An innovative on-line hot slab inspection system, integrating novel conoscopic holography, is able to determine the slab quality in real time. This system, which operates in the real environment of an industrial continuous casting facility, allows hot slab inspection, detecting on-line cracks-and inclusions in the product. The new integrated system is an important technological breaktrhough.

New technology for on-line surface inspection in continuous casting

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In the current global economy framework, the steel industry is evolving in a complex market, and the long term success requires an ongoing excellence in the development and implementation of new products or technologies, as well as in the assessment of their impact on the production processes.

This is a key factor for ensuring a sound technological position, aimed at obtaining a competitive, differentiating and sustainable advantage on which the company builds its leadership, providing the push required for its future.

ACERALIA is investing heavily in technological development in order to guarantee it's capacity to manufacture high quality products in modern facilities.

On-line quality control of the production is becoming a key factor for cost minimization in any industry. Full on-line production checking gives many benefits: early detection of defects in the product and problems in the process, providing rapid feedback, reduced costs due to rejections, reduced customer claims, etc.

In a Continuous Casting steelmaking facility, on-line production inspection adds to the above benefits a very important factor: energy saving. The defect-free steel product can be directly hot charged in the following process (hot rolling), whereas the product susceptible of having defects has to be cooled and checked prior to sending it to the rolling mills.

A new and advanced technology for hot slab surface inspection has been developed and installed in ACERALIA (Spain). This project was funded by the EU ECSC-Steel Programme.

An innovative on-line hot slab inspection system, integrating novel conoscopic holography, CCD cameras, a complex mechanical system and intelligent tools is able to determine the slab quality level in real time.

This system, which operates in the real environment of an industrial continuous casting facility, allows hot slab surface inspection, detecting cracks -without removing the surface scale- and inclusions (for which a small band on the upper side of the slab is cleaned).

The new integrated system is an important technological breakthrough. The new technology offers a wide range of possibilities for implementing an automatic surface inspection system, which will enable the steel maker to raise productivity, assess the surface quality level of the slabs and increase hot charging in the following downstream facility (hot strip mill, plate mill), thus achieving a substantial cost reduction and improving the yield of the process.

The implementation of this new system allows the hot charged to be increased, resulting in a reduction of energy consumption and improvement of the environmental impact, thus creating the framework required for sustained development.

Objectives

The production of slabs in a continuous caster is an intermediate step in the steel making process. Various defects may appear in the product (slab) at this stage, which can lead to problems in the subsequent manufacturing stages.

Thus, it is of utmost importance to guarantee the quality of the product and to ensure that the slabs sent to the following production process are absolutely free of any surface defects.

For that purpose, ACERALIA has developed a project aimed mainly at on-line inspection and diagnosis of the surface of hot slabs without the removal of surface scale. This system enables the status and quality level of each slab to be assessed, so increasing the hot charge capacity in the following stage of the process (hot rolling), and improves process knowledge, due to the automatic feedback.

Out of all the possible defects, surface defects are the ones most likely to occur and, apparently, the easiest to be detected. Surface defects are mainly of two types: cracks and inclusions/pores. We will focus only on surface defects in this paper (see figures 1 and 2 below).

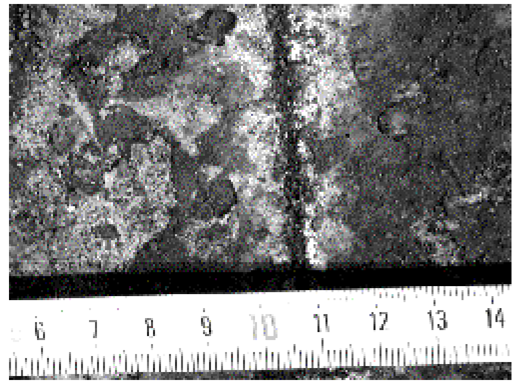

Fig. 1 - Longitudinal crack

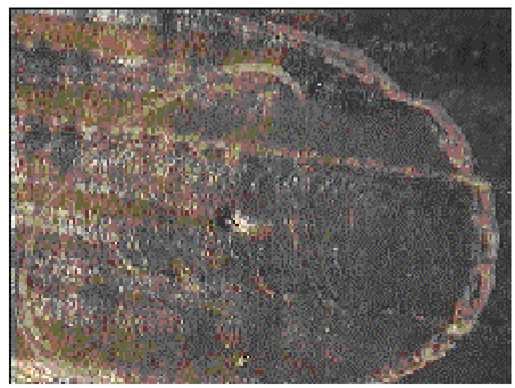

Fig. 2 -Inclusion

The economic and environmental impact of inspecting suspect slabs which turn out to be defect-free is significant: in the actual inspection way, the slabs must be cooled to ambient temperature (which takes about 3 days' storage), visually checked by an operator, and then reheated at the entry to the hot rolling process.

On-line assessment saves this cooling and inspection time, allowing the defect-free material to go on to the following process without a significant temperature loss. Therefore, this inspection system performs an on-line assessment, providing, in a matter of seconds, an indication of what to do with each inspected slab: conditioning or hot charge.

Data base storage of the results of the inspection, together with the process parameters, enables the process engineers for a better knowledge of the causes of the appearance of the different defects, allowing a valuable process feedback that will redound in surface conditioning costs reduction and a better product quality.

The conditions in which the product has to be inspected are the major problem in defect detection: the inspection system must operate on-line for 100% of the production, i.e., it must detect defects on a moving, scale-covered slab at more than 700ºC. Overdetection is preferred to underdetection, as its impact on the performance of the overall process is much lower.

General description

Due to the process conditions, it is clear that surface contactless NDT techniques must be used to reliably assess the surface quality of the slabs on-line.

In this project, two technologies have been used: conventional imaging and conoscopic holography-based rangefinders.

Conventional imaging—

This wide-spread and well-known technique is used in many fields: a camera takes colour or grey-level images of the surface being inspected; these images are digitalized and fed to an algorithm which processes the data to highlight the desired parts of the scene (the defects in this case).

For this application, conventional imaging by itself is not a reliable solution. The presence of scale on the surface of the slabs makes it almost impossible to produce an algorithm that clearly discriminates cracks from other surface formations. Figure 3 shows an image obtained of a hot slab, where this difficulty becomes evident.

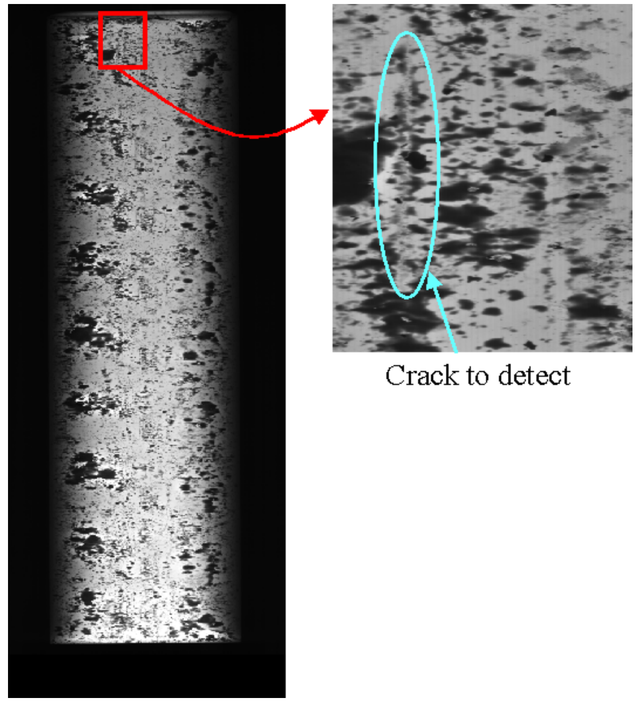

Fig. 3 - Image of a crack in a hot slab

Although conventional imaging provides very useful information, other techniques are required to achieve reliable defect detection.

Since the defects are alterations in the surface, topography can be used to detect them by means of a no-contact distance measurement technique. In this case, defects can be 'easily' discriminated from scale, as the variation of distance is in the opposite direction (measured from the slab surface).

The no-contact measuring technology to be used must have the following characteristics: line measurement (profilometer), long working distance (above 1 m), able to work with hot product, good discrimination (around 0.2 mm) over a small working range (20 mm). Only one technology can currently fulfil all these requirements: conoscopic holography-based rangefinders.

Conoscopic Holography—

As conoscopic holography is not widely known, a brief explanation of this technology follows.

Conoscopic holography (referred to as CH in the following) was developed by Prof. Gabriel Sirat and Prof. Demetri Psaltis at the California Institute of Technology.

CH is a form of incoherent light interferometry, based on the interference that occurs between ordinary and extraordinary rays into which polarized monochromatic light is divided when crossing a uniaxial crystal.

The interference figure is a Gabor Zone Lens that can be captured by a standard CCD camera. Once the interferogram has been processed, the distance to the light emitting point can be obtained. Figure 4 shows the scheme of the conoscope.

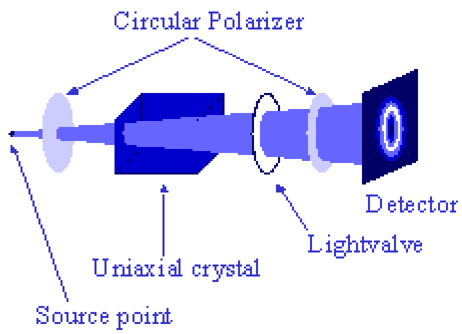

Fig. 4 - Scheme of the basic conoscope

The light for illuminating the point is provided by a laser source installed inside the sensor.

This technique has many advantages over its competitors: it is completely collinear and very accurate; the range of measurement can be easily changed (by simply exchanging lenses); it can measure surfaces with a slope of nearly 90º.

Using appropriate optics, the laser ray can be expanded to form a line, and the CCD sensor can acquire one interferogram for each point in the line. By processing the array, a complete measurement of the profile of the object is obtained. The sensor with this configuration is called conoline (figure 5).

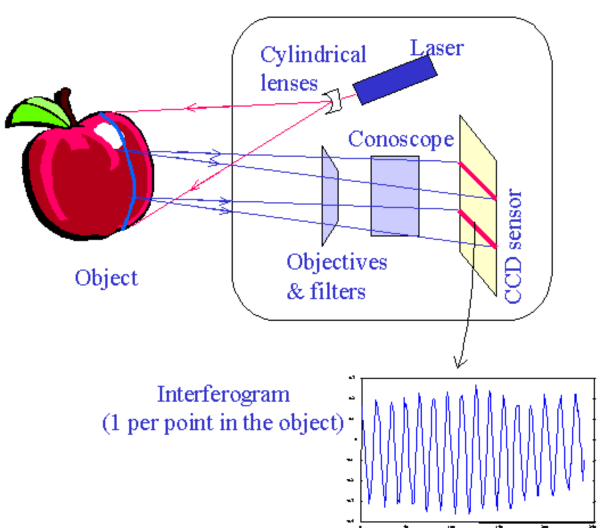

Fig. 5 - Simplified scheme of the conoline

Figure 6 shows the output of the conoline for a sample object.

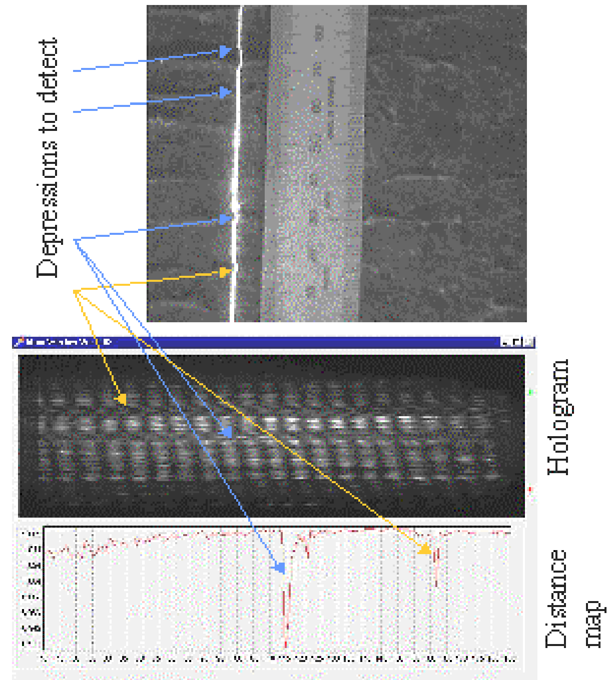

Fig. 6 - Results from the conoline

Optical structure

The layout of the elements in the system for on-line slab inspection in continuous casting is shown in Figure 7. Both conventional imaging techniques (line scan and CCD array cameras) and conoscopic holography rangefinders are used. The complete slab surface is captured taking advantage of its advance on the rolls.

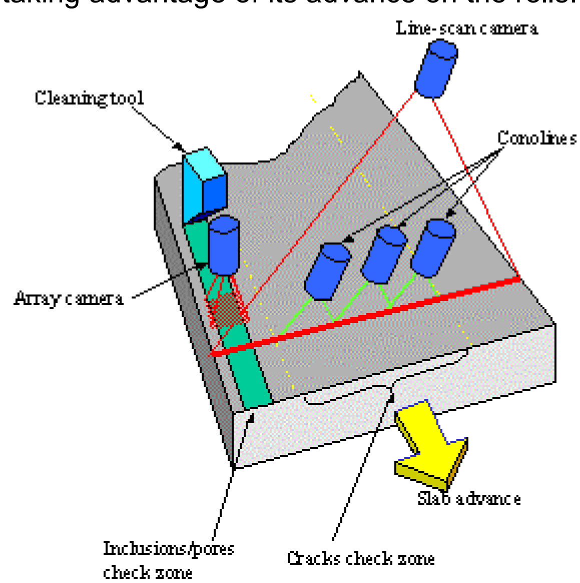

Fig. 7 - System architecture

Cracks appear in the central 2/3 of the width. Longitudinal cracks are more common, although transversal ones can also occur. The cracks to be detected are those longer than 100 mm. Scale is present, so the two types of sensors capture the scene as described below:

- One linescan grey level CCD camera (1000 lines/second, 0.3 mm transversal resolution) gives a light intensity image of the surface.
- Three conolines (30 lines/second, 0.3 mm distance resolution, 0.3 mm transversal resolution) give a topographic image of the surface.

Inclusions and pores can occur anywhere in the slab surface, but it is enough to check them only in a narrow longitudinal strip near the edge all along the slab, and then extrapolate the results to the full surface. As neither defect appears on the surface but lies about 1 mm beneath the skin, a peeling mechanism is needed for their detection.

Shaping has been selected as the 'peeling' technique, as it provides a very smooth surface in comparison with other usual methods such as blow-torches.

The minimum diameter of the inclusions and pores to be detected is 1 mm. This makes it impossible to use conolines for their detection, due to the acquisition speed (30 lines per second, which means that, at a process speed of 10 meters/minute, one line-scan camera integrates 5.5 mm in down web direction).

In this case, the absence of scale on the surface allows only conventional imaging to be used for detection. A CCD array camera is used for this purpose, as it can be applied to the upper or lower surface. It also serves for measuring the instantaneous slab speed.

Technical development

The information from the various sensors is processed by the computing system, which has to treat a huge volume of data in order to produce a single indication of the slab's surface quality.

The hardware configuration required for this task (see figure 8) includes several computers for data acquisition and processing, communications between them and with the slab yard process computer, as well as an interface with the inspection system hardware (in charge of camera positioning, control of the cleaning system for inclusion detection, and other auxiliary sensors required).

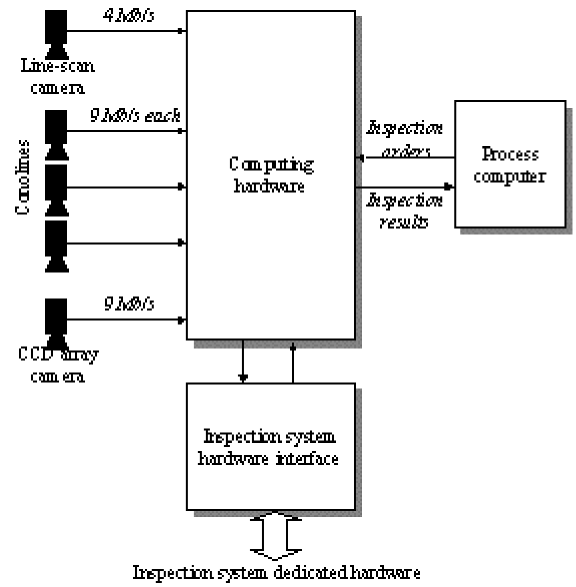

Fig. 8 - Sensors and hardware setup

The key point for all the processing algorithms is that they must operate in real time, as the response from the system must be produced only a few seconds after the complete slab has passed under it. This allows the inspection system to be installed in the production line without reducing its throughput.

Figure 9 shows the processing scheme.

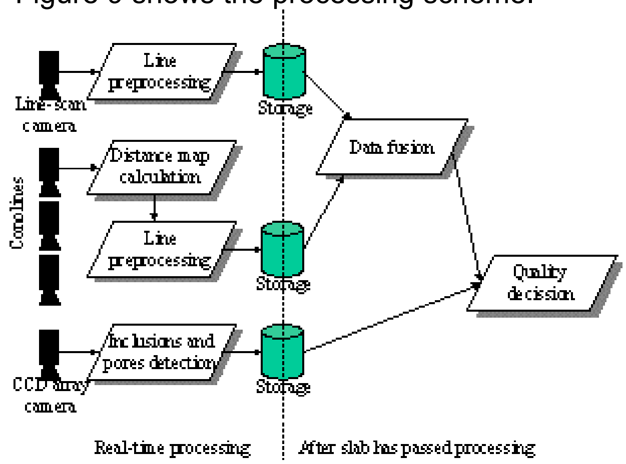

Fig. 9 - Processing scheme

- The line-scan camera pre-processing algorithm filters the light intensity data, eliminating the scale and outlining the cracks. This is a highly complex task for a conventional filter, as can be seen in figures 3 and 12. A novel algorithm has been developed for this task, with several parameters that can be tuned to achieve a good balance between false detections and individual cracks. This algorithm produces a preliminary map of the cracks, showing their location and the degree of probability.

- The lineprobe data processing is a two-step process: calculation of the distance from the interferogram and filtering the distance data, in order to outline the cracks. The output is a second crack map, with the same features as the previous one.
- An intelligent data fusion system, based on Neural Network Technology, merges the results from the previous maps into a single map of cracks with a probability of close to 1 (100% accuracy).
- At the same time, a shaping tool cleans an 80 mm wide, 1 mm deep strip on the surface, which is scanned by a CCD matrix camera. A third algorithm processes this information, producing two results: a map of inclusions and pores, and an estimate of the instantaneous speed of the slab.
- In the last stage, the final map of cracks and the inclusion/pore map, together with other process information (steel grade, slab dimensions, etc.) are used to determine - according to predefined rules - the slab surface quality and, consequently, its route can be changed from the one previously foreseen.

Current results

Currently, the project is divided in two parts: the detection of longitudinal central cracks system and the detection of inclusions/pores. Both systems are installed and in operation under real production conditions in the Continuous Caster of Aceralia's steel making plant in Aviles (Asturias – Spain).

Cracks detection subsystem—
Figure 10 shows a global view of the cabin housing the Cracks Inspection Prototype installed in the line, and figure 11 shows a detail of the sensors scanning a hot slab.

Fig. 10 - System installed in the continuous casting strand

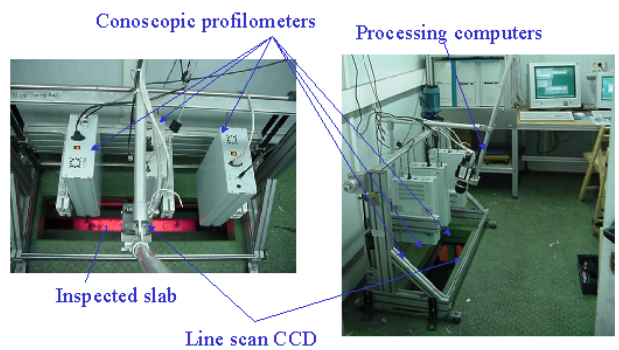

Fig. 11 - Detail of the sensors

The first detection results obtained in the plant are very satisfactory. Figure 12 shows the image of a 7000 x 300 mm portion of a slab, seen both by the line-scan camera and by the conoline.

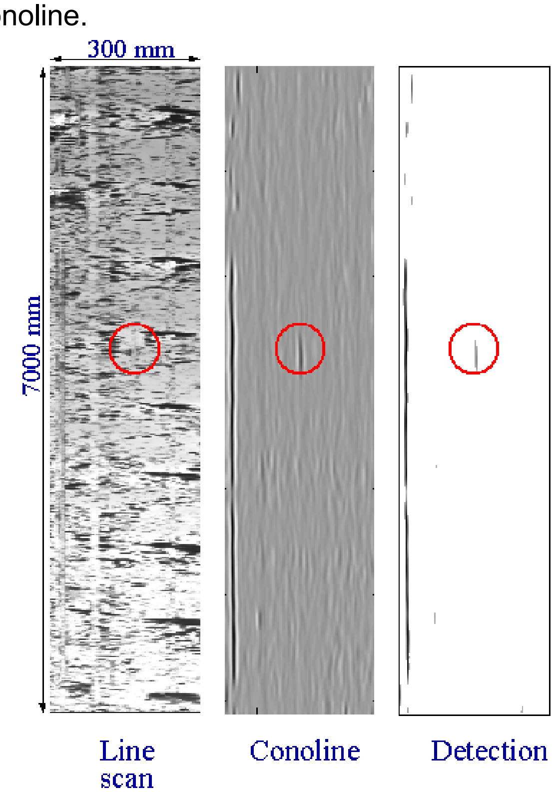

Fig. 12 - Results of detection

After both images have been processed, the results are combined giving a single reliable detection. Figure 13 shows in more detail the crack outlined in the previous figure.

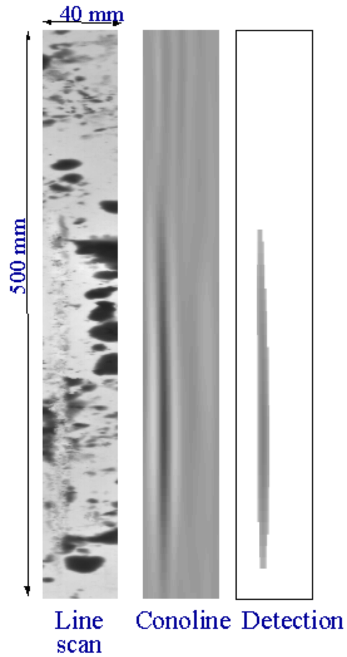

Fig. 13 - Detail of detection

The cracks inspection system has been continuously working on-line since January-2.001, yielding very good results. Detection of cracks over 200 mm is almost 100% reliable, while smaller cracks are detected with a confidence of above 90 %. Fig 14 summarises detection statistics from suspicious slabs produced in several casting sequences.

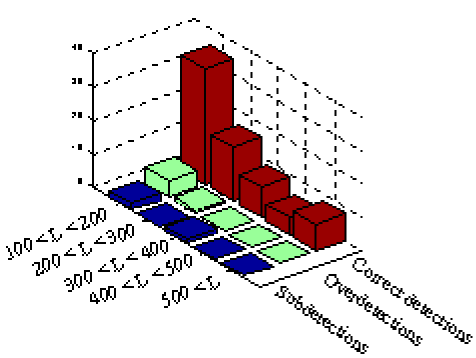

Fig. 14 – Statistics of detections

It should be noted that, in the last months conoscopic sensors have been refurbished and installed, producing much better results in hot slabs. Figure 15 shows the improved sensitivity in the topographic map with the new sensors. Results with these new sensors have improved the detection of small cracks.

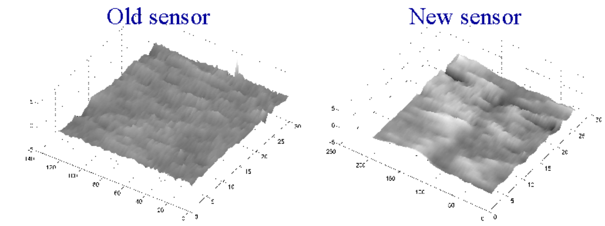

Fig. 15 – Improvement of sensitivity in hot slabs with new conoscopic sensors

Inclusions detection subsystem—
Inclusions detection has been a very difficult development, due to the cleaning tool needed. A shaping system has been designed, constructed and installed in the line, being able to remove a 80 mm wide and 1-2 mm deep surface strip all along the edge of the slab. Figure 16 shows the cleaning system in operation, and figure 17 shows details of the cleaned strip on the surface of the slab.

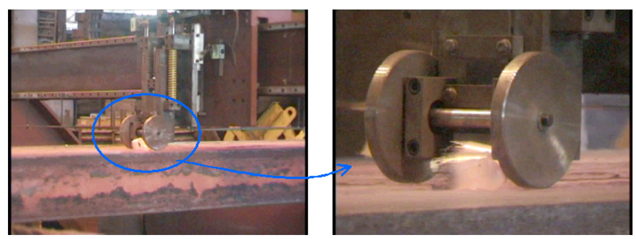

Fig. 16 – Strip cleaning system working on a hot slab

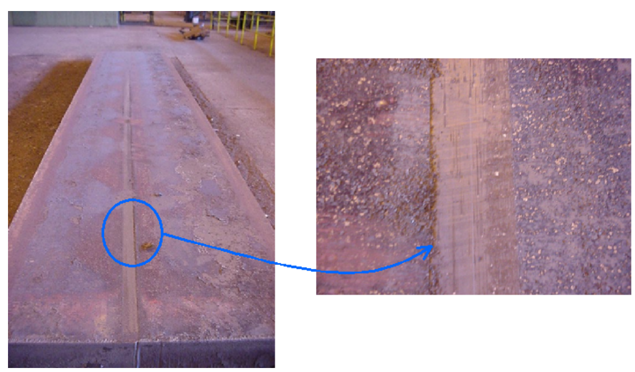

Fig. 17 – Aspect of the cleaned strip

A monochrome CCD matrix camera installed just after the shaping tool scans the strip, obtaining the inclusions map that can be seen in figure 18.

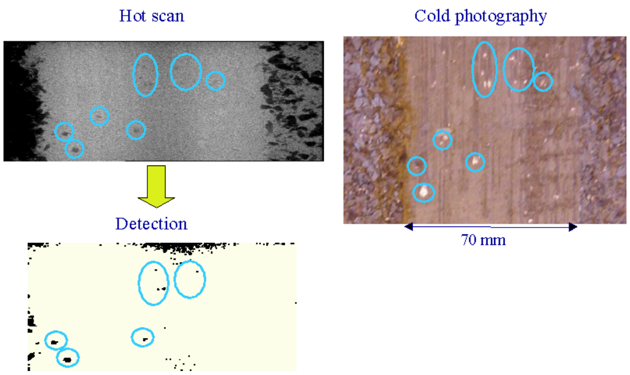

Fig 18 – Inclusions map obtained on-line

Conclusions

The first results obtained regarding on-line detection of surface defects in hot slabs are very promising. On-line detection has proved to be feasible and accurate in an industrial environment. This allows a quick discrimination of the slab quality level.

- Very useful system for Production and Quality Control;
- Able to detect and classify surface defects in hot slabs;
- Reduces production costs in several ways.

Summary

On-line surface quality control in continuous casting is a great benefit for the steel industry.

Conoscopic holography-based rangefinders are the only sensor capable of discriminating between defects and scale. By combining them with conventional imaging, an accurate detection can be achieved in real-time. This allows a subsequent calculation of the quality level of the product to be made, determining the new process route the slab must follow.

The fusion of data coming from different sensors gives the necessary accuracy to the detection system. The algorithms used for data treatment are complex. The effects of the different sources of error are minimised by fusing the results from different types of sensors.

This project is accomplishing this task with very good results. Tests at Aceralia's steel making facilities in Asturias (Spain) have shown that the system is robust and reliable. The system is at present installed in the LDA plant where it is integrated with the process, providing invaluable information and saving time, energy and operations.

Summing up, this system provides the following benefits:

- Energy saving;
- Automated inspection;
- Improved quality analysis methods;
- Homogeneous inspection criteria
- Possibility of improving the production plan;
- Improved slab conditioning;
- Reduced number of inspection operations;
- Reduction in repair time;
- Flexible slab yard management;
- Automatic process feedback.

With these characteristics, the system provides not only direct economic benefits but it also offers the possibility of implementing systematic criteria for determining the quality of the product and for assessing the results, thus providing a powerful tool for helping the production practices and, consequently, improving the yield of the facilities, as well as the deliveries of the product.

Acknowledgements

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