Novel on-line surface quality control for hot slabs in continuous casting*

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A new, advanced and breakthrough technology has been developed for hot slab on-line surface inspection and installed in Aceralia (Spain). This innovative inspection system, integrating novel Conoscopic Holography, CCD cameras, a complex mechanical system and intelligent tools, operates in the real environment of a continuous casting facility, allows on-line hot slab surface inspection of 100 % of the production, detecting cracks -without removing the surface scale- and inclusions (peeling a narrow strip on the surface).

■ INTRODUCTION AND OBJECTIVES

Introduction

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 its capacity to manufacture high quality products in modern facilities.

On-line automatic 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 two very important factors: energy saving and surface conditioning resources reduction. In fact, 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. In many cases, a preventive surface repair for all the production is accomplished in order to ensure that the product is in proper condition for rolling.

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

This innovative on-line hot slab inspection system, that integrates novel conoscopic holography profilometers, conventional imaging, 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 a 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).

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Nouvelle technologie pour le contrôle « on-line » de la qualité de surface des brames chaudes en coulée continue

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Une technologie nouvelle, avancée et innovatrice pour l'inspection « on-line » de la surface de brames chaudes dans la ligne de coulée continue a été développée et installée à Aceralia (Espagne). Les partenaires qui ont participé à ce projet, financé par le programme CECA-Acier de l'UE, sont : Aceralia et l'Université d'Oviedo (Espagne), CSM (Italie) ; la technologie de détection a été fournie par le sous-traitant CDO (France).

Dans toutes les industries, le contrôle de qualité « on-line » de la production devient un facteur clé pour minimiser les coûts. L'inspection « on-line » de toute la production rapporte des bénéfices importants : une détection précoce des défauts sur le produit et des problèmes dans le procédé permet une réaction rapide, réduit les coûts liés aux « rebuts », réduit les « réclamations » des clients, etc.

Dans une installation de coulée continue, l'inspection « on-line » du produit a aussi d'autres bénéfices : économies d'énergie, réduction des ressources nécessaires pour l'inspection manuelle et la réparation de défauts de surface, réduction des frais de stockage. En effet, les brames n'ayant pas de défauts peuvent être enfournées directement à chaud dans le procédé suivant en aval (laminage à chaud), tandis que les produits susceptibles d'avoir des défauts doivent être refroidis, inspectés manuellement, et finalement réparés avant d'être transportés aux laminoirs.

Conception et fonctionnement de l'équipement

Le nouveau système d'inspection « on-line » de brames chaudes, qui intègre la technologie innovatrice d'Holographie Conoscopique, des caméras CCD, un système mécanique complexe et des outils intelligents, est capable de déterminer la qualité de surface de la brame en temps réel. Ce système, qui opère dans l'environnement réel d'une installation industrielle de coulée continue, permet l'inspection « on-line » de la surface des brames chaudes pour 100 % de la production, détectant les fissures – sans éliminer la calamine – et les inclusions (après avoir enlevé une petite frange de peau en surface).

La détection des deux types de défauts, fissures et inclusions, nécessite deux approches différentes. Les inclusions n'apparaissent pas en surface ; on a donc besoin d'un mécanisme pour enlever la peau de la brame (environ 1 mm). Cette opération s'effectue uniquement sur une frange étroite dans le sens longitudinal de la brame, et les résultats obtenus dans cette frange sont extrapolés au reste. La technique choisie pour enlever cette frange est le rabotage.

On a conçu un rabot capable d'enlever 1-2 mm de peau, donnant une très bonne qualité de surface pour la détection postérieure des défauts. Cette technique permet également d'obtenir des copeaux contenant une partie des inclusions pour leur analyse chimique.

Après le rabotage, une caméra CCD prend des images de la frange mise à nu, où les inclusions et les pores sont détectés par des méthodes traditionnelles d'analyse d'images.

Le deuxième type de défaut concerné, les fissures, est détecté sur toute la largeur de la brame, dont on ne veut pas éliminer la calamine. Donc, les méthodes traditionnelles, comme l'analyse d'images, ne sont pas capables de fournir des résultats valables.

On utilise dans le système une technologie très innovatrice de mesure sans contact, l'holographie conoscopique, pour obtenir une carte topographique de la surface, où les fissures sont facilement détectées par différence de distances. L'holographie conoscopique est une technique de mesure interférométrique, où l'interférence est obtenue en se servant de la propriété de double réfraction des cristaux uniaxes.

Étant donné que la calamine peut compliquer la détection, les cartes topographiques obtenues par l'holographie conoscopique sont fusionnées avec des images optiques classiques pour avoir une détection précise. Des algorithmes spécialisés, capables d'identifier les fissures au milieu de la calamine sur la surface ont été développés.

Résultats obtenus

Les résultats obtenus jusqu'à présent sont excellents pour les deux types de défauts détectés. Le système de détection de fissures est installé en permanence sur une ligne industrielle (machine de coulée continue d'Aviles) depuis le début de 2001. Le système a prouvé son efficacité pour détecter des fissures longitudinales d'une longueur supérieure à 100 mm sur des produits chauds sans éliminer la calamine, avec un niveau de fiabilité de près de 100 %. Le système de détection d'inclusions est capable d'obtenir une information très précise concernant la présence d'inclusions et de pores. La détection se réalise totalement « on-line », sur la brame chaude, et sans interférer avec le procédé de coulée continue. Le système est conçu de façon à pouvoir travailler de la même manière sur les faces supérieure et inférieure de la brame.

Ce projet est très important pour l'installation de coulée continue, permettant aux producteurs de réduire les coûts de réparation de défauts de surface, d'augmenter le taux d'enfournement à chaud dans le procédé suivant en aval, et d'améliorer la connaissance du procédé pour prévenir l'apparition de défauts.

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 steelmaker to raise productivity, assess the surface quality level of the slabs, reduce resources allocated to surface conditioning and slabs storage, 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.

All these factors together, and especially the increment of hot charge ratios, result 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 steelmaking process. From the various defects that may appear in the product (slab) at this stage, which can lead to problems in the subsequent manufacturing stages, surface defects (cracks and inclusions) are the most usual (*fig. 1*). It is of utmost importance to guarantee the surface quality of the product, ensuring that the slabs sent to the following production process are absolutely free from any surface defects.

The economic and environmental impact of inspecting potentially defective 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 many occasions, surface repair is accomplished as a preventive task to all potentially defective slabs, wasting resources that could be saved if 100 % of the production were checked.

On-line inspection saves this cooling and inspection time, allowing the defect-free material to go on to the following process without a significant temperature loss, and sending to repair only the slabs that objectively need it. Therefore, this novel system performs an on-line inspection, providing, in a matter of seconds, an indication of what to do with each inspected slab: conditioning or hot charging.

Database storage of the results of the inspection, together with the process parameters, provides to the process engineers 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.

This on-line inspection can be easily integrated in the process, avoiding on one hand the reduction of the plant throughput, and on the other hand any important modifications of plant layout and common plant practices for installation or maintenance. So, inspection can be done on the hot product (above 700°C), without modifications on the strands or their speed, without removing all the scale in the slab, and for 100 % of the production.

Due to these constraints, the system is installed at the exit of the caster strands, when individual slabs are already labelled, and just after the deburrer to take advantage of the small speed at that point (*fig. 1*).

Over-detection is preferred to under-detection, as its impact on the performance of the overall process is much lower. This allows to get around a very difficult problem, not solved satisfactorily with other technologies to the present.

■ TECHNICAL DEVELOPMENT

It is clear, due to the process conditions described above, that non-contact scanning techniques must be used to reliably assess the surface quality of the slabs on-line. Among these, conventional technologies have not shown to be robust and effective in this application, so novel technologies have been introduced in order to have a reliable solution. In fact, novel Conoscopic Holography non-contact measuring technology is the key for crack detection.

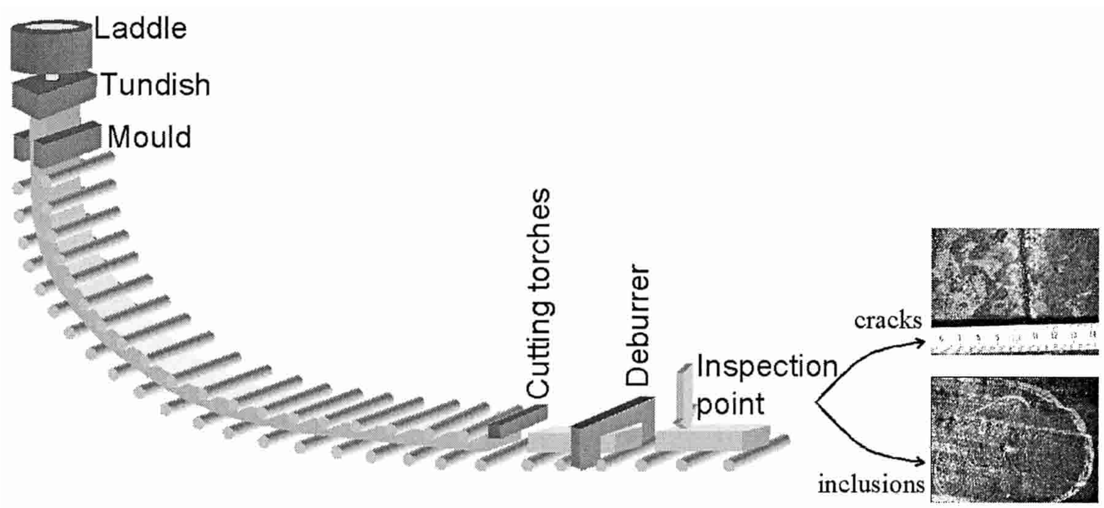


Fig. 1 – Location of the inspection system and defects to be detected.

Fig. 1 — Emplacement du système d'inspection et défauts recherchés.

The two types of defects to be detected, cracks and inclusions/pores, require two different approaches. Cracks appear on the surface, although merged with scale that may cover them partially or totally. Cracks are to be detected over the full width of the slab – as they appear scarcely and randomly – without removing the surface scale.

Inclusions and pores do not break in the surface, so a peeling mechanism is needed to make them visible. Also, inclusions and pores are more uniformly distributed in the surface. Because of these two reasons, it is acceptable to check the inclusions/pores in a narrow strip (about 70-80 mm) that must be peeled, and extrapolate the results to the full width.

As the technologies involved in both types of detection are different, the system may be split into two : crack detection subsystem and inclusions/pores detection subsystem. The final decision regarding slab surface quality will be obtained by merging the results of both subsystems.

Inclusion/pore detection subsystem

Inclusion detection has the complexity of a cleaning tool needed for removing the skin of the slab in a narrow strip. Among the technologies available, shaving has been selected for this peeling, as it provides a smooth strip very well suited for its posterior scan and detection of defects.

Shaving at high temperature has been a breakthrough of this project, in which a planing system has been designed, constructed and installed in the line, being able to remove automatically a 80 mm wide and 1 to 2 mm deep surface strip all along the edge of the slab. The advantages of the prototype developed include not only a smooth strip for detection, but also the production of chips of the surface longer than 100 mm containing a part of the inclusions, that can be subject of off-line chemical analysis in order to determine their origin.

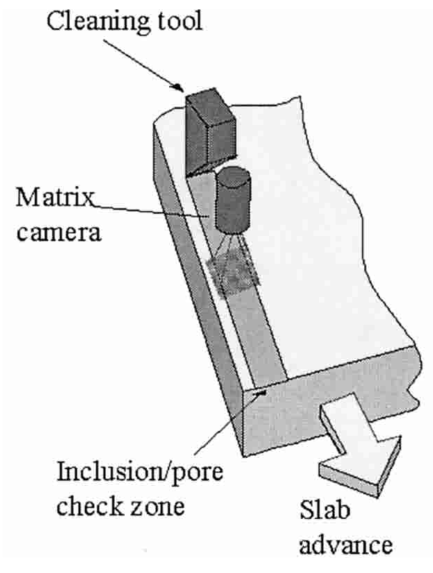


Fig. 2 – Set-up of the inclusion/pore detection subsystem.

Fig. 2 – Structure du sous-système de détection d'inclusions et de pores.

Immediately after the shaving tool, a conventional imaging system scans the cleaned strip (*fig. 2*), being able to detect inclusions and pores by means of the appropriate algorithms.

The following figures show the peeling tool working on-line, and the aspect of the strip and the chip obtained with it.

Figure 3 shows the cleaning system working on-line, *figure 4* details of the cleaned strip on the surface of the slab and the chip obtained, and *figure 5* the results of off-line laboratory analysis performed on the chip.

Crack detection subsystem

For crack detection, conventional techniques as imaging are not by themselves 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 features. *Figure 6* shows grey-scale images obtained for different hot slabs with cracks present, where this difficulty becomes manifest.

Although conventional imaging provides very useful information, other techniques are required to achieve reliable defect detection. The surface topography yields the most important information in this case, as the cracks are alterations in the surface in the opposite sense than scale. Conoscopic holography non-contact measuring technology has been selected to provide this more reliable information, as it is the only technique able to work in the conditions needed : long stand-off (1200 mm), high temperature (800°C), high depth discrimination capability (around 0.2 mm in a 50 mm range).

Conoscopic holography

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

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

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 uni-axial crystals. 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 of the light emitting point can be obtained. *Figure 7* shows the scheme of the conoscope. The light for illuminating the point is provided by a laser source installed inside the sensor.

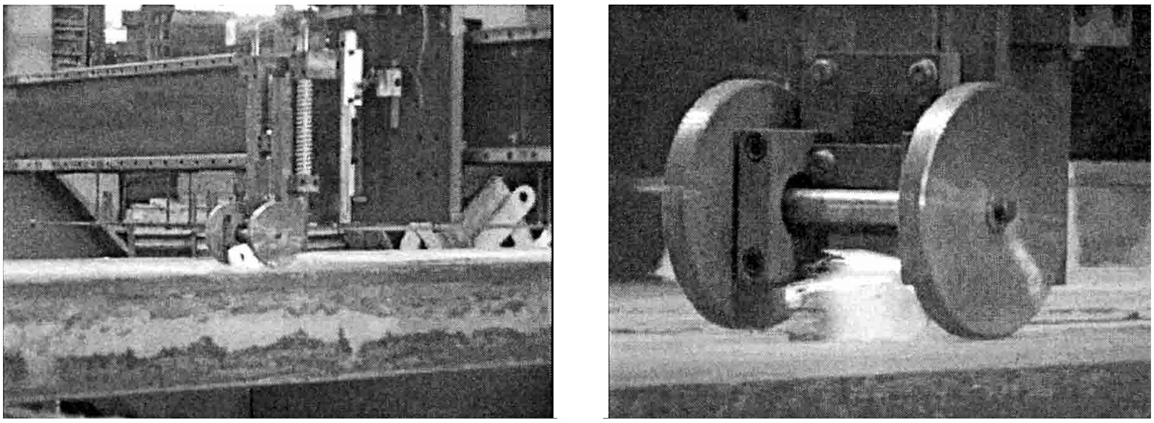


Fig. 3 – Shaping system working on a hot slab.

Fig. 3 – Système de rabotage en fonctionnement sur une brame chaude.

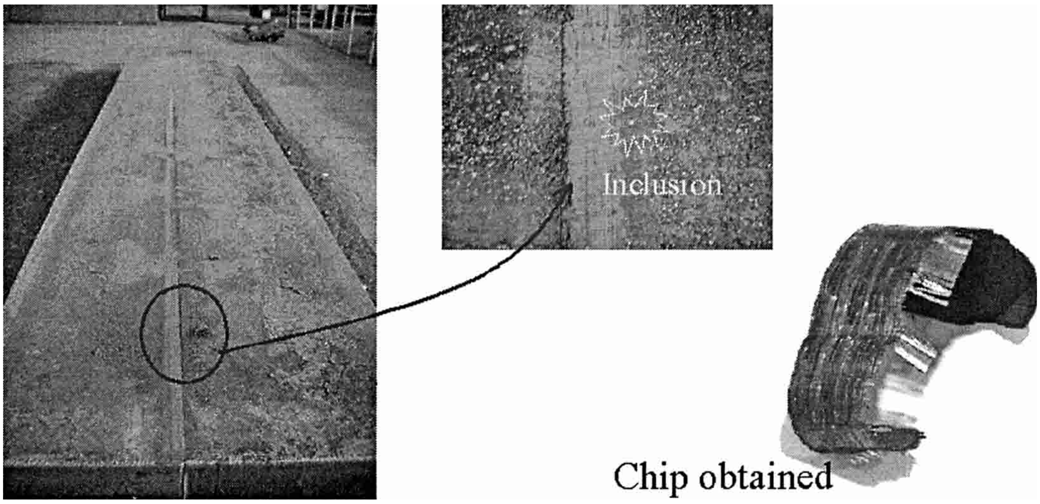
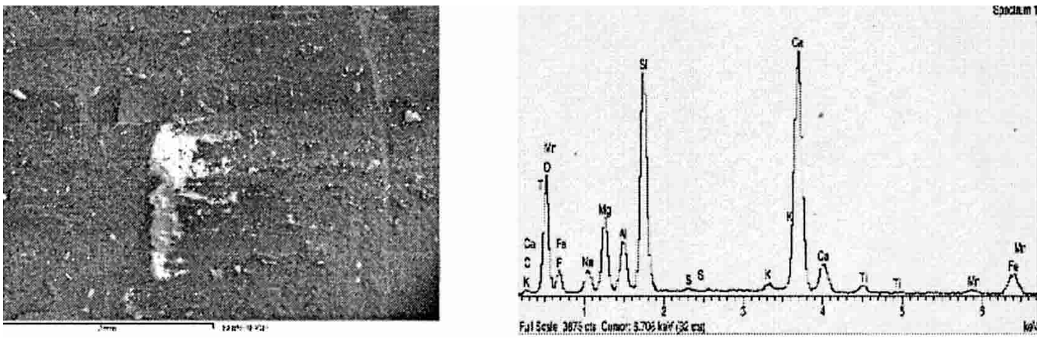


Fig. 4 – Details of cleaned strip and chip (with inclusions).

Fig. 4 – Détails de la frange rabotée et copeau (avec inclusions).



a) Microscopic view of the inclusion.

b) Spectrometric analysis of the inclusion.

Fig. 5 – Off-line laboratory analysis of the chip.

Fig. 5 – Analyse hors-ligne du copeau au laboratoire.

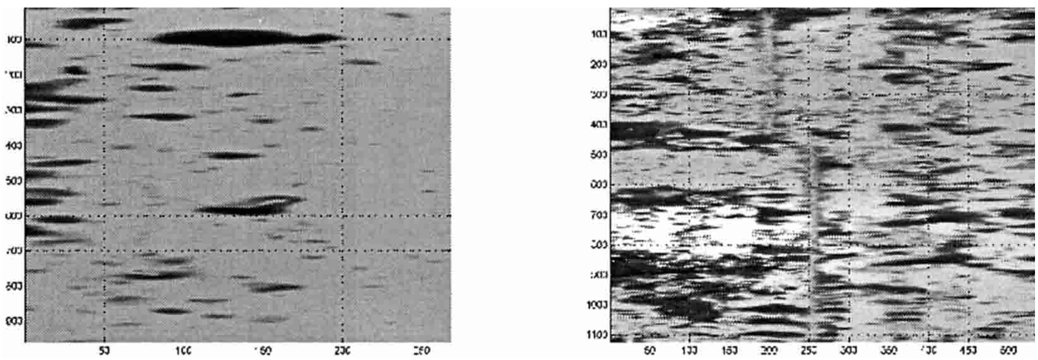


Fig. 6 – Gray-level images of slab zones with cracks present.

Fig. 6 – Images en niveaux de gris des parties de deux brames comportant des fissures.

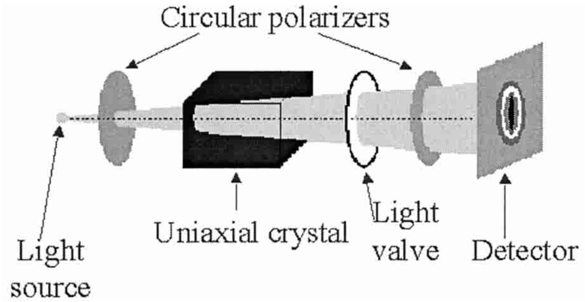


Fig. 7 – Set-up of a point conoscopic sensor.

Fig. 7 – Schéma d'un capteur conoscopique ponctuel.

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 90° ; it can be extended for direct 2-D measurement (profilometry), or even to 3-D.

Indeed, 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 (*fig. 8*), and is the one being used for crack detection.

Optical structure for crack detection

The layout of the elements in the system for crack detection is shown in *figure 9*. Both conventional imaging techniques (line scan camera) and CH based range-finders are used. The complete slab surface is captured taking advantage of its advance on the rolls.

Cracks appear typically 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 :

– the line-scan grey-level CCD camera (1000 lines/second, 0.3 mm transversal resolution) gives a light intensity image of the surface ;

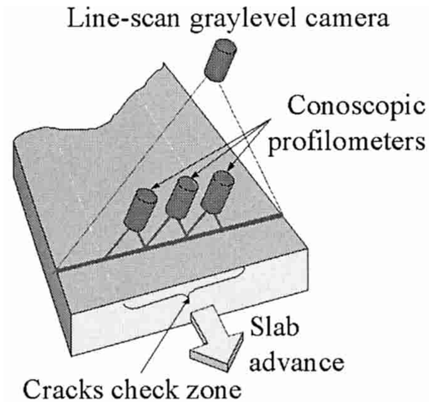


Fig. 9 – Optical set-up for crack detection.

Fig. 9 – Configuration des capteurs pour la détection de fissures.

– three conolines (30 lines/second, 0.2 mm depth resolution, 0.3 mm transversal resolution) give a topographic image of the surface.

Figure 10 shows the external and internal views of the crack inspection system installed in the plant.

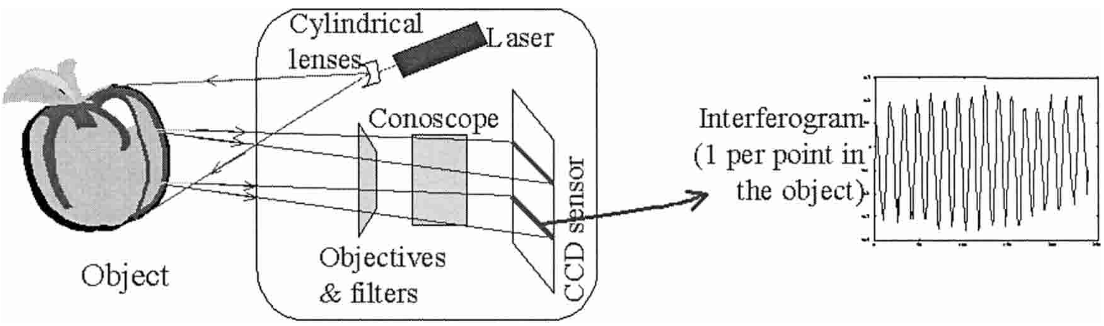
Data processing

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 surface quality. The hardware configuration required for this task includes several last generation 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).

The key point for all the processing algorithms is their real-time operation, as the response from the system is 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.

Fig. 8 – Set-up of a conoscopic long-standoff range-finder (conoline).

Fig. 8 – Schéma d'un profilomètre conoscopique à longue distance frontale (conoline).



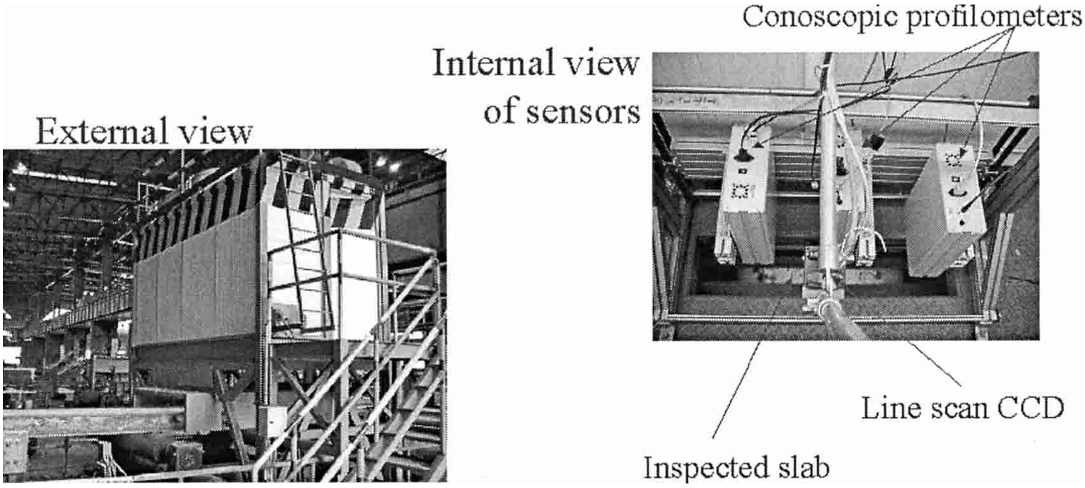


Fig. 10 – Crack inspection system installed on the line at Aceralia LDA plant.

Fig. 10 – Système de détection de fissures installé dans la ligne de production de l'aciérie LDA d'Aceralia.

A computer is assigned to each sensor (matrix CCD for inclusion detection, line-scan CCD for crack detection, conoscopic range-finders for crack detection), acquiring and pre-processing the data that it obtains in real time. Each algorithm is specialized in its own task, giving as output a tentative map of defects.

For crack detection, results from both types of sensors are fused by means of a neural network, in order to have a single map of the cracks. The fusion of data coming from different sensors provides the necessary accuracy to the crack detection system, in spite of the complexity of the algorithms used for data treatment and the important computational effort they require. The effects of the different sources of error are minimized by fusing the results from the two different types of sensors.

In an ultimate 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.

■ RESULTS

As has been underlined previously, the project is divided in two parts concerning the detection of longitudinal central cracks system and inclusions/pores detection system. Both systems are installed and in operation under real production conditions in the continuous caster of the Aceralia steelmaking plant in Aviles (Asturias – Spain).

Inclusion/pore detection system

The inclusion and pore detection prototype has been developed and works on hot slabs above 700°C. Results of a real detection can be seen in *figure 11*. No statistics can be presented so far as the shaving tool is under redesign, in order to provide the necessary robustness for 24 h unattended automatic work.

Crack detection subsystem

The detection results obtained in the plant for the crack system are very satisfactory. *Figure 12* shows the image of a (7000 x 300) mm^2 portion of a slab, seen both by the line-scan camera and by the conoline. Once both data have been processed, the fused detection is a reliable indication of the presence of cracks.

The crack inspection system is continuously working on-line since January 2001, giving very good results. Detection of cracks over 200 mm is almost 100 % reliable, while smaller cracks are detected with a confidence of above 90 %. *Table I* summarises detection statistics in several casts of potentially defective slabs.

It must be noted that, in the last months, the conoscopic sensors have been refurbished and installed, giving much better results in hot slabs. Results with these new sensors have improved the detection of small cracks (*table I*).

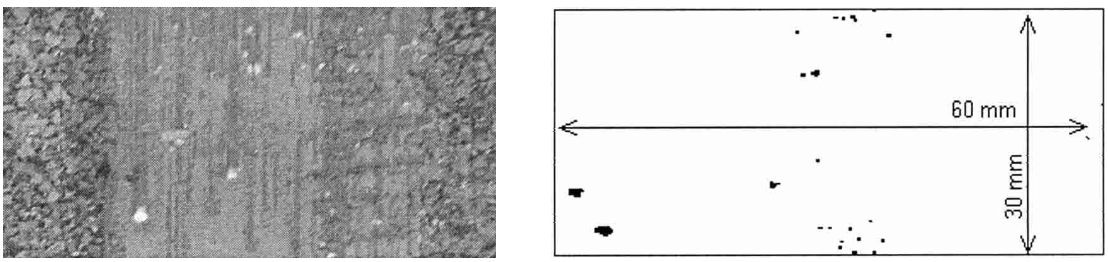


Fig. 11 – Inclusion detection results.

Fig. 11 – Résultats de la détection d'inclusions.

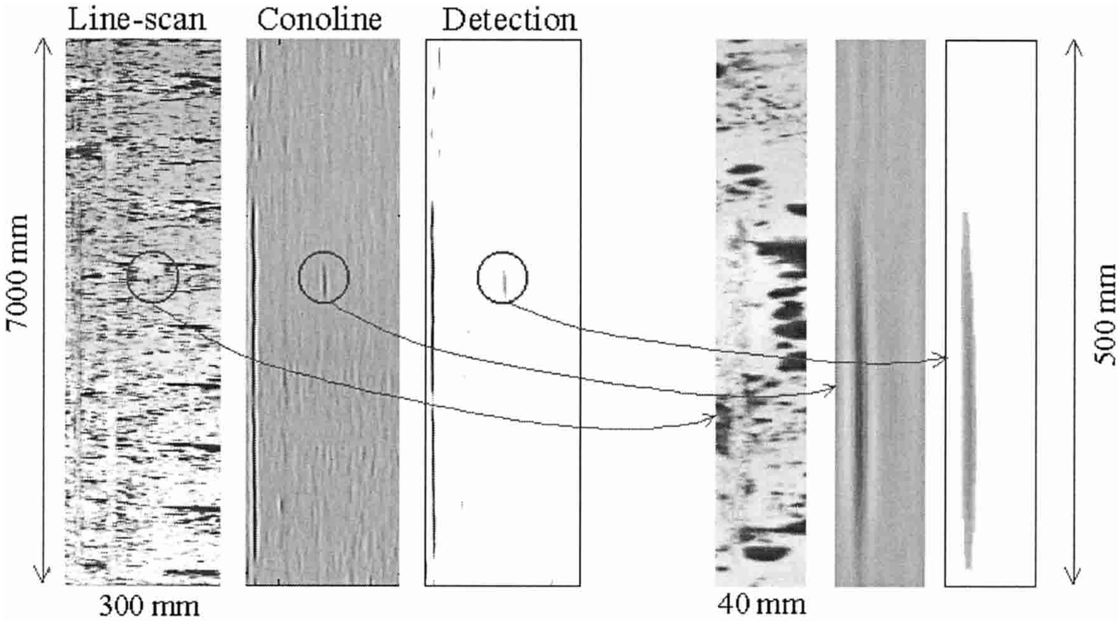


Fig. 12 – Results of the detection of longitudinal cracks.

Fig. 12 – Résultats de la détection de fissures longitudinales.

It must be noted that, for selecting the parameters of the algorithms, over-detection has been preferred to under-detection, as it is less harmful for the process.

TABLE I : Summary of crack detection statistics.

TABLEAU I : Résumé des statistiques de détection de fissures.

Crack length (mm)	Correct	Over-detected	Under-detected
100 < L < 200	36	6	2
200 < L < 300	17	1	0
300 < L < 400	10	0	1
400 < L < 500	7	0	0
500 < L	9	0	0

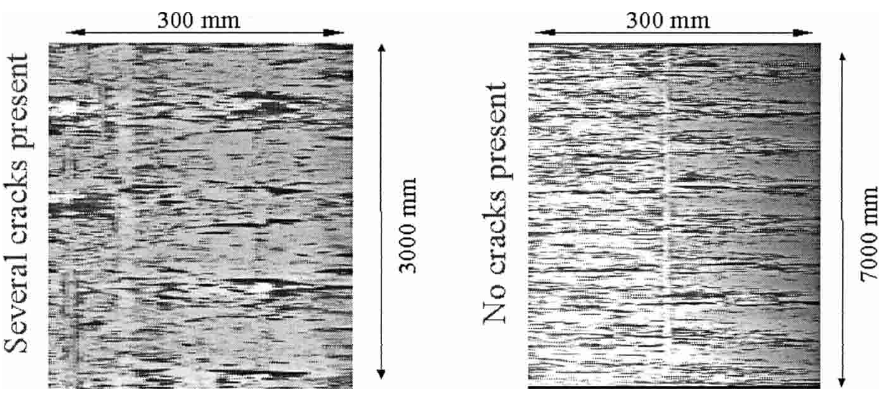


Fig. 13 – Grey-level images of two slabs. Only the slab on the left has cracks.

Fig. 13 – Images en niveaux de gris de deux brames. Uniquement la brame de gauche a des fissures.

A very important fact of the crack detection system is its reliability, i.e., its capacity to discriminate cracks from other surface features and defects. *Figures 13 and 14* show the major contribution of the CH based profilometers in this task.

■ CONCLUSIONS

On-line detection of surface defects in hot slabs has proven feasible and accurate in an industrial environment. The project developed has allowed to build an inspection system, the robustness and reliability of which have been proven in Aceralia steelmaking facilities in Asturias (Spain). The system developed is a very powerful tool for Production and Quality Control departments, enabling to detect and classify surface defects in hot slabs, and as result improve their process knowledge, the feedback, and reduce production costs in several ways.

Summing up, this system provides the following benefits :

- energy saving, improving hot charging ratio ;
- automated inspection ;
- improved quality analysis methods ;
- homogeneous inspection criteria ;
- possibility of improving the production plan ;
- improved slabs conditioning ;
- reduced number of inspection operations ;

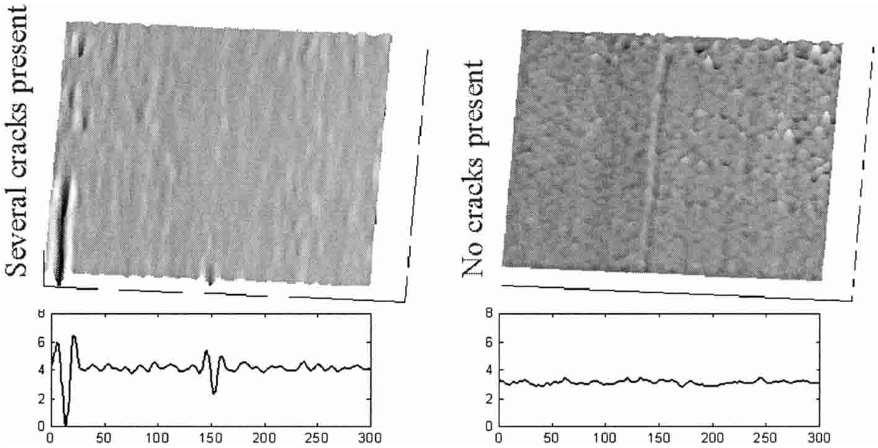


Fig. 14 – Topographic maps for the same slabs. CH makes the difference for crack detection.

Fig. 14 – Topographie des brames de la figure précédente. La CH fait la différence pour mettre en évidence les fissures.

- reduction in repair resources ;
- flexible slab yard management ;
- improved process knowledge ;
- automatic process feedback.

With these characteristics, the system not only provides direct economic benefits, but 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.

Finally, the introduction of Conoscopic Holography non-contact measurement technology has shown to be an important breakthrough for steel industry. CH based range-finders are the only sensor that has been found capable of discriminating between defects and scale, working on-line in hard conditions with a long standoff.

The uses of CH inside this industry will not only limit to this application, but others taking advantage of the special characteristics of this technology are already under development : high accuracy internal punctual measurements can be done using a 1000 mm long, 20 mm diameter periscope ; 3-D one-shot roughness measurements can be done with an adaptation of the basic principle; rail 2-D profile obtention can be done on-line with CH range-finders ; and many other possibilities in hot and cold products can be addressed with novel Conoscopic Holography.

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