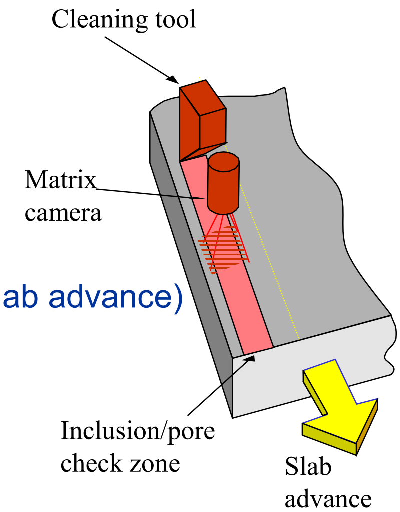


The data received from all the sensors are pre-processed on-line, using specially developed algorithms. Then, once the full slab has been scanned, the defects are outlined. Crack inspection requires a subsequent data fusion algorithm to merge results from both types of sensors. The defect maps obtained are fed to an intelligent classification system that produces a single indication of the quality of the slab. This indication is used for assigning the slab its new process route (hot charge, repair, storage) according to operator-defined rules. The inspection results are saved together with the process parameters, to enable the process engineers to exploit them for improving process knowledge, due to the feedback process.

The detection systems have been split into two subsystems as they involve different technologies: inclusions/pores inspection and crack inspection. They will be presented separately in the following slides.

Inclusion/pore inspection subsystem

- Technologies involved
  - Surface strip removal
    - ➔Developed shaping tool
    - ➔70 mm strip width
    - ➔1 - 2 mm strip depth
    - ➔12 m/min operation (using slab advance)
  - Strip scanning
    - ➔Monochrome array CCD
    - ➔640 x 480 points
    - ➔30 frames/second

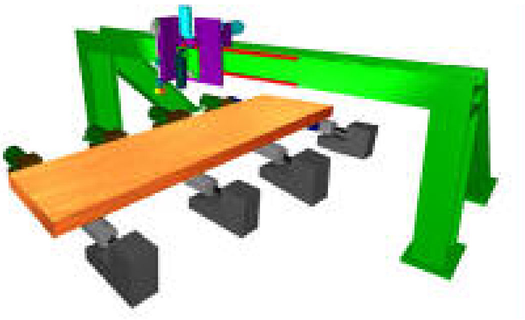


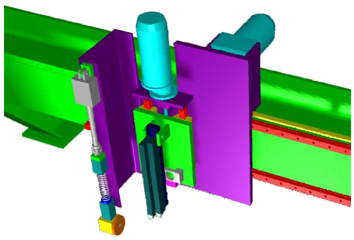
The detection of inclusions and pores requires two main technologies: a cleaning tool able to remove a 1 mm deep, 70 mm wide, surface strip; and a scanning device that enables inclusions and pores to be detected on the clean surface.

The clean strip is scanned with a CCD matrix camera, that allows the system to detect inclusions and pores, and also provides an indication of the actual speed of the slab.

Surface strip shaping prototype

- Main characteristics
  - Adapts to all slab heights and widths
  - Automatic operation
  - Smooth clean surface
  - Generates analyzable chips





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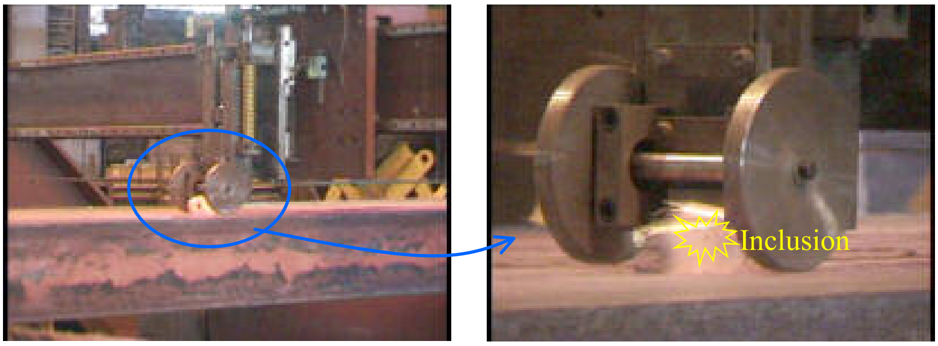
For the removal of the surface strip, shaping has been selected as cleaning technology. A novel shaping tool has been designed and constructed, permitting on-line strip cleaning with variable depth in all steel grades at high temperature, using the slab normal forward movement in the strand. The device adapts automatically to any lateral position and slab height selected.

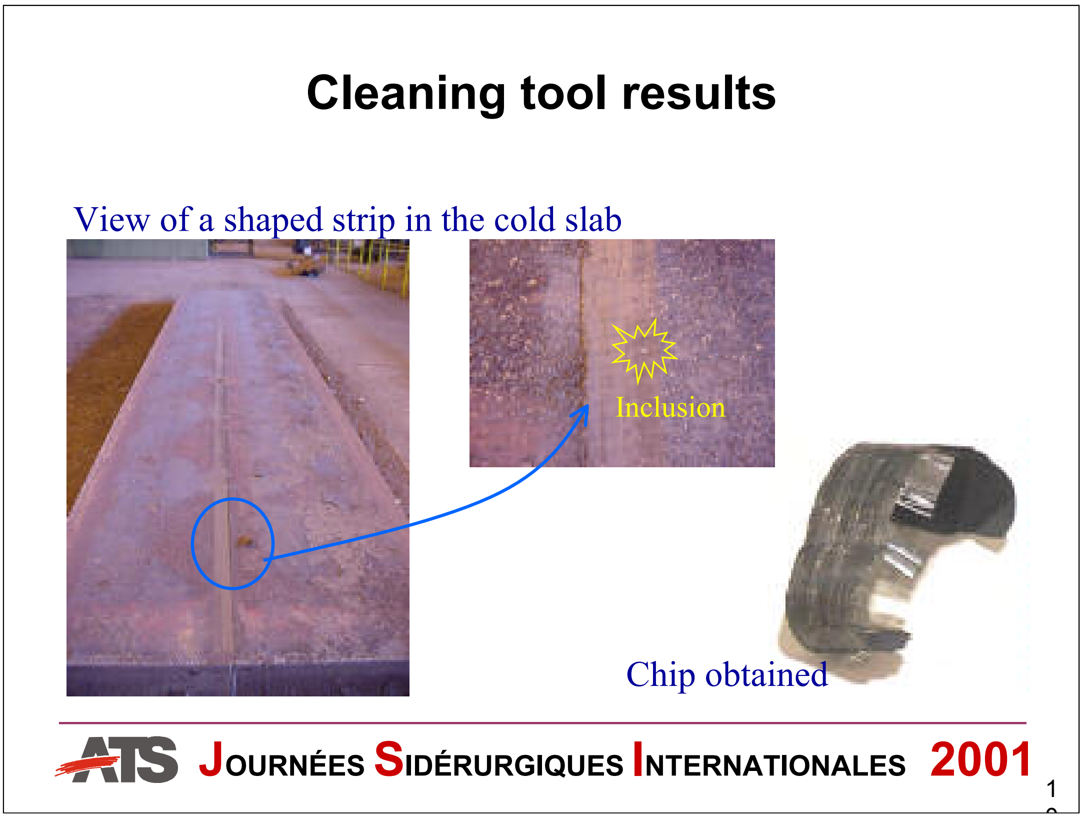
The technology used offers two main advantages over other possibilities such as scarfing. The first advantage is the uniform quality of the strip obtained. The second one is that it provides chips containing a part of the inclusion which can be subsequently used for off-line tests such as chemical analysis, very useful for determining the origin of the inclusion.

Cleaning tool in operation

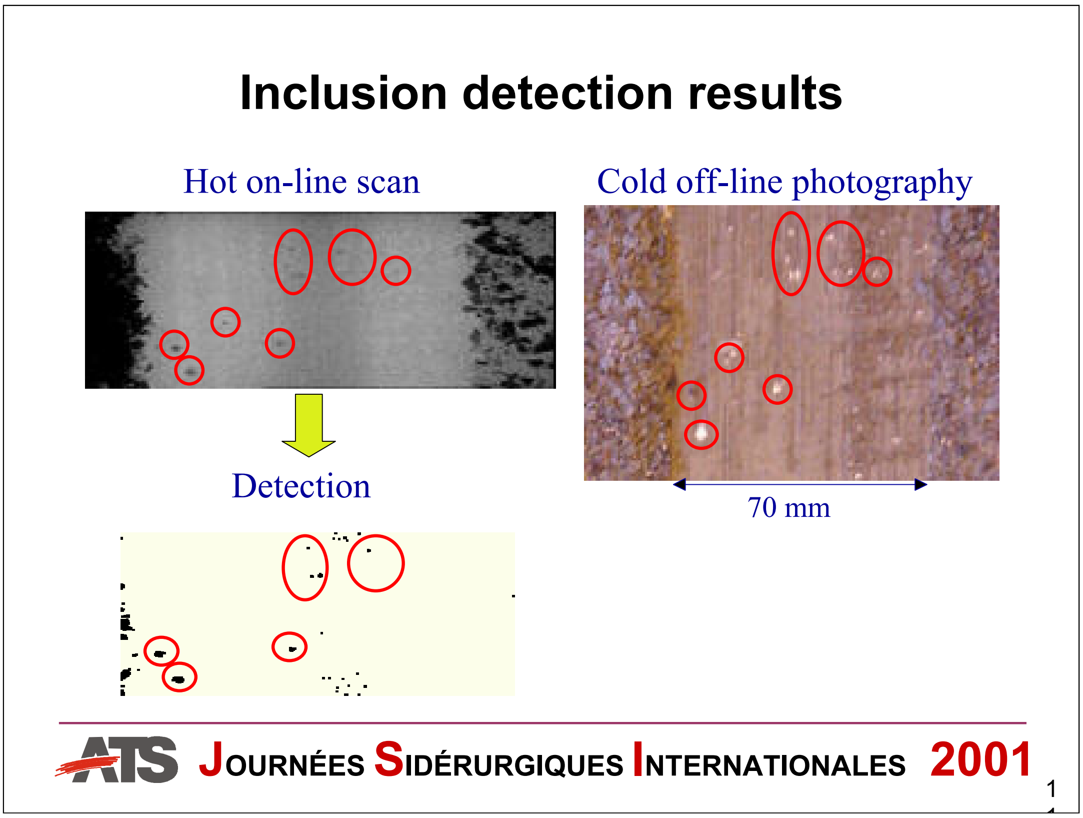
- Shaping prototype cleaning a strip in a hot slab
  - Depth selected 1 mm
  - Surface temperature 900 ºC
  - Up to 150 mm long continuous chips obtained



The results of surface removal are very good, although further effort is required in order to provide the machine the robustness needed in an industrial environment. The photographs show a real pass of the tool on a hot slab and the detail of the chip obtained. An inclusion can be seen in the chip even at this temperature.



The figures show the aspect of the cleaned strip once the slab has been cooled. Continuity and smoothness are good, and cracks emerge at the surface when the adequate depth is selected. The chip can also have important information, and some portions may be collected for further analysis.

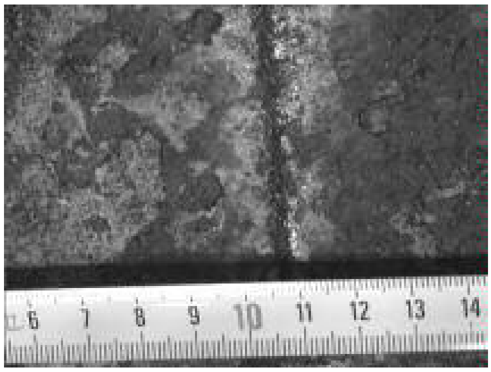


Selecting a depth of around 1 mm the inclusions emerge at the surface, enabling a conventional CCD camera to scan them and, using the appropriate filters, to detect them with good reliability. The figures show the results of the hot detection in a small zone, compared to the photograph of the same zone after the slab has been cooled. The scanning operation and the detection algorithms must still be optimised in order to produce accurate results.

Crack detection subsystem

- Favoring the detection
  - Valley around the cracks
  - Cracks interior is dirty
- Disturbing the detection
  - Scale is present
  - Variable surface aspect
  - Heat (above 700ºC)
- Technologies used
  - Conventional imaging
  - Conoscopic Holography based profilometers

Aspect of a crack



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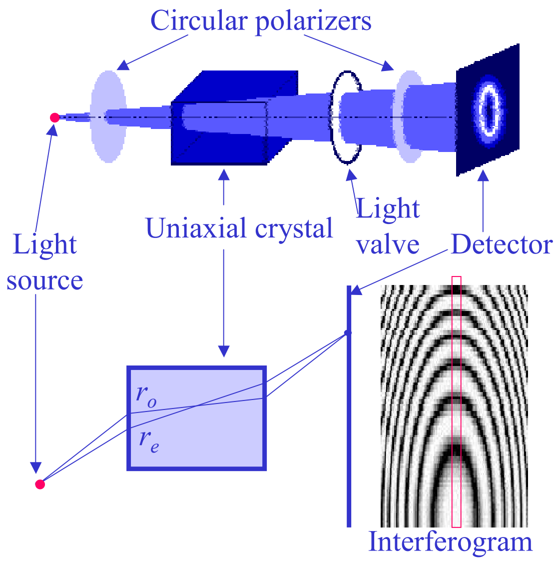
In the case of crack detection, the main problem is actually detecting the defects without removing the surface scale. Using conventional scanning techniques such as imaging, it is very difficult to discriminate scale formations from cracks, as can be seen in the figure.

A novel non-contact measurement technology called Conoscopic Holography is able to obtain topographic profiles of the surface, which are the key to crack detection, as the cracks appear in the centre of a valley that can be discriminated from scale taking into account the sense of the topography alteration.

Conoscopic holography principle

Main characteristics

- Incoherent light interferometry
- Based on double refraction property of uniaxial crystals
- Fringes frequency in the detector indicate the distance of the light emitting poing

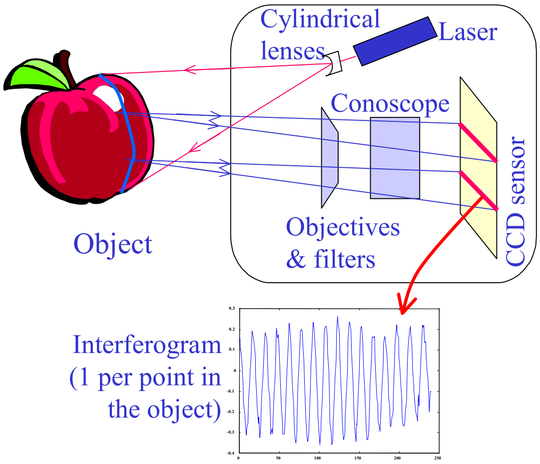


As Conoscopic Holography is not widely known, a brief explanation of the technology follows. Conoscopic Holography is an incoherent light interferometry, based on the double refraction property of uniaxial crystals. When a polarized monochromatic light ray crosses a uniaxial crystal, it is divided into two orthogonal polarizations, called ordinary and extraordinary rays, which travel at different speeds through the crystal. While the speed of the ordinary ray is constant, the speed of the extraordinary ray depends on the angle of incidence.

When both rays interfere in a detector, the interference figure formed is a Gabor Zone Lens, with the particularity that the density of the fringes depends on the distance to the light emitting point. Thus, obtaining the frequency and phase of the fringes, it is possible to estimate the distance to the point.

Conoscopic profilometer principle

Each point in the projected line has it's own separate interferogram



Main characteristics
- 1200 mm scanning distance
- 50 mm depth of field
- 300 mm aperture
- 640 pixel lateral resolution
- 0.2 mm depth sensitivity
- 30 frames/second speed

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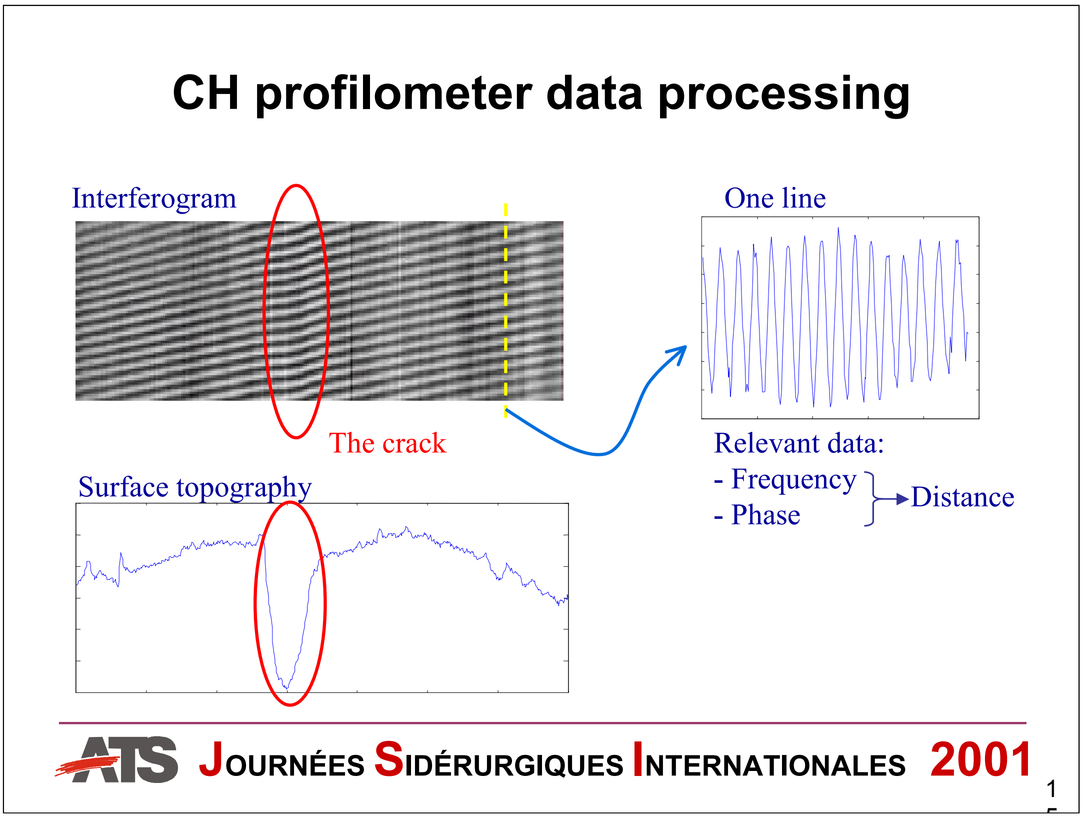
Using a laser source that provides a light plane and the appropriate optics, it is possible to obtain a device that records, in each row, the interferogram of one point in the laser line. This device is a Conoscopic Holography based profilometer. Such profilometer has been designed by CDO for this project, with a long standoff of 1.2 m and depth resolution of 0.2 mm in hot slabs.



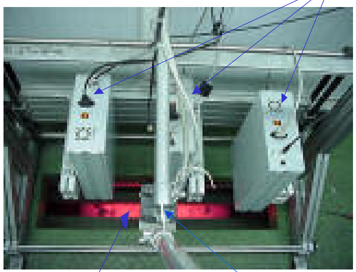
The figures in the slide show the interferogram obtained in a real case, and the processing that produces the topographic map where the crack can be easily outlined. Two important facts favour the use of this technology in this case and for similar applications: it is not affected by heat due to its co-linearity, and also the movement of the specimen enhances the quality of the measurement instead of disturbing the precission.

Crack inspection subsystem prototype

↳ System installed on-line in Aceralia facilities

External view

Internal view
of sensors



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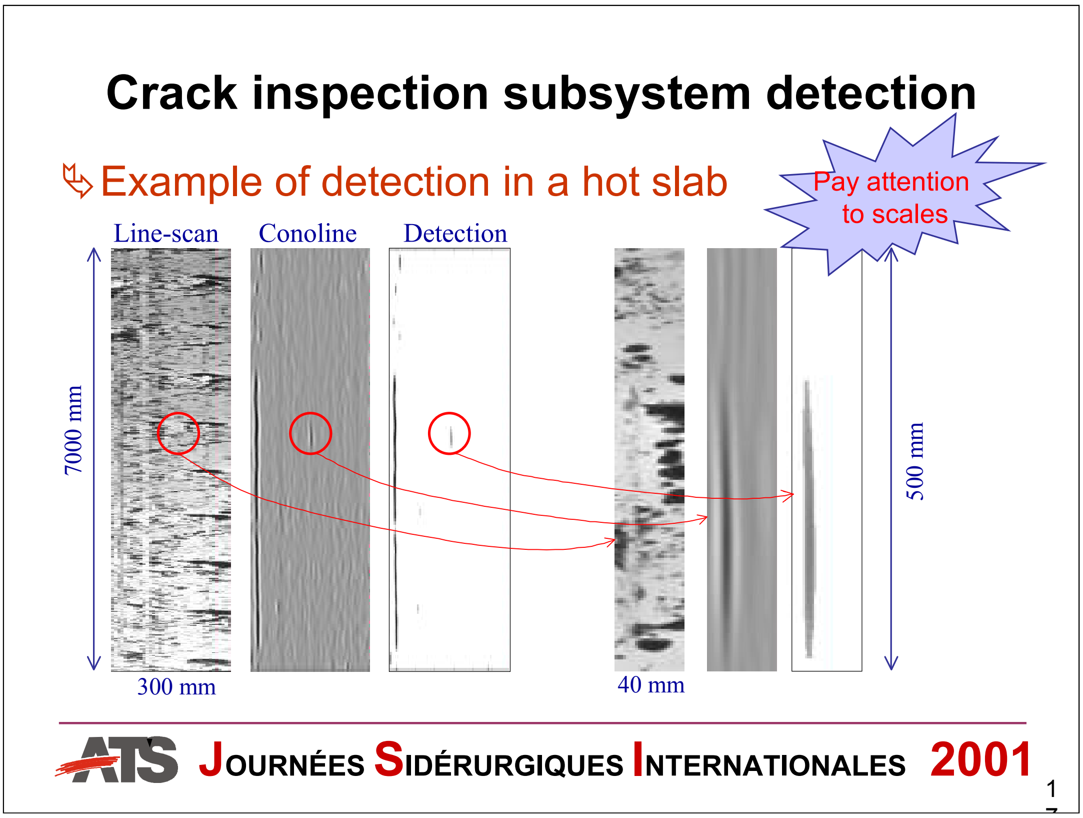
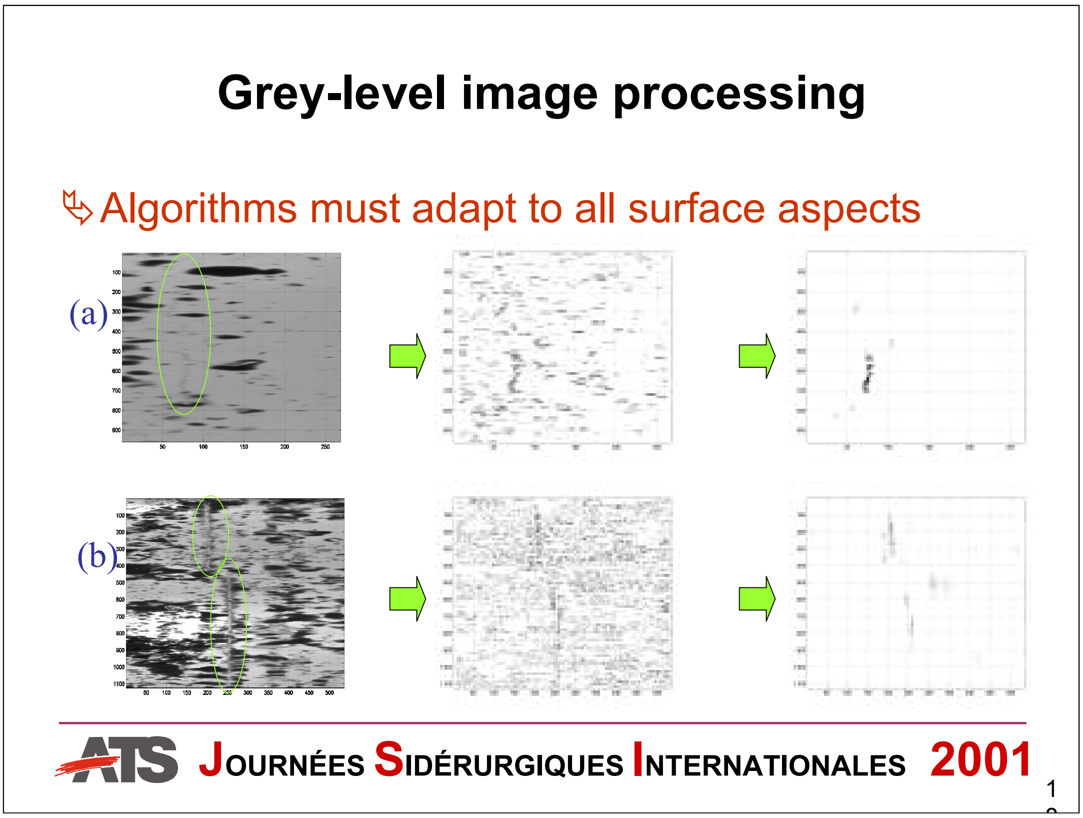
The crack detection prototype has been designed and constructed as can be seen in the figure. It consists of one line-scan CCD camera and 3 conoscopic profilometers, installed in a cooled cabin over the caster strand. The system has been installed in Aceralia's LDA continuous casting plant in Asturias - Spain, and is currently scanning hot slabs, as can be seen in the photographs. As the system requires very high processing power, several last generation PC computers have been installed in the prototype. They will be replaced by DSP cards in the next evolution of the equipment.



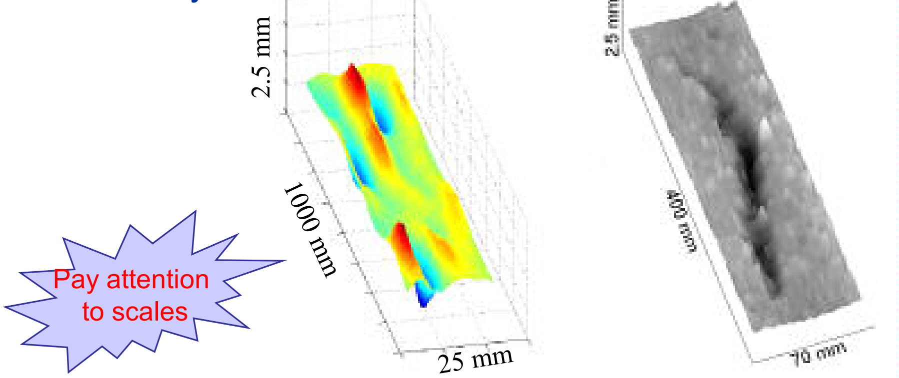
The figure shows the raw data obtained from both types of sensors when a hot slab is scanned. The slab's own radiation provides a grey-level image of the surface in the line-scan CCD, while the Conoscopic Holography sensors produce a topographic map of the same surface. As can be seen in the figure, both data are complementary and may be used to obtain a single indication of the presence of cracks.



The images obtained by the conventional imaging camera are excessively complex for automatic detection, because of the presence of scale and the different surface aspects of the various steel grades. The figures show real acquisitions from different steel grades. A specially developed algorithm is able to outline the cracks, although detection noise remains high. Anyway, the information provided is very useful and will enable the results of the Conoscopic profilometers to be confirmed. Furthermore, the image is also useful for the on-line or off-line display to the operators.

Topographic image processing

- 3-D topographic data processing
  - The depression surrounding the crack appears very clearly



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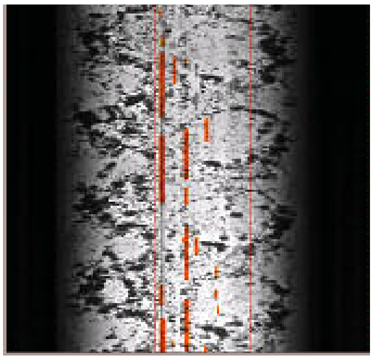
The data provided by the conoscopic profilometers are the key to the detection. The depression surrounding the cracks appears very clearly on the topographic map; thus, cracks can be easily discriminated from the scale. The figure shows the 3-D aspect of several cracks (seen as depressions in the figures) scanned by the conoscopic profilometer where this becomes manifest.

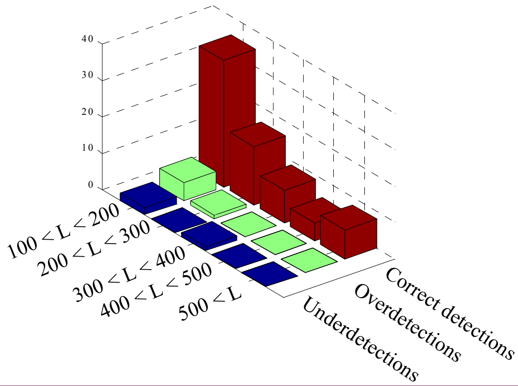
Cracks detection results

- More than 95% of cracks detected
  - Detection statistics to be improved with last CH sensors generation

Example of detections superposed



Statistics of detections



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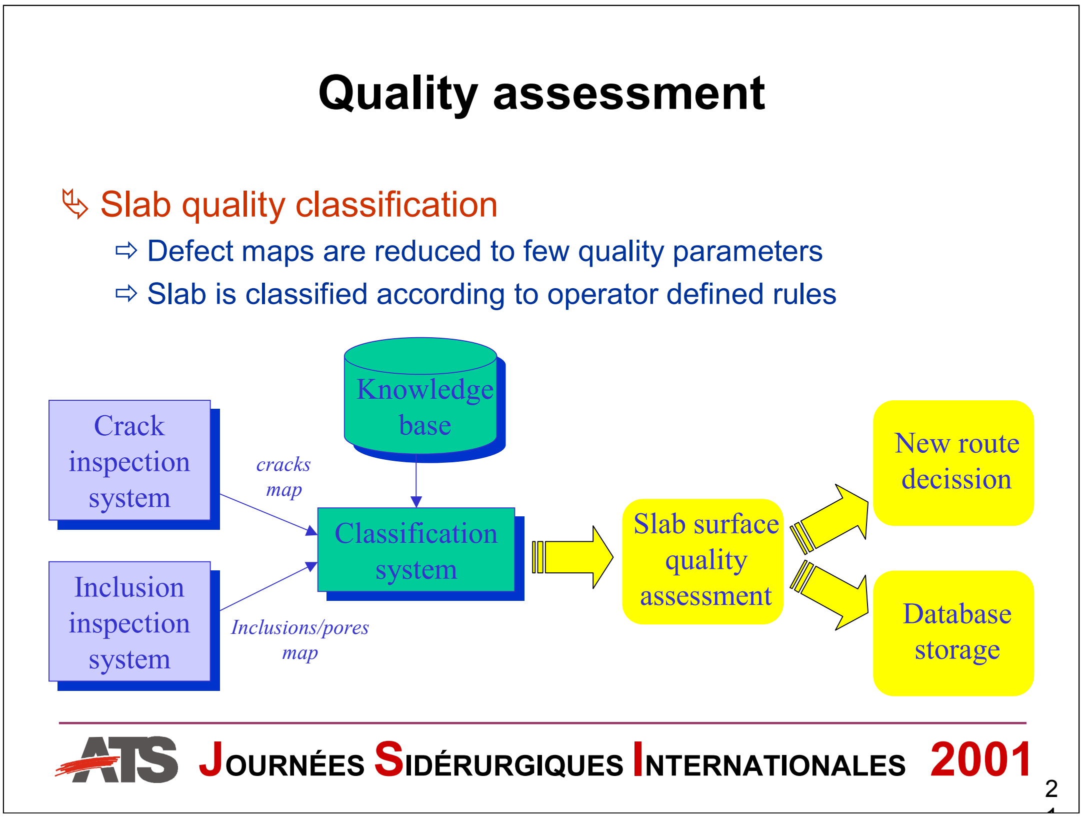
Once the results of both types of sensors are fused, a single and reliable indication of the cracks is obtained. This detection is saved in a database and can be presented to the operator, as can be seen in the figure in which the cracks are outlined over the conventional image of the slab. The detection results have been confirmed by visual inspection in several casting sequences, showing a very high rate of correct detections. For selecting the algorithm parameters, overdetection has been preferred to underdetection, as it is much less harmful for the process. It should be noted that the conoscopic sensors used for these statistics where not the final version. The latest generations must still improve the figures as they greatly reduce the noise level in the interferograms from hot slabs.



Based on operator-defined rules, the crack map and the inclusion/pore map are used to classify the surface quality of the slab. The surface quality is the final output of the system, and is used for real-time action in the process, assigning the new route to the slab (repair, hot charge, storage, etc.). It can also be used for automatic or manually assisted feedback to the continuous casting process: it is the first tool that permits the engineers to have absolute and instantaneous knowledge of what is actually happening in the production as regards surface quality.

Conclusions

- Results of the project
  - Prototype in on-line operation
  - Accurate detection of cracks and inclusions
- Benefits
  - Significant cost reductions in manual inspection/repair and hot charge
  - Improved process knowledge and feedback
- Conoscopic Holography
  - Non-contact measurement technology
  - Very useful tool for steel industry measurement and detection problems
  - Solves difficult or unaddressed problems

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The conclusions of the project can be summarized in three main points.

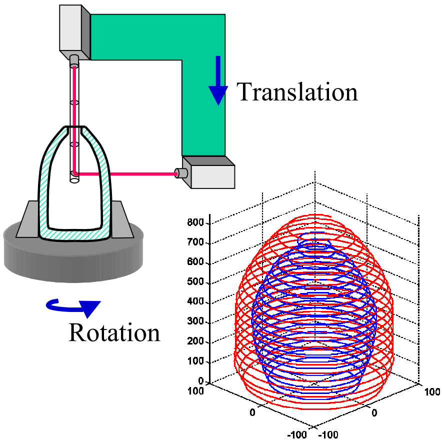
The results of the project developed are very important: We now have a prototype in operation that is able to detect cracks and inclusions in hot slabs without disturbing the continuous casting process. Although further improvements could be needed, especially in the computing hardware, the crack detection system has proven accurate and reliable in real plant conditions during several months of operation. The inclusions/pores inspection system requires some more effort for industrialisation, especially in the part concerning the peeling machine, but the initial results are very good and will be improved in the near future.

A second point concerns the benefits of the project: significant cost reductions and improvements in the continuous casting process are expected. Manual inspection and automatic or manual surface conditioning will be reduced as only defective slabs will undergo these operations; consequently, hot charge ratios can be improved resulting in energy savings; and the improved process knowledge will lead to a substantial reduction in defects produced.

Finally, some words about the basic detection technology, conoscopic holography. This novel non-contact measurement technique has proven a very valid tool for the steel industry, as it is able to operate in the harsh plant conditions with high accuracy.

Conoscopic Holography

- Internal surface scanning



- Variablerange and precission
  - Ranges from hundreds of µm to hundreds of mm
  - Precissions from several µm to hundred µm
  - Sub-micron precission under preparation for roughness measurement
- Variated configurations
  - 1-D measurements
  - 2-D one-shot profilometry short and long stand-off
  - 3-D one-shot (in preparation)

Other projects developed using this technology confirm these results, providing a wide range of solutions for several types of measurement and detection problems. For instance, the co-linearity of the technology gives access to internal surfaces by means of a periscope, a technique that is being used to measure the internal surface of cannon shells using a 1-meter periscope with an accuracy of 0.1 mm. It also provides the possibility of working at long distances, working on hot material, and taking 2-D measurements in a single shot. The measuring range of conoscopic holography devices can be easily adjusted using different optics, being able to operate at short distances on cold material. This last feature is currently being used in a project focussed on roughness measurement in the galvanising line, aimed at providing 3-D roughness measurements on the line.