Mould Level Fluctuations during Billet Casting at Hoogovens' BOS No. 1.

A. Hamoen *, J. van der Stel ***, S. Duysters ***, F. Mensonides **, P.G.J. Broersen *

* Hoogovens Staal Lange Produkten, BOS No. 1,
** Hoogovens Staal Lange Produkten, Quality Department,
*** Hoogovens Research and Development
+31-(0)251-495867

ABSTRACT

Mould level fluctuations at the meniscus influence the surface quality of the billet. These fluctuations, detected by the Co60 mould level detector, have been digitalized and presented as a level fluctuation number per billet cast. The influence of the tundish flow pattern and the fall-height between tundish and mould level has been investigated. A relationship between the fluctuation number and surface defects has been found. The fluctuation number can be a suitable tool for controlling and further optimizing the billet casting process.

1. Introduction.

Steel for billets is produced in BOS no. 1 in 105-tonne LD charges. In 1988 two 6-strand billet casters of Hoogovens Steel Long Products were put into operation. Since the start-up the production has totalled about 1.2 million tons of billets per annum in nine different sections ranging from 100 to 200 mm square. The production has gradually increased towards 65% billets for the market in mostly quality steels and 35% material for Hoogovens' own rebar mill.

Using modern secundary steelmaking facilities including a ladle furnace, the following types of steel are cast:

* Si-killed commercial steels (reinforcing bar/mesh- and merchant wire/bar/sections)
* Rimming substitutes (low carbon wire drawing, welding wire)
* Si-killed quality steels (medium/high carbon, welding, spring, free cutting)
* Al(Si)-killed quality steels (forging/SBQ, CHQ)

The product mix of quality steels comprises about 25% forging/SBQ, 15% CHQ, 40% medium/high carbon, welding, spring etc. and 20% rimming steel substitutes.

Various casting methods for shrouding between tundish and moulds are used:

* open stream casting through metering nozzles without any shroud (Si-killed);
* bellow casting through metering nozzles and a bellow as shroud (Si-killed);
* submerged entry nozzle casting using adjustable sliding gates and the SEN as a shroud (Al-containing steels), for 115 mm square and larger.

Of the total production about 40% is open cast, 30% bellow shrouded and 30% submerged. Si-killed steel casting through metering nozzles and oil lubrication is for billet casting the most practised and economical production method. At the same time for this casting system it is in general more difficult (more challenging), to get the necessary consistent surface quality than for the submerged casting with powder lubrication. For this paper the focus is on metering nozzle casting.
For metering nozzle casting of Si-killed steel (including rimming steel substitute) the most common surface defects are laps, pinholes (surface and subsurface) and slag inclusions. In this respect we think that meniscus level fluctuations have a large influence on surface quality.

There have been a lot of publications about the processes at the initial stage of solidification in the meniscus region. Kumar et al. [1] deliberately speak about "chaos at the meniscus". The most significant random disturbances occur with casting through metering nozzles into the mould pool. Rougher streams entrain more gas in the pool, creating more bubbles which, upon eruption from the meniscus, generate surface turbulence and waves.
The stream is influenced by the flow pattern in the tundish, the nozzle diameter and the nozzle geometry. The next important factor is the height between the outlet point of the nozzle and the steel meniscus in the mould.
The continuous movements of the steel meniscus in the mould interact with the oil weeping down the mould wall. This interaction can lead to the capture of oil (vapours) into the billet surface and/or hydrogen pick-up in the steel. Surface defects like surface and subsurface pinholes can result.

A lot of effort has already been put into the search for measuring the phenomenon occuring at and around the meniscus. This is done mostly by using heavily instrumented moulds (indicated by Brimacombe [4] as "the intelligent mould"), special measuring computers and special trial programmes [2,3].
Although most of the work reported in this paper was done using special off-line computers for data logging, attention was given to the on-line measurement of the mould level fluctuations. For this the BOS data logging system was upgraded and presentation software makes the results

visible to the people on the shop floor. The next step will be the transformation into a level fluctuation number per billet and the presentation of this number followed by an (automatic) system for quality control.

In this paper the level fluctuation number per billet was established by using the off-line equipment. The effect of a several casting parameters was investigated. These parameters were:

- tundish flow pattern resulting in different level fluctuation numbers per strand. The results of water modelling can be helpful to understand/explain the results and even to introduce flow control devices;
- mould size: eight different sizes were used during the measurement period;
- casting speed, or rather nozzle diameter;
- fall-height between tundish and mould.

One trial sequence has been used to determine if there is a relationship between level fluctuation number and a surface pinhole. A fairly straight correlation between these parameters was found. The higher the level fluctuation number the more pinholes.

2. Measurements.

The mould level is monitored by means of a radioactive Co-60 source coupled to a sensor (scintillation counter). The source randomly emits gamma-pulses through the steel in the mould and the sensor, which is mounted at the other end detects some of these pulses. The amount of pulses detected in a certain time interval depends on the level of the steel in the mould (figure 1).

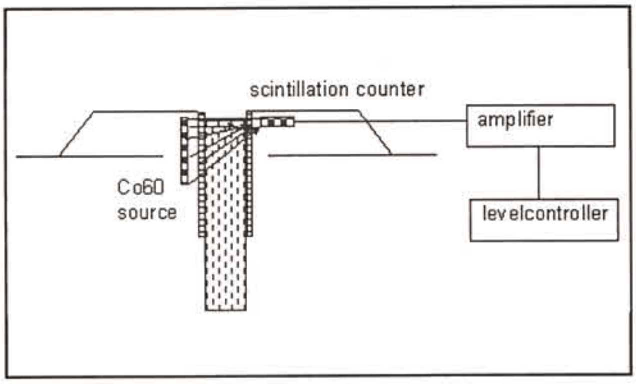

Figure 1. Mould level measurement.

An increase of the amount of steel in the mould by setting a higher mould level or another billet format, results in a decrease of gamma-pulses detected by the sensor. The amplifier which is connected to the scintillation counter converts the pulses into an analogue signal (0 - 10 V). In the amplifier a frequency to voltage conversion is done (level 0% is 0V and level 100% is 10V). This signal is put into the mould level control system.

The time constant of conversion determines the time period of counting the gamma-pulses and the level measured. A decrease of the time constant will give a less stable signal due to the actual fluctuations on the average level and the background noise of the radioactive source. An increase of the time constant will result in a more stable signal due to the smoothing of the fluctuations. This can therefore be a disadvantage to investigate the size and derivative of the actual fluctuations (figure 2). To compare the measurements it is important to define the mould level fluctuation number (mlfn) at a fixed time constant.

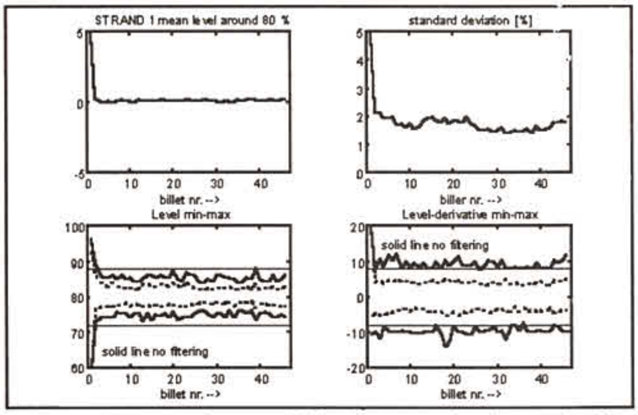

Figure 2. Proces data per billet (average level, standard deviation, minimum and maximum level).

In BOS no.1 the mould level signal is presented in the control room, traditionally on a chart recorder. For presentation purposes and for billet quality research, this way of presenting the mould level is not very suitable. By the use of R&D-equipment, a fast datalogging system, several casting parameters such as the mould level (figure 3), casting speed, "billet-is-born" indication and tundish weight were digitalised and put into a database.

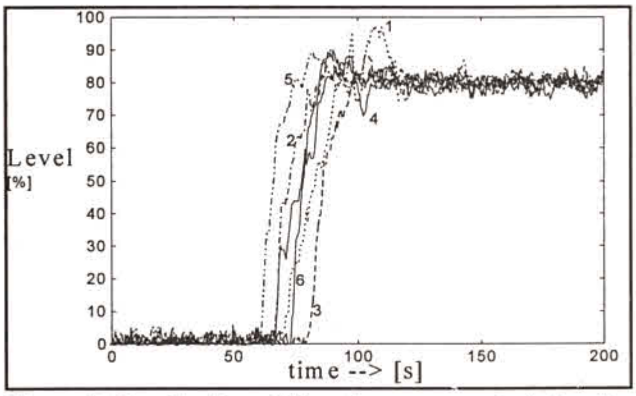

Figure 3. Results of mould level measurements in the six strands. The beginning of a cast is shown.

The mould level fluctuations were translated into a mlfn per billet (figure 4). The mlfn per billet is the standard deviation of the mould level during the casting of one billet.:

$$\text{mlfn} = \sigma$$

Assuming the mould level distribution to be Gaussian, the 6 σ equals the difference between the minimum and maximum level (99.73% of the measurement) in a billet.

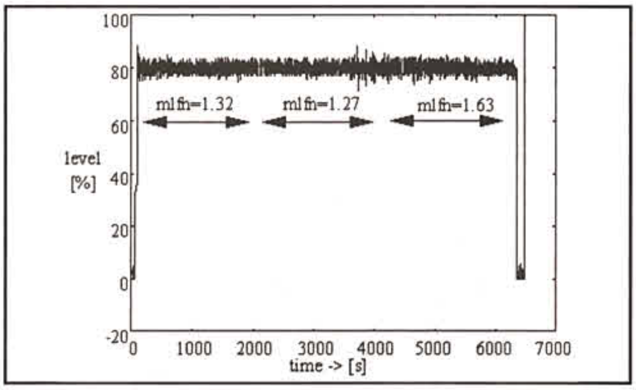

Figure 4. The mould level of mould no. 2 with the mould level fluctuation number (mlfn).

This means that in a billet with a mlfn of 1.63% (figure 4) the level fluctuated ± 3 x 1.63% = ±4.9%. For all billet sizes the average level is measured at 80%. This level is 115 mm beneath the top of the mould (100% is 75 mm beneath the top of the mopuld). The 0% level however is different due to the position and size of the mould with respect to the Co-60 source and the scintillation counter. The 0% level is 219 mm for the 200# mould and 190 mm for the 100# mould beneath the 100% level. This means that the mould level fluctuations in (mm) is different for the several billet sizes. For 200# ±4.9% is ±10.7 mm and for a 100# this is ±9.8 mm.

With the mould level fluctuation number the cast billets in a heat or in a sequence can be compared (figure 5). It can be seen that strand number 3 has a higher mlfn, starting at the

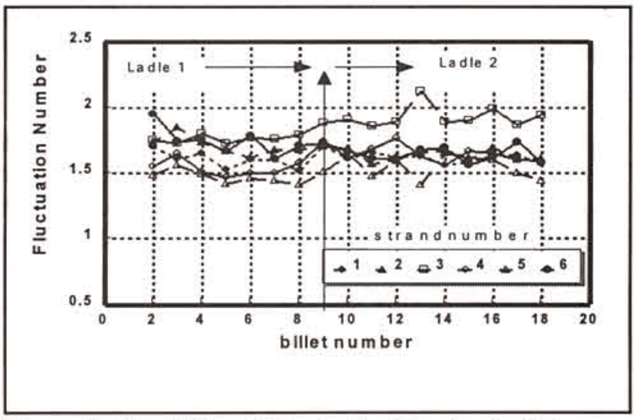

Figure 5. Mould Level Fluctuation Number (mfln) per billet for six strands in a sequence of two ladles.

end of heat number 1. From these data metallurgical and quality research can be done. The R&D measurements showed the necessity to install a modern data collection system on the continuous caster.

Early 1996 the BOS data logging system was upgraded to comprise all this. This system is now fulfilling the database function and shows the mould level and its fluctuations on a computer screen (figure 6). The newly installed system allows investigation of mould level signals as well as presentation of the data as a number per billet cast .

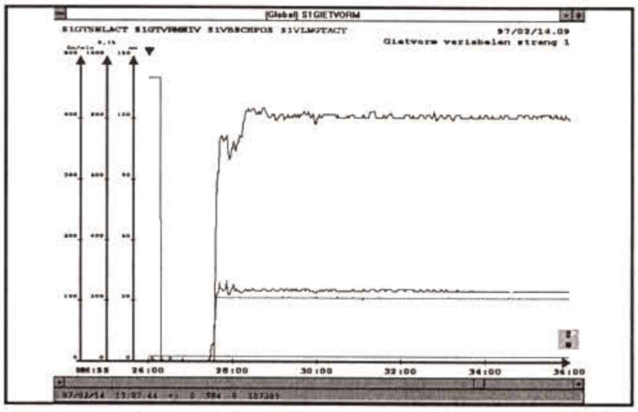

Figure 6. An example of the mould level with the BOS no. 1 data collection system.

3. Mould level fluctuations and casting parameters

With the use of the mould level numbers per billet various casting parameters can be investigated. The following parameters will be described: the mould size, the casting speed (or rather the nozzle diameter) and strand number, the latter being directly related to the flow pattern in the tundish. Water modelling of the flow patterns helps to explain the measured results.

3.1 Strand number

Without doing special trials, about 330 heats in different sizes have been analysed The results can be summarized in many ways. Looking at the influence of strand number the mfln per strand per heat is used. For the influence of casting speed and mould size an average mlfn per heat is used. Also the standard deviation of the data range is give.The data are presented in tables 1 and 2.

Table 1. Unfiltered data (number of heats, average mfln with standard deviation).

strand no.	1	2	3	4	5	6	heat ave-rage
avrg mlfn %	1.50 ± 0.22	1.51 ± 0.26	1.44 ± 0.29	1.55 ± 0.30	1.45 ± 0.27	1.37 ± 0.20	1.48 ± 0.24

This is an unfiltered representation of all the data, only in exceptional cases the start or end billets has been excluded.

For the filtered data in table 2 part or the whole of the mlfn's have been removed.

Strand no. 3 and 6 have the lowest average mlfn. This can be explained as follows:
The so called "dead zones", areas with very little movement or flow of the liquid steel, are thought to be responsible for good stream practice and very little level fluctuations. In the explanation for the influence of strand number and with the help of water modelling it can be seen that both strand 3 and 6 are strands in the "dead zone".

Table 2. Filtered data (number of heats, average mlfn with standard deviation).

strand no	1	2	3	4	5	6	heat ave-rage
avrg mlfn %	1.48 ± 0.23	1.48 ± 0.26	1.41 ± 0.25	1.47 ± 0.23	1.42 ± 0.25	1.37 ± 0.21	1.44 ± 0.22

Filter percentages are 35% for strand no. 4 , 20% for strands 1 and 2 and 5% for the other strands. For strand 4 the filtering results in a significant drop in the standard deviation and also alters the average level fluctuations. In the unfiltered case strand 4 is the worst with the largest standard deviation and in the filtered case it is no longer exceptional. During the measuring period strand 4 may have been misaligned, the oscillation bellows damaged or the discrepancy may have other structural causes for such.

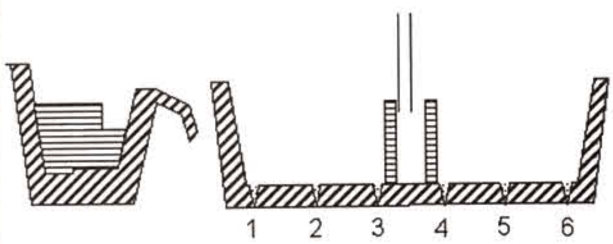

Figure 7. Sketch of the wall geometry in the tundish.

The differences in the strand numbers in table 2 can be explained from the flow patterns in the tundish. BOS no. 1 operates the tundish with two dividing walls (figure 7).

Water modelling of this tundish geometry (performed by Magneco Metrel) clearly shows the origin for the difference in flow as shown in figure 8.

As figure 8 shows, the strands 3 and 4 are "short circuited". This could be the cause of the streams being disturbed. On the other hand the presence of the walls can disturb the flow through the nozzles. Strands no. 1 and 6 show clearly the "dead zones" and this is possibly the cause for good stream practice and little level fluctuations. Strands 2 and 5 are between these two extremes. The values in table 2 do not totally agree with the results from the model.

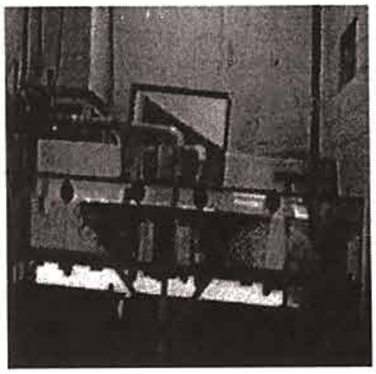

Figure 8. Results of watermodel experiments with wall near the long nozzle.

Since the start-up of the machine there has been a difference between the left side (nos. 1, 2 and 3) and the right side (nos. 4, 5 and 6). This always occurs during start-up of a sequence where the right side starts casting before the left side. This is not because of not being horizontal but because the ladle shroud is not in the middle of the tundish, it is actually about 10 cm to the left. This effect has not been water modelled yet.
It is possible that the ladle shroud not being in the middle causes the "short circuiting zone" to move from strand 3 to strand no. 2. Strand no. 3 will be in a more quiet or dead zone, but not as quiet as strand 6 because of the walls. Strand no. 1 is therefore also more turbulent than strand no. 6. This corresponds with the values in table 2.

As a result of these findings we are now experimenting with flow control devices which diminish the differences between the strands and which makes the flow independent of the ladle-shroud position in the tundish. The effect of the devices will be measured with the mlfn as mentioned in the tables 1 and 2. This will be done after running the operational trials.

3.2 Mould size

In figure 9 the filtered data per mould size are given:
The larger the mould size the less the mould level fluctuations occur. This is to expected because the relative impact area of the stream in the mould becomes larger with decreasing cross section of the mould.

The greater number of fluctuations for 115 # compared to 100 # can be explained by the fact that 100 # is cast with only one nozzle size i.e. 14.5 mm. This to create a relative

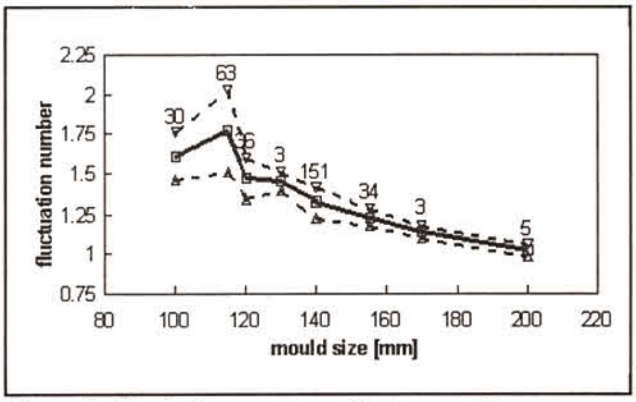

Figure 9. The influence of mould size on mlfn.

low casting speed to avoid break-outs. For the 115 # a much larger variety of nozzle sizes (15.0 to 16.0 mm) and casting speeds are used. This effect is discussed in the next section.

3.3 Casting speed (nozzle diameter)

In 115# the large range in nozzle diameter (and therefore casting speed) is used. The results are in table 3.

Table 3. Results of 115 # billets.

heats cast	nozzle diameter (mm)	aim cast. speed (m/min)	mlfn %
20	15.0	2.73	1.56±012
13	15.5	3.03	1.56±0.12
30	16.0	3.45	1.97±0.20
total			1.77±0.26

The results can be explained as follows:
When there is no effect of steel grade and casting speed, the difference in mlfn will depend only on the nozzle diameter. The larger the diameter the more fluctuations can be expected. This is not found for the 15.0 - 15.5 mm nozzles. The 15.0 mm nozzle however is specially reserved for high carbon (> 0.6% C) grades. We found that casting these high carbon grades at a high speed caused unacceptable level fluctuations. Therefore the casting speed was lowered (15.0 mm nozzle). High carbons are more prone to sticking [5]. Together with a relative big taper this may cause the fluctuations to be higher than expected for 15.0 mm nozzles.
The extremely high value for 16.0 mm nozzles might be caused by the fact that at this casting speed and stroke the maximum frequency of the oscillation is reached. This can cause extreme level fluctuations.

4. Effect of fall-height between tundish and mould

The influence of the fall-height between tundish and mould level has been investigated. The lower the fall-height the less fluctuations occur. This can be shown both by a water model and by the fluctuations number.

In BOS no. 1 the distance between the bottom of the tundish (outlet nozzle) and the meniscus was thought to be very high. Because of the emergency gutters and the bellow shrouding this distance is 60 cm. In comparable steel plants this is less than 40 cm. Usual this height might also influence the level fluctuations.

Water modelling of this effect clearly shows that the larger the fall-height the more turbulence occurs. It can also be shown that lower fall-heights result in a more stable level but the penetration depth of the incoming stream is much larger. Figure 10 shows the results of this water modelling. For this reason trials were done with lower fall-heights.

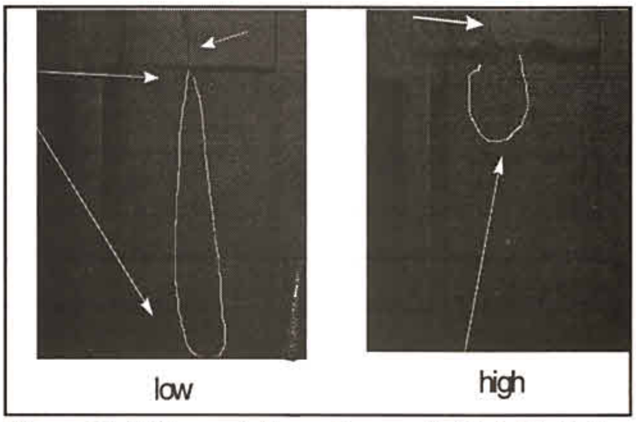

Figure 10. Water modelling of low and high fall-height.

Casting without gutters was needed and the tundish was also deepened. For this trial one of the tundishes was cut in half and 20 cm of steel and monolite were added (figure 11). The tundish volume increased from 15 to almost 20 tonnes. Together with the possibility to lower the tundish an extra 5 cm a fall-height of 35 cm instead of the previous 60 cm was reached.

We made three trials using this tundish:

- high carbon 140 # and 16.0 mm nozzle
- high carbon 120 # and 15.5 mm nozzle
- high carbon 115 # and 14.0 mm nozzle

In analysing the results the figures per billet were used without filtering except for the first, last and the billets for which the fall-height or the tundish weight had been changed.

Trial 1:

The trial was performed with 16.0 instead of 15.0 mm nozzles and compared to the reference heats (see chapter 3) because we thought that the higher fluctuation numbers from a bigger nozzle could be compensated by a lower fall height. Three stages were tested as shown in the following table:

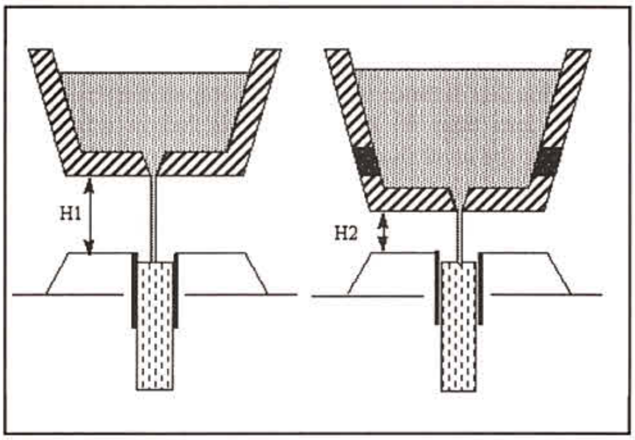

Figure 11. Sketch of the deepened tundish.

Table 4. Test program deepened tundish trial 1 in 140#.

situation	mlfn
reference: 60 cm, 15.0 mm nozzle, 12.5 ton in tundish	1.34 ± 0.11%
1) 60 cm, 16.0 mm nozzle, 12.5 ton in tundish	1.40 ± 0.09%
2) 35 cm, 16.0 mm nozzle, 12.5 ton in tundish	1.30 ± 0.05%
3) 35 cm, 16.0 mm nozzle, 19.0 ton in tundish	1.51 ± 0.09%

For the standard situation (fall height 60 cm) the difference between 15.0 and 16.0 mm nozzles can be explained (see chapter 3.3). A lower fall-height gives a better result: 1.30% compared to 1.40%.

For the 19.0 ton tundish the situation is worse again. The maximum oscillation parameters at this extremely high casting speed might be the cause or the higher ferrostatic pressure may have an influence by disturbing the perfect stream through the nozzle.

Trial 2:

Trials in 120# with a 15.5 mm nozzle.

Table 5. Test program deepened tundish trial 2 in 120#.

situation	mlfn
reference: 60 cm, 15.0 mm nozzle, 12.5 ton in tundish	1.54 ± 0.17%
1) 60 cm, 15.5 mm nozzle, 12.5 ton in tundish	1.65 ± 0.11%
2) 35 cm, 15.5 mm nozzle, 12.5 ton in tundish	1.58 ± 0.04%
3) 35 cm, 15.5 mm nozzle, 19.0 ton in tundish	1.88 ± 0.07%

The results are the same as found in the first trial an improvement by about 5% for the lower fall-height was found. Comparing only high carbon steels the influence of nozzle diameter is more predictable (see chapter 3). A 15.5 mm nozzle gives somewhat higher level fluctuation numbers than a 15.0 mm nozzle.

Trial 3:

In order to reach the standard speed of 2.73 m/min with 19.0 ton in the tundish a 14.0 mm nozzle was used instead of 15.0 mm.This high tundish weight or ferro static pressure might disturb the perfect flow through the nozzle. The one situation being tested is shown in table 6.

Table 6. Test program deepened tundish trial 3 in 115#.

situation	mlfn
reference: 60 cm, 15.0 mm nozzle, aim speed 2.73 m/min	1.68 ± 0.16%
1) 35 cm, 14.0 mm nozzle, aim speed 2.73 m/min	1.65 ± 0.04% (unfiltered) 1.58 ± 0.04% (filtered)

During this trial strand 3 (as strand 4 during the first measuring period) behaved exceptionally badly with 15% higher values. Remove this strand data and the difference between 60 cm and 35 cm becomes clear (filtered data in table 6).
Not running into the conditions for maximum oscillation the extreme fluctuations disappeared. Casting at the same speed, the 14.0 mm nozzle gives better results than the 15.0 mm nozzle (filtered). The influence of the ferrostatic pressure suggested when explaining trial 1 seems to be negligible.

It is clear that the beneficial effect of a lower height can be largely outweighed by one or more extreme strand(s). The parameters responsible for this must be found in the flow

pattern in the tundish (see the results of chapter 3.2) or the oscillation behaviour in the mould or the lubrication might be considered. On this latter subject some trials were run in BOS no. 1 a few years ago and presented in an article by van der Stel et al. [2].
We are working now on a LVDT (linear velocity displacement transducer) measurement. By putting the signals into the data collection system they can be used as the mould level fluctuation measurement.

5. Influence of mould level fluctuation number on surface-pinhole defects

The meniscus, which is the region of initial solidification, affects the nature of oscillation marks as well as the surface quality of the cast strand [1,4]. A number of studies have focused on events occuring in this region to understand the mechanisms generating defects in continuous casting. All these mechanisms originate from a basic sketch given by Brimacombe (figure 12).

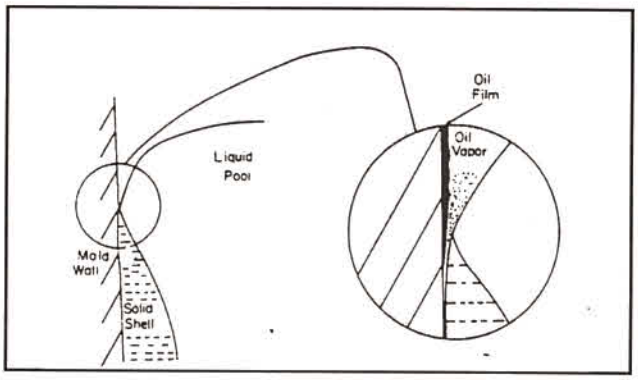

Figure 12. Sketch of oil flow down the mould wall into the meniscus region [1].

In [1] the mechanism for lap formation and bleed formation from this basic sketch are given. We consider the oil vapour in the sketch in combination with level fluctuations to result in surface pinholes.

A major reason for developing an instrument to registrate the mould level fluctuations is to relate the fluctuations to the presence of surface pinholes in the billet. An industrial trial was made in order to investigate this relationship.
For this trial 120 mm square billets were observed from the first and the last heat of a sequence of Si-killed steel with 0.69% carbon content (trial 2). The billets were cast with bellow shroud and oil for mould lubrication.
To initiate a wide range of mould level fluctuations, the fall-height was reduced halfway through casting the first heat. The casting speed was increased by up to 15% halfway through casting the last heat. Since the mould level fluctuations of the first cast billets have another origin than the other billets and for reasons of operational/registration problems for the last two billets of the last heat, these billets were excluded.

For each billet, the corresponding mould level fluctuations are translated into a mould level fluctuation number as described before.

To determine the contamination of the billet surface pinholes, the billets have been shotblasted to remove the oxide layer followed by visual inspection. On all 4 sides of the billets the number of surface pinholes is manually counted and registered.

To express the rate of contamination of pinholes per billet, a pinhole number coefficient is introduced:

$$PNC = \frac{\text{number of pinholes per billet}}{\text{maximum number of pinholes per billet}} \times 100\%$$

Figure 13 shows that a good relationship is established between the pinhole number coefficient PNC and the mould level fluctuation number where the pinhole number coefficient PNC increases with increasing mould level fluctuation number.

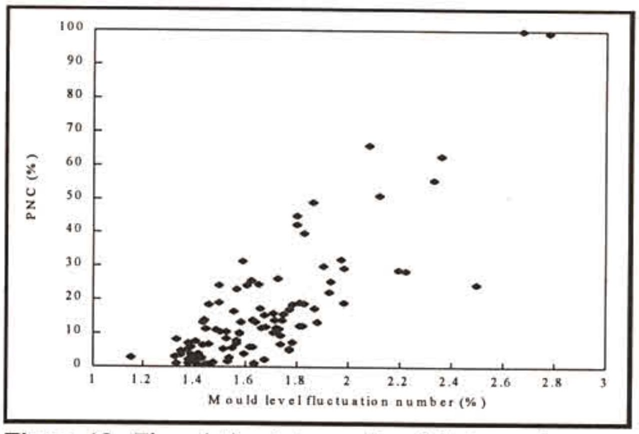

Figure 13. The relation between the pinhole number (pnc) and the mould level fluctuation number (mlfn).

In this way for each steel quality and mould size an automatic indication system can be developed for quality control purposes to the extent that a certain value of the level fluctuation number must not be exceeded. This was also one of the conclusions drawn by Jenkins et al [6], " mould thermocouple and level signals should be used as part of a quality monitoring system to produce quality alarms".

6. Summary and Conclusions

Investment in modern data-logging equipment at Hoogovens BOS no. 1 to record the mould level fluctuations resulted in optimisation of the casting practice and an on-line quality performance indicator.

Important parameters influencing the level fluctuations investigated were:

- tundish flow pattern
- mould size
- nozzle diameter
- height between tundish and meniscus level in the mould.

However the effect of these parameters could be outweighed by other parameters not studied in this paper. Oscillation and lubrication will be investigated further. Maintenance of the caster may also affect performance. For this purpose the level fluctuation numbers can also be used. A fair relationship between mould level fluctuation number and surface pinholes was found.

7. References

[1] S . Kumar, B.N. Walker, I.V. Samarasekera and J.K. Brimacombe, "Chaos at the meniscus - the genesis of defects in continuously cast steel billets" *Conference: Process Technology. Vol. 13, Continuous Casting.* Nashville, Tennessee, USA, 2-5 April 1995, pp 119-141.

[2] J. van der Stel, J.M Rabenberg, M.C.M Cornelissen and J. Cijsouw, "Oil lubrication and shrouding for billet casting", *Proceedings of the 1st European Conference on Continuous Casting,* Florence, September 23-25 1991, Vol. 2, pp 377-386.

[3] Tingju Li, Shinji Nagaya, Kensuke Sassa and Shigeo Asai, "Study of meniscus behaviour and surface properties during casting in a highfrequency magnetic field", *Metallurgical and Materials Transactions B,* Volume 26B, April 1995, pp 353 - 359.

[4] J.K. Brimacombe, "Empowerment with knowledge - towards the intelligent mold for the continuous cating of steel billets", *Metallurgical and Materials Transactions B,* Volume 24B, December 1993, pp 917 - 935.

[5] Samarasekera et al. "Mould shape, heat transfer and mould - strand interaction in the continuous casting of steel billets", *Invited paper, plenary session - Conference on continuous casting of steel in developing countries,* The Chinese Society for Metals, Beijing China, September 14-18 1993.

[6] M.S. Jenkins, B.G. Thomas, W.C. Chen and R.B. Mahapatra, "Investigation on strand surface defects using mould instrumentation and modelling", *Steelmaking Conference Proceedings,* 1994, pp 337-345.