MOULD OSCILLATION MONITORING IN CONTINUOUS CASTING

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Abnormal performance of critical operational elements of the continuous casting machine (CCM) can produce surface defects on continuous casting (CC) products or even break-outs. Moreover, surface and sub-surface defects in the CC semis are not usually along all the semis length, but only in some places, highlighting the existence of transitory phenomena. Those facts have shown the importance of reaching stable CC operation conditions and the need of knowing when transient conditions are happening during casting. To achieve that involves several things: to identify relevant CC parameters, to monitor them, to identify abnormal transient values and to relate transient values to semis quality.

Both, off-line and on-line, mould monitoring techniques have been employed by SIDENOR I+D including mounted sensors (accelerometers, linear voltage displacement transducers (LVDT), strain gauges) and instrumented moulds. This paper pays special attention to the assessment of the friction between billet and mould and its application for breakout forecasting using advanced on-line monitoring techniques.
An index for billet-mould friction assessment has been defined using strain gauges installed in the cam rod of the oscillation mechanism. Through the study of the information related to casting parameters prior to fifty-eight breakouts it was concluded that almost 50% of them could have been forecast through the behaviour of the monitored parameters prior to the breakouts. A monitoring program called SIROL has been developed to judge on-line the CCM performance. Another index for billet-mould friction assessment, using accelerometers placed in the oscillating mould cassette, has been recently obtained; and in this paper the preliminary results are presented. It can be said that the mould monitoring is a useful tool to improve the system operation and product quality as well as to optimise the predictive maintenance work.

Keywords: continuous casting, billet, monitoring, breakout

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1. INTRODUCTION

Surface and sub-surface defects in the continuous casting (CC) semis are not usually along all the semis length, but only in some places, highlighting the existence of transitory phenomena. This fact has shown the importance of reaching stable CC operation conditions and the need of knowing when transient conditions are happening during casting. To know those transient moments involves several things: to identify relevant CC parameters, to monitor them, to identify abnormal transient values and to relate them to semis quality. In case of billet CC many of the transient situations seem to be related to in-mould solidification.

Monitoring of mould oscillation and mould heat flux has been the subject of many papers describing the usefulness of mould movement monitoring in order to detect any malfunctioning of the mould oscillation system[1,2,3,4]. Other recent papers deal with measurements of billet/mould friction force during casting, describing the influence of mould design, mould powder, casting speed and other operational parameters on friction force[5-8]. However, only a few number of papers are devoted to a further step: namely the study of the relationship between billet/mould friction and the quality of continuous casting semis and end product[9].

SIDENOR I+D has been working on continuous casting machine (CCM) monitoring for some years as a tool for the improvement of the casting process. This technique has allowed the study of different transient phenomena of critical operational elements such as mould oscillation system, mould lubrication and heat flux, mould liquid level, withdrawal machine and cut-off unit. To an important extent, the research has been carried out within two ECSC Projects[10,11]. Part of the results has been recently published[12].

This paper describes firstly the monitoring techniques used by SIDENOR I+D. Afterwards, the billet/mould friction force assessment on measurements using strain gages situated in the cam rod of the oscillation system and measurements of the electrical intensity of the oscillation drives will be explained. Additionally a study of how the on-line measurements of the friction force can be used for breakout prediction during casting is described. And, finally, a brief presentation will be made concerning the new experimental techniques under development for both off-line and on-line mould oscillation monitoring, including the definition of a new billet-mould friction index based on the mould acceleration signal.

2. MONITORING TECHNIQUES

Monitoring activities in SIDENOR I+D have been focused to a large extent on the mould oscillation system and other mould related variables because of its important influence on the friction between billet and mould, the lubrication and the billet solid layer formation itself. The research has been carried out at two different billet CCMs, and their main characteristics are shown in **Table I**.

Concerning the monitoring architecture, data comes from both the CCM electric control room and from the sensors installed at different locations of the CCM (accelerometers, strain gauges, LVDTs and thermocouples). There are two different data acquisition systems with different acquisition frequency requirements. On the one hand, some of the signals require high acquisition frequency (200 samples/sec) and simultaneous FFT (Fast Fourier Transformation) calculations, so fast multi-channel measurement units have been used for that purpose; and the original data only is stored when a transient phenomenon takes place. This data acquisition system is PC controlled and includes a full range of functions for logging and data processing. On the other hand, other signals (mould thermocouples, mould cooling water temperature increase,…) are logged at a lower sample acquisition frequency (0.5 samples/sec), and original data is continuously stored for all the duration of the sequence.

	CCM1	CCM2
Starting date	1985	2001
Billet section (mm)	155x155 & 185x185	
Casting speed (m/min)	1.0 ÷ 1.8	1.0 ÷ 2.3
Oscillation system	Lever Electromechanical (DC motor)	Leaf spring Electromechanical (AC motor)
Mould length (mm)	800	1000
Mould taper	Linear	Parabolic
Stroke (mm)	4.6	5.7

Table I. Main characteristics of both CCMs where the research has been carried out.

3. STUDY OF THE FRICTION BETWEEN BILLET AND MOULD IN CCM1

Two different techniques were used for assessing the friction between billet and mould in CCM1:

- Strain gauges located in the cam rod of the oscillation system
- Direct measurement of the electrical current intensity of mould oscillation motor

3.1. STRAIN GAUGES IN THE CAM ROD

Strain gauges were installed in the cam rod of the CCM1 oscillation system in order to assess the friction force between billet and mould. **Figure 1** shows a cam rod already instrumented with a strain gauge.

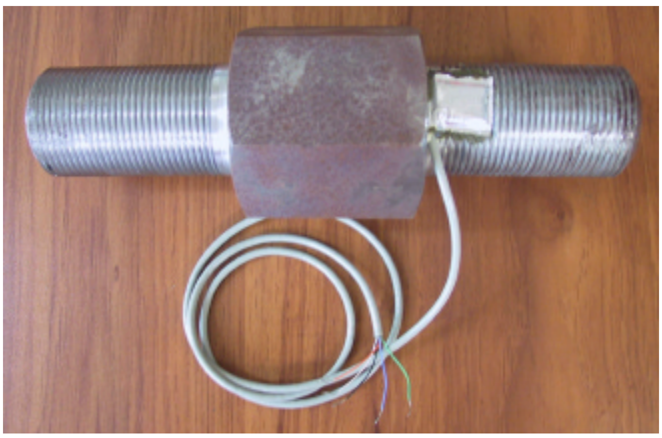

Figure 1. Cam rod after installing the strain gauge.

In **Figure 2** a comparison between the wave shape of the force measured during casting and just after the end of cast is shown. The differences in the peak to peak value, the mean value and the wave shape between casting and no casting conditions are all due to friction between billet and mould. Therefore, the increase of friction conditions involves an increase in the peak to peak value (20% in this example), an increase in the mean value and a less square shaped signal (the example shows how the wave shape after casting is almost a square shaped signal).

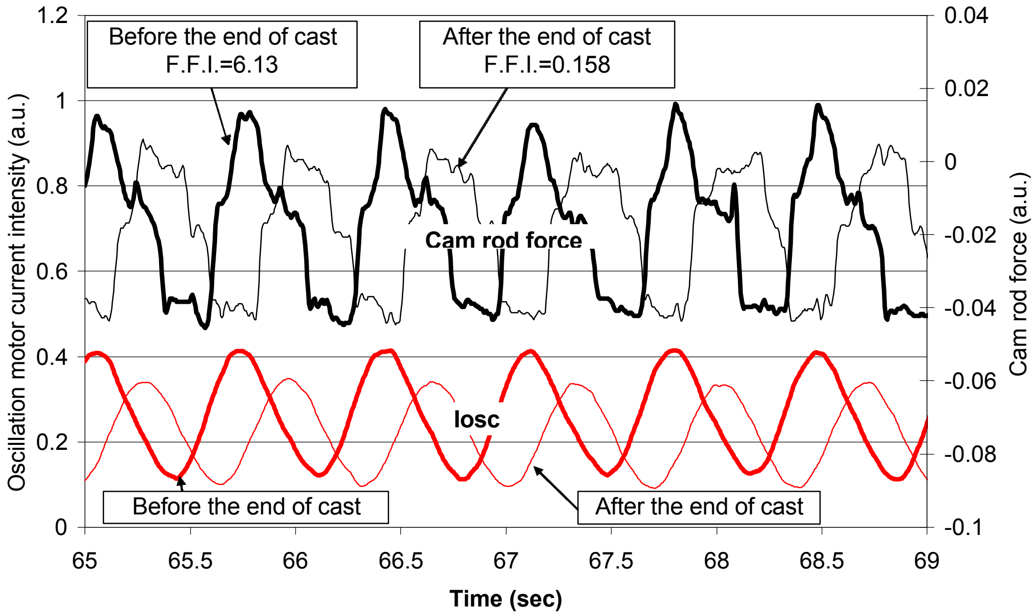

Figure 2. Comparison of the force measured by means of strain gages in the cam rod and the electrical intensity of the oscillation motor (Iosc) during casting and just after end of casting. CCM1 (Heat number: 46843. Steel grade: C38Mn5R).

A Square Resembling Index (S.R.I.) of the force signal was defined in order to assess the friction between billet and mould:

$$\text{S.R.I.} = \frac{f_3 + f_5}{f_2 + f_4}$$

where f_2 is the amplitude of the 2nd harmonic in the Fourier Transform of the force signal, and so on. This S.R.I. definition is based on the fact that a square wave signal is only composed of odd order harmonics.

The values of the S.R.I. before and after the end of cast, whose force signals are shown in **Figure 2**, are the following:

$$(\text{S.R.I.})^{\text{during casting}} = 0.16$$

$$(\text{S.R.I.})^{\text{after casting}} = 6.33$$

A Friction Force Index (F.F.I.) was defined as the inverse of the S.R.I.. Therefore, in this case, during casting the F.F.I. was 6.13 and after casting it was 0.158; and it means that this parameter has much more sensitivity than the peak to peak variation when changing the friction conditions.

3.2. ELECTRICAL CURRENT INTENSITY OF THE MOULD OSCILLATION MOTOR

The electrical current intensity signal of the motor which drives the oscillation system (Iosc) has also proved itself to be a valid indicator of the friction conditions between billet and mould. **Figure 2** shows an example of the Iosc behaviour at CCM1 comparing both casting and mould idle oscillation; and it is possible to see how in that case, as well as for the cam rod force, the friction between billet and mould also involves an increase in both the Iosc mean value (22%) and the Iosc peak to peak value (20%). The value of the Iosc peak to peak parameter is quite dependent on the casting speed, as the oscillation frequency changes linearly with the casting speed.

4. SIROL PROGRAM

The SIROL on-line monitoring program was developed in order to get a tool able to detect abnormal working conditions in the CCM related to the appearance of transient phenomena that could give rise to an impairing of the billet quality or even a breakout. **Figure 3** shows the flow chart of the SIROL program. The data acquisition units log four different variables for each of the six strands. Once the CCM is working, detected by a software trigger, high frequency data are saved to 40 seconds temporary files. Some parameters, as mean values, standard deviations, Friction Force Index,… are calculated each 2 seconds and the results are saved in a permanent file. When the program detects an abnormal transitory phenomenon, like a breakout, the two last temporary files containing high frequency data are saved to permanent files, with additional information for its later analysis. Using this method, low frequency information is obtained for all the heat, and high frequency information for a brief period just before each transitory phenomenon.

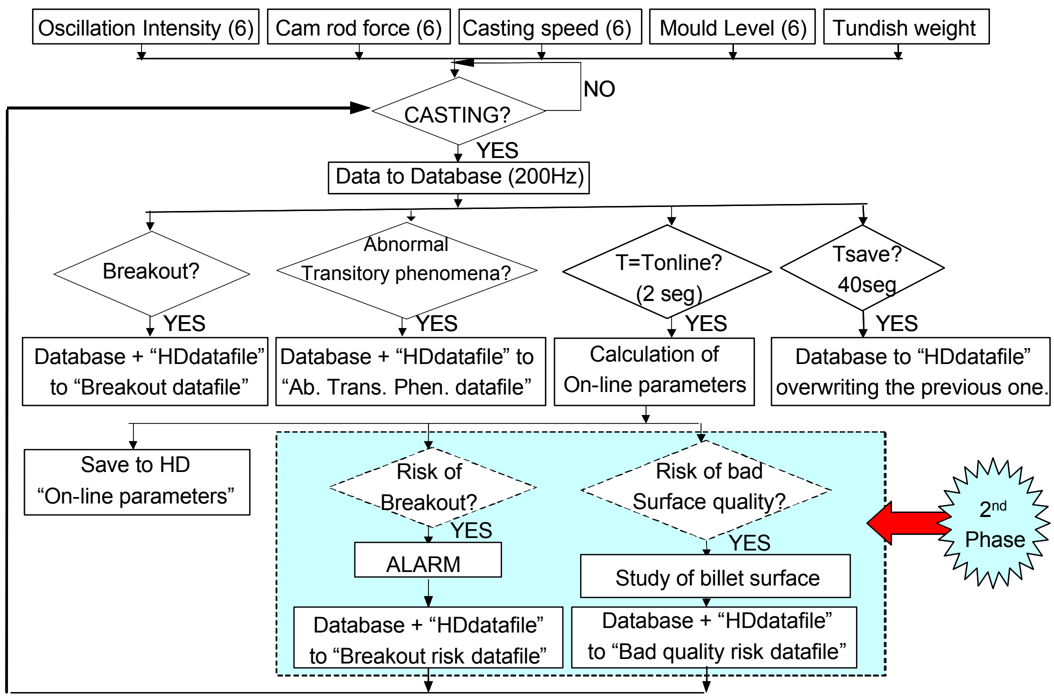

Figure 3. Flow Chart of SIROL program, developed for studying abnormal transient values of monitored parameters during continuous casting operation.

A first version (flow chart shown in **Figure 3** with the exception of the block identified as "2nd phase") was installed in the CCM1 for a period of six months in order to save to hard disk (HD) the monitored signal values prior to the appearance of an abnormal phenomenon during casting. This first phase would allow the definition of the criteria for the quality alarms to be incorporated in the SIROL program. A 200 samples/sec/channel data acquisition frequency was selected for the 25 channels. A large amount of data related to abnormal casting phenomena was collected during this tuning process of the SIROL program at the CCM1, and a thorough analysis was performed in order to understand the appearance mechanism of different abnormal transient phenomena.

4.1. BREAKOUT FORECAST

The first application of the SIROL program aimed to find some criteria that could indicate when a breakout was going to happen through the study of the abnormal transitory values in the friction conditions just before the breakout. In this respect information on the casting parameters prior to fifty-eight breakouts was studied. **Figure 4** shows the variation of the oscillation motor intensity and strain gauge force for cast number 46430 just before a breakout. It was a sticker breakout, and after the breakout it was observed that a tube sticker shell had remained inside the mould. Abnormally high peak values can be seen in both signals before the breakout.

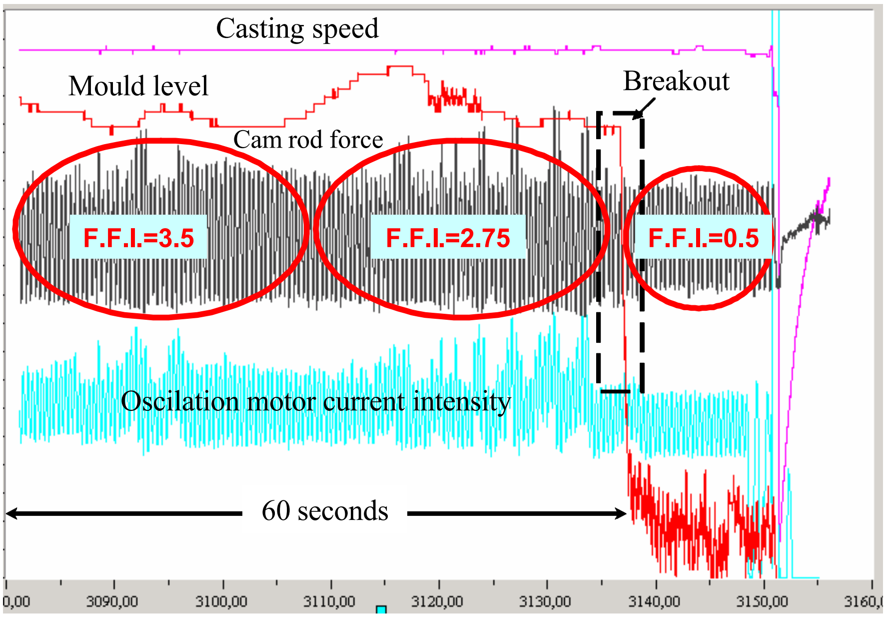

Figure 4. Mould level, casting speed, motor oscillation intensity and cam rod force before a breakout at casting time 3137 seconds. Data from SIROL program. Heat number 46430, Strand #5.

A similar analysis was carried out for the rest of breakouts registered. In that study, only the breakouts that happened during normal casting conditions were considered; this means that fourteen breakouts that appeared during casting starts and link-castings were not taken into account. A statistical study of the relationship between the breakouts and abnormal transitory values before them was carried out for the remaining forty-four breakouts. **Table II** shows the results of the statistical analysis.

Seventeen out of forty-four heats (38%) turned out to have abnormal transitory values before the breakout: peaks in the electrical intensity of the oscillation motor and in the friction force; the situation was not so clear in other six heats. On the other hand, some of the non detectable breakouts had an abnormally high casting superheat, and logically those breakouts are not expected to have high friction values. The statistical study also showed that, although the cam rod force was the most sensitive parameter for early detection of the breakouts, the oscillation motor intensity gave almost the same precision, being this measuring system easier to be implemented in the CCM.

Breakouts during normal casting conditions		
Detectable by SIROL program	17	38%
Not detectable by SIROL program	21	48%
Not clearly detectable	6	14%
Total	**44**	**100%**

Table II. Breakout predictability through the study of the abnormal transitory values in the oscillation parameters before the breakout.

As explained in section 4, the final purpose of the breakout information storage and further study was to set up a breakout detection system at the CCM1. Unfortunately the transfer of the principal production program from the CCM1 to the CCM2 did not allow the deduced criteria to be checked for the breakout prediction by means of assessing the accuracy of the alarms generated using those criteria.

5. OFF-LINE AND ON-LINE MOULD MONITORING TECHNIQUES IN CCM2

The promising results obtained in CCM1 encouraged the application of the mould monitoring techniques in CCM2. As far as mould oscillation monitoring is concerned, the activities carried out in CCM2 have covered the following activities:

- Mould displacement control
    - Off-line control (Iosc, LVDTs and accelerometers)
    - On-line control (Iosc and accelerometers)
- Friction assessment (accelerometers)

Some of those methods have already turned out to be useful for early detection of problems in the oscillation system as well as for maintenance operations; and others are nowadays under study in order to test their feasibility for becoming a valuable tool. In the following sections some examples are shown concerning those activities.

5.1. Mould displacement control

As shown in **Table I**, the oscillation mechanism in CCM2 is leaf spring guided and the light oscillation mass makes it possible for the Iosc signal to be really sensitive to any abnormal working condition. Therefore, that signal (Iosc) has proved itself in CCM2 to be helpful when trying to define whether the oscillation system is working properly. **Figure 5** shows a screen of the SIROL program installed at CCM2. The electrical current intensity of the oscillation motor of the six strands is displayed. A large distortion is observed in strand #6 signal. This distortion was related to a poor condition of the transmission mechanism, and the normal sinusoidal wave shape was restored after repairing the oscillation system.

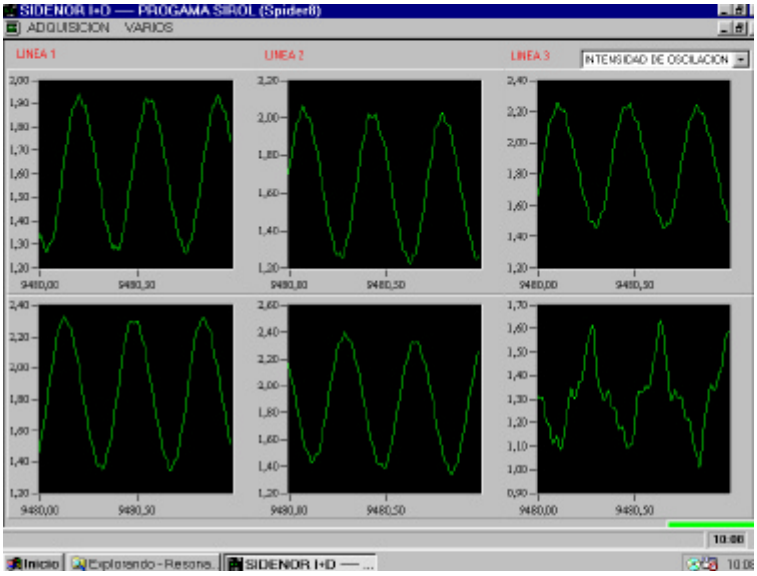

Figure 5. Display of one of the SIROL PC screens. Electrical intensity of the oscillation motor of the six strands of CCM2 during casting (1 second).

Figure 6 shows an example in which both, the mould real displacement and the mould real acceleration, are compared for idle oscillation to the ideal sinusoidal curves. The real displacement was measured using a LVDT and the real acceleration was measured by means of an accelerometer. In that figure it's possible to see how, although the displacement wave quality is almost perfect, the acceleration signal, due to its high sensitivity, highlights each small deviation of the displacement signal.

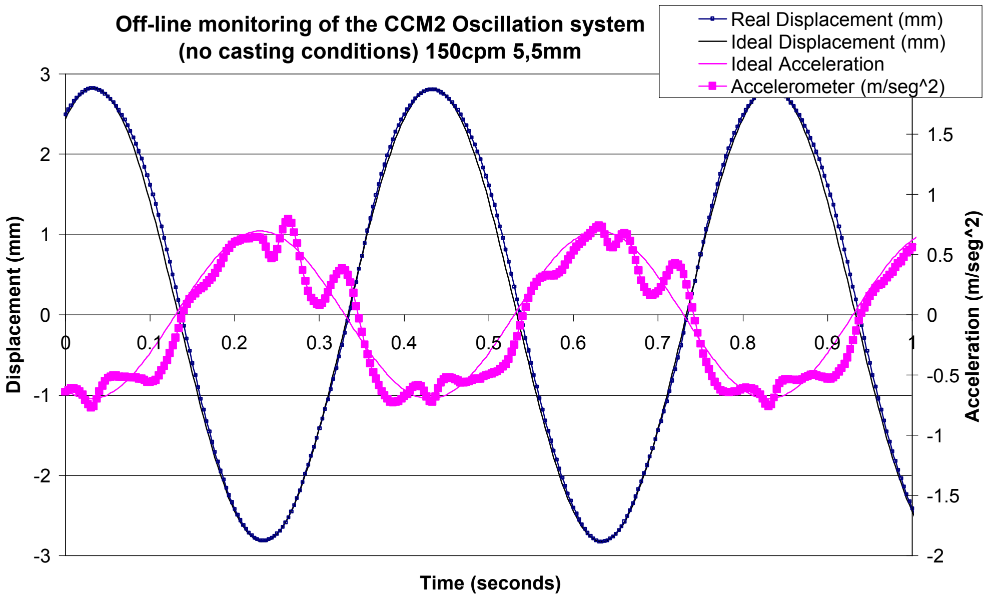

Figure 6. Off-line monitoring of CCM2. (No casting conditions) (150cpm 5.5mm). Good working conditions.

In order to illustrate the effectiveness of the accelerometer, **Figure 7** shows the same signals for a situation in which a malfunction was detected. It consisted of an abnormal friction between the oscillating mould cassette and the stationary stirring coil. As a result of that problem, a slight deformation of the sinusoidal displacement signal appeared, as well as an important deterioration of the acceleration signal.

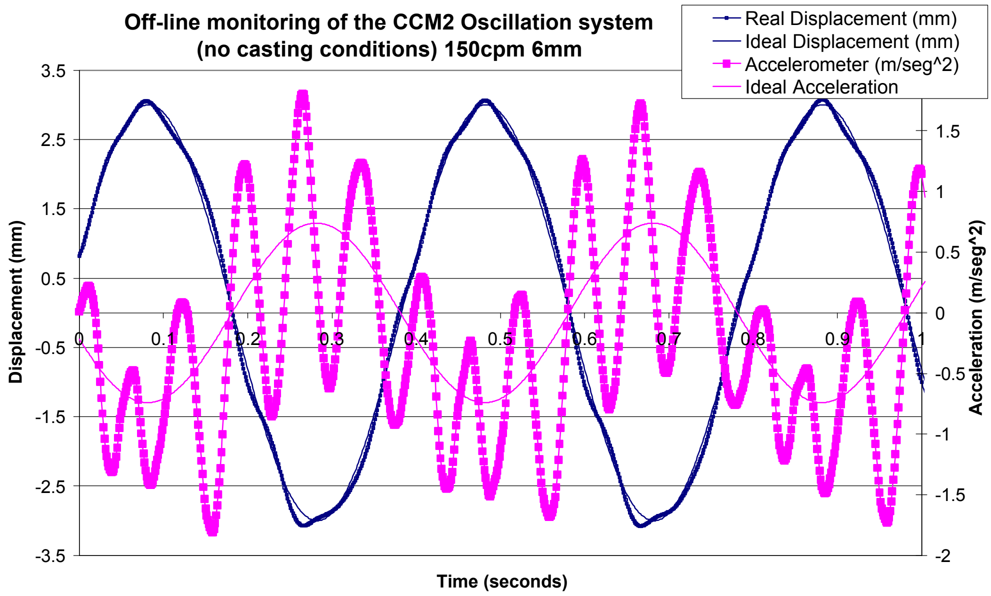

Figure 7. Off-line monitoring of CCM2. (No casting conditions) (150cpm 6mm). Bad working conditions (friction between mould cassette and stirring coil).

This example highlights the high sensitivity of the accelerometer signal as an amplifier of any abnormality in the mould displacement accuracy; and, subsequently, its utility for the off-line monitoring of the oscillation mechanism status. Because of that, an accelerometer per strand was installed in CCM2, and in **Figure 8** an example of the moulds oscillation performance is displayed

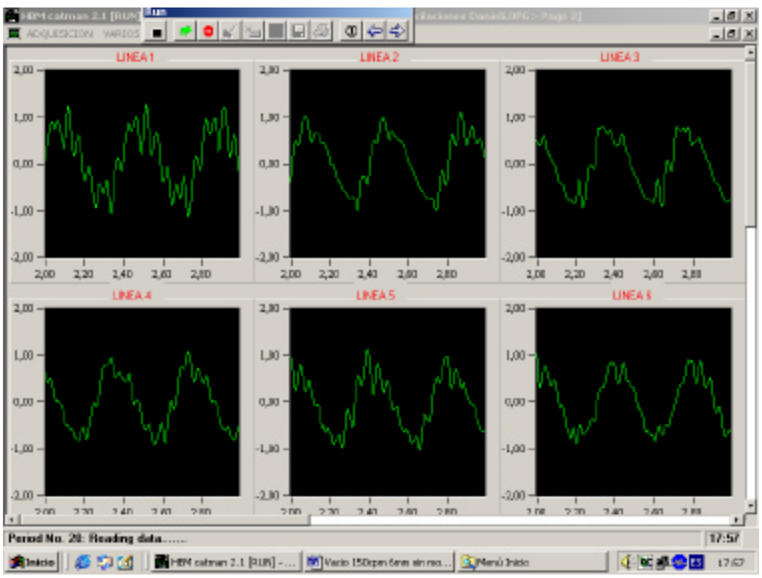

Figure 8. Display of one of the SIROL PC screens. Mould acceleration of the six strands of CCM2 (no casting conditions) (1 second).

In order to assess numerically the oscillation mechanism status, an index (I.B.O.) was defined by means of the harmonics decomposition analysis of the acceleration signals. **Table III** shows the results obtained for the example shown in **Figure 8**.

	Strand #1	Strand #2	Strand #3	Strand #4	Strand #5	Strand #6
I.B.O. (%)	81.7	93.3	90.5	92.3	90.1	94.0

Table III. I.B.O. values for the example shown in Figure 8.

An I.B.O. equal to 100% would mean that the acceleration signal is perfect; therefore, the lower the I.B.O. the higher both the deformation of the acceleration signal and the vibration of the mould movement. According to that criterion, in the case shown in **Figure 8**, it's possible to say that strand #1 performance is slightly worse than the rest of strands.

5.2. Billet-mould friction assessment

The research work aiming to study de accelerometer aptness for on-line friction assessment is underway; but, according to the results obtained up to now, it's possible to say that this device could be a quite accurate tool for the assessment of the friction between billet and mould.

Figure 9 shows an example in which the I.B.O. of the strand #4 is displayed together with the casting speed, the mould level, the stopper rod position and the tundish weight for a sequence of three heats. **Table IV** shows the main characteristics of the trial displayed in **Figure 9**.

	Trial characteristics (sequence of three heats)		
Heat number	22816	22817	22818
Steel grade	15NiCrPb6GR	17NiMoCr6EJ	19NiCrMoBi2E

Table IV. Characteristics of the trial shown in Figure 8.

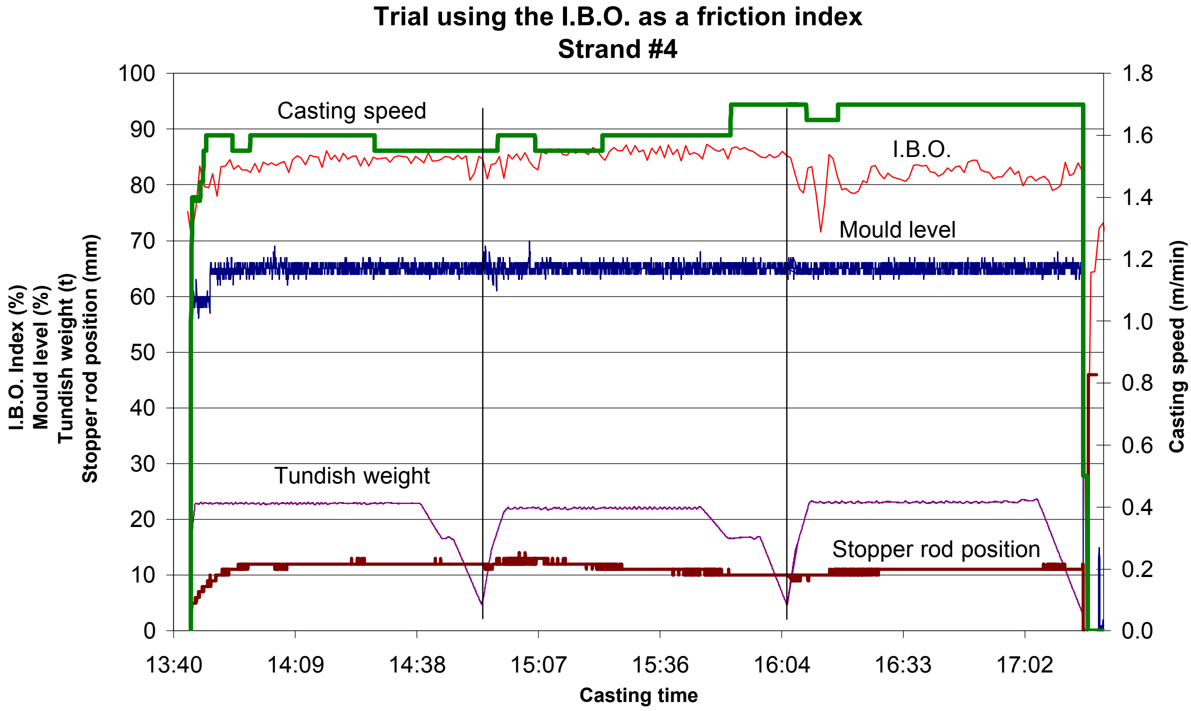

Figure 9. Trial using the I.B.O. Index (Strand #4) (Heats: 22816, 22817 and 22818).

The I.B.O. presented a lower value during the 3rd heat of the sequence, just from the moment the 3rd ladle was opened (the same phenomenon is observed in the rest of strands), and it seems to be indicating that during the third heat the friction was higher, thus causing a bigger distortion of the acceleration signal. Taking into account that the mould powder grade was the same for the three heats, that friction increase could be related to the different steel grade, or to a possible slag carry over to the mould. More trials are required to clarify that phenomenon.

The I.B.O. will be further investigated in order to corroborate its feasibility for billet-mould friction assessment.

6. CONCLUSIONS

An on-line monitoring system was set up providing valuable information that has allowed the study of some transient phenomena that appear during the continuous casting operation.

As far as the friction between billet and mould in CCM1 is concerned, both the cam rod force measured by strain gages and the electric current intensity of the mould oscillation motor (Iosc) were studied in order to obtain some criteria for friction evaluation.

- A Friction Force Index (F.F.I) was defined using the results of the Fourier Transform of the cam rod force signal.
- The increase of both peak to peak value and mean value of the cam rod force are related to an increase in the friction conditions between billet and mould. The same criteria are valid for the Iosc, but only for constant casting speed.
- Iosc signal has proved itself to have enough sensitivity for assessing the friction conditions particularly for a leaf spring guiding oscillation system.

A monitoring program called SIROL was developed in order to judge on-line the CCM performance through the analysis of the oscillation status and other mould related parameters. A first version of the program was working for six months at the CCM1 saving to hard disk a large amount of data related to abnormal transient casting phenomena for its later study. Using this method, information related to casting parameters prior to fifty-eight breakouts was obtained.

- The analysis of that information gave rise to some criteria that would allow to predict approximately 50% of the breakouts that took place during normal casting conditions.
- It was observed that the Iosc signal seems to have almost the same sensitivity as a breakout forecast index as the more complex strain gauge measurement.

Concerning the new CCM2, as a result of the application of the monitoring techniques, the following conclusions can be drawn:

- The on-line assessment of the motor oscillation intensity has proved itself to be a useful tool for early detection of problems in the oscillation system as well as for maintenance operations.
- The accelerometer is able to amplify any abnormality in the mould oscillation movement, so it's an useful tool for the off-line monitoring of the oscillation mechanism status.

- The accelerometer signal distortion analysis seems to be able to become a valid method for the friction assessment.

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8. LIST OF SYMBOLS

S.R.I.: Square Resembling Index of the cam rod force
F.F.I.: “Indice Bondad Oscilación”, friction force index based on the strain gauge installed in the cam rod
I.B.O.: “mould oscillation status index based on the accelerometer signal analysis
Iosc: oscillation motor current intensity
a.u. arbitrary units