Soft reduction in the continuous casting of billets

The new billet caster at Saarstahl AG uses a soft reduction unit instead of conventional pinch rolls. The hardware and software design is such that the degree of soft reduction can be easily optimised so as to improve internal segregation.

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The six-strand circular-arc continuous caster S0 at Saarstahl AG in Völklingen, Germany was commissioned in April 2004. With its casting radius of 11m and multipoint straighteners, it is designed to satisfy the demand for both high surface and internal quality of the billets *(see Fig. 1)*.

The caster' s specific features include moulds capable of operating at high casting speeds of up to 4m/min with covered casting, a hydraulically powered resonance oscillator, high capacity and wide frequency range moulds, strand stirrers, segment-type strand guiding system for exact guiding of the billets, high-capacity cooling with a high pressure stage and combined air and water cooling. The billet sizes are 150 x 150mm, with lengths ranging from 8 to 15.5m and 180 x 180mm with lengths ranging from 6 to 13m.

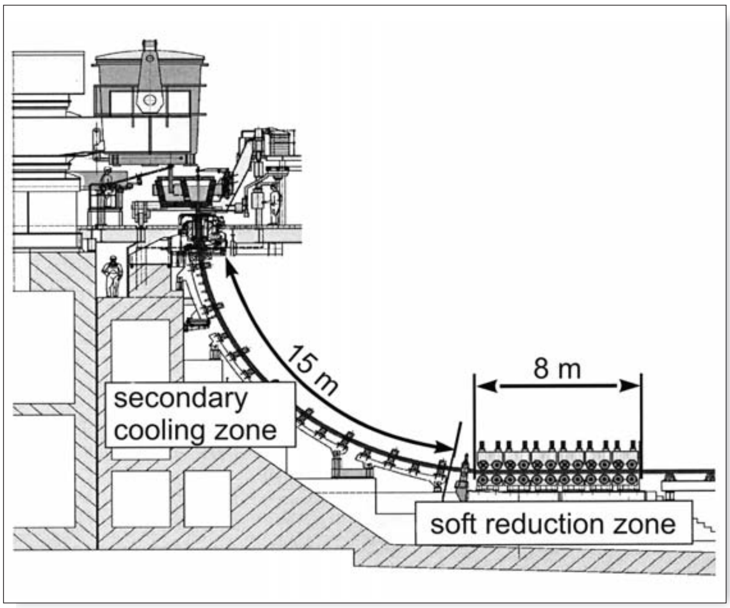

Fig.1 Cross-section of the billet caster

A core component of the facility is a segment-type Soft Reduction unit instead of conventional pinch-roll units. A dynamic computation model DSC (Dynamic Solidification Control) is used to optimally match secondary cooling and Soft Reduction.

THE SOLIDIFICATION PROCESS

In the continuous casting of steel, the course of solidification may be divided into different phases. Inside the mould, a thin strand shell solidifies first which is a few millimeters thick and is characterised by a fine-grained microstructure owing to the high solidification rate, and where differences in chemical composition caused by diffusion can barely be compensated. For this reason the composition of the alloying elements in the strand shell differs from the bulk of these elements in the molten steel, and some elements (for example, C, Nb, P, S, Mn, Cr) are enriched in the remaining liquid (positive segregation).

As the strand shell increases in thickness, the transfer of heat from the liquid steel in the strand core through the strand shell to the outside reduces. A phase of directed, dendritic solidification starts, with the main axis of the dendrites being aligned along the direction of the heat flux. Here too the solidification speed is high enough to allow some alloying elements to become enriched in the remaining liquid. Some of the enriched molten metal is left between the dendrite arms such that the chemical composition of the solidified strand shell may change significantly within distances of only a few µm (microsegregations).

At a certain point in time the geometric conditions between the growing strand shells prevent further exchange of liquid. This is the critical mushy diameter (CMD) which is where the final solidification phase starts. Since the reduction in volume in phase conversion from liquid to solid is higher than the shrinkage of the strand shell which occurs at the same time, cavities are formed at the strand centre. At the same time, the remaining liquid that has been segregated by the ensuing negative pressure solidifies at the strand centre producing macrosegregation.

THE SOFT REDUCTION PROCESS

Soft reduction is a particularly effective method of reducing unwanted segregation effects and hence improving the quality of continuously cast steel. In this process, in addition to normal thermal shrinkage, the strand thickness in the area of final solidification is reduced by external forces in order to balance the volume reduction of the liquid strand core and to prevent the enriched remaining liquid from being taken drawn into the cavities. While this method has been used for slabs and blooms for many years, despite the positive results of tests, the geometric conditions of billets did not result in practical implementation until now where it has been

Fig.2 **Billets during soft reduction**

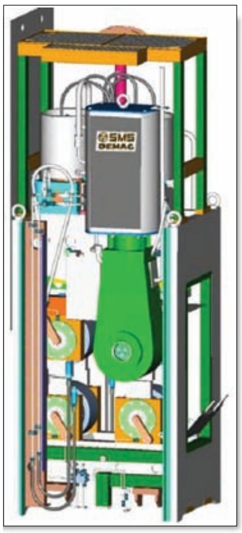

Fig.3
Pinch-roll segment

Fig.4
Pinch-roll segment

successfully put into practice on the new billet caster S0 at Saarstahl *(see Figs. 2,3,4)*.

This unit comprises six hydraulically adjusted segments per strand which each have two separately adjustable rollers which allow adjustment and transmission of forces in the area of solidification, and hence directly influence internal microstructure. The caster is particularly suited for optimising the soft reduction feature since a square section becomes self-supporting immediately on leaving the mould. The distance between the rollers is 680 and 720mm *(see Fig.5)*. This configuration makes it possible to precisely adapt the start and end of soft reduction as well as the degree of the individual soft reduction steps to the specific requirements. ▷

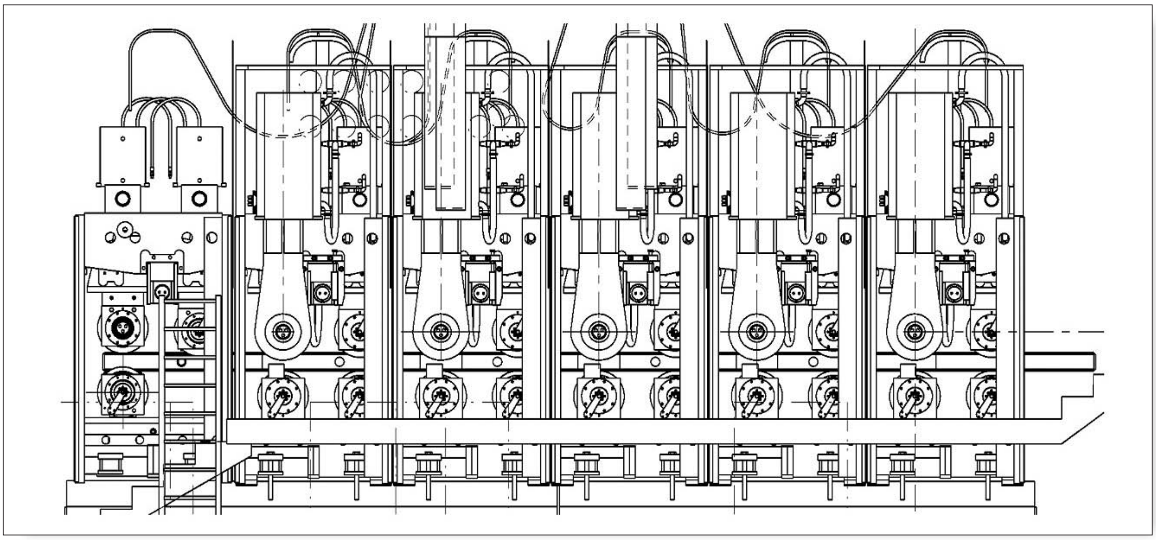

Fig.5 **Pinch-roll and soft reduction segments**

SOME PREREQUISITES FOR THE SUCCESSFUL APPLICATION OF SOFT REDUCTION

Ideally, the strand thickness should be reduced to the extent that the arising differences in volume between shell and core are completely balanced. This would best be attained if soft reduction proceeded continuously as this would minimise mechanical loading of the sensitive strand shell. However, forces can be transmitted to the shell only at those points at which variable-position rollers are available. This means that higher reductions are required at these points than with continuous loading, which may result in the solidifying strand shell at the liquid/solid phase boundary being torn open between the dendrites or on the primary grain boundaries (zero ductility) if the load exceeds the yield stress.

These resulting internal cracks are detrimental to product quality because they will be re-filled with segregated liquid and may thus have a negative influence on the mechanical properties of the cast product during casting or further processing. If the strand shell is subjected to further stress, segregated internal cracks that have already been produced may enlarge.

The technical literature describes the temperature range between the zero-solidification temperature (ZST, solidification factor fs = 0.8) and the zero-ductility temperature (ZDT, solidification factor fs = 1.0) as critical temperature points. Any supercritical loading within this range leads to segregated or open internal cracks. The position and length of the cracks makes it possible to draw conclusions about the temperatures or the degree of solidification at the point at which cracks occur.

A factor which is equally important for the success of soft reduction is knowing the exact position and optimum length of the final solidification range. In view of the causes for the occurrence of cavities and macrosegregation at the strand centre, soft reduction should start at the critical mushy diameter and end before final solidification. A further thickness reduction (hard reduction) immediately after full solidification of the strand may further reduce the volume of the remaining cavities. To avoid further cracks at this stage hard reduction should only take place at temperatures below the ductility trough.

Since both the critical mushy diameter and the position of final solidification are not accessible for direct measurement, casting conditions and adjusting parameters for a suitable soft reduction strategy must be established by way of tests and adhered to as accurately and consistently as possible in each sequence. This cannot always be accomplished with the necessary accuracy, especially where smaller strand cross sections are involved.

Thus in order to minimise segregation and cracking during soft reduction it is important to fully optimise the reduction both to the casting conditions and the steel grade.

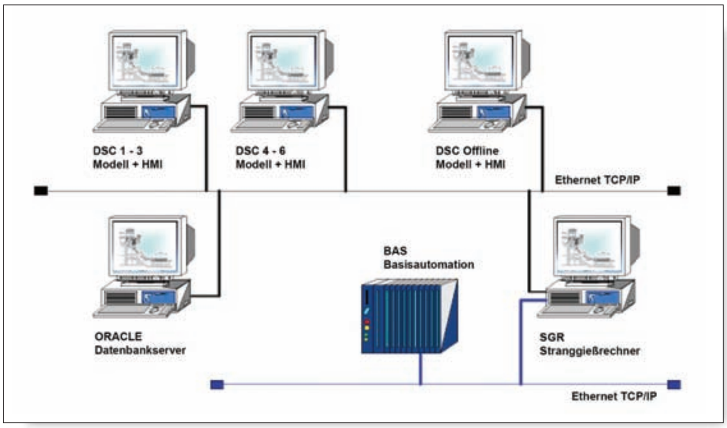

Fig.6 **DSC computer configuration**

OPTIMISATION OF SOFT REDUCTION AT SAARSTAHL

Hardware A new way of minimising the cost of optimising soft reduction has been successfully tested at Saarstahl. All the rollers involved in soft reduction or located downstream of the soft reduction area can be simultaneously lifted from the strand, thus a sample piece of billet is produced which no longer undergoes deformation in the course of further solidification. After cooling down, the effect of the individual reduction stages on cavities, segregation and internal cracks can thus be assessed by metallographically.

Software *Figure 6* shows the computer configuration for the Saarstahl caster. Here the DSC online models of three strands each are grouped together in one computer. The data obtained from the casting process are saved on the database server. An additional computer containing the DSC models is available offline for planning of the casting process and for subsequent evaluation of process data. A network connection ensures communication between the continuous caster and the DSC computers.

DSC is a software tool that includes a wide range of options and can, for instance, calculate and control the location of final solidification and the diameter of the liquid area at the centre of the strand (liquid core) for any position over the length of the strand. For this reason, as an alternative to the above, the location of the point of solidification and the length of the area of full solidification may be calculated. This makes it possible to adapt the various reduction steps to the respective casting conditions, and in so doing, minimise the cost involved in finding suitable soft reduction parameters for new steel grades.

DSC thus supports steelmakers both in the planning and implementation of the casting operation as well as in the subsequent review and assessment of stored process data for quality assurance. For these tasks DSC makes three functions available: DSC Online, DSC Offline and Replay mode.

DSC Online The purpose of DSC Online is to control the cooling water secondary cooling system flow rates during casting. Depending on the control mode and process data (current analysis, casting speed, casting temperature, etc.), the water flow rates are established for the various cooling circuits. The available control modes are temperature control, solidification point control (position of final solidification) and control of the critical mushy diameter (CMD).

The control modes of the online model are:

- **Surface temperature control** In this mode, the strand surface temperatures at the points of transition are controlled between the various secondary cooling zones through adaptation of the spray water flow rate. The set point temperatures at these points are specified by production personnel.
- **Dynamic solidification control** In dynamic solidification control mode the point of final solidification of the strand is controlled by changing the water flow rate in the secondary cooling system.
- **Control of critical mushy diameter** Control of the CMD means that its position is held at a preset point by changing the spray water flow rate in the cooling zones.

DSC Offline The offline DSC helps to determine and check suitable process parameters by simulating the casting process. In this way changes to the steel composition, casting speed, casting temperature and soft and hard reduction can be evaluated. The offline model may be used for planning casting sequences (spray patterns, casting speeds, reductions for soft and hard reduction, and evaluate reactions when changing the casting parameters). The effect of scheduled changes may also be examined in advance (planning of test series, analysis of quality problems, modification of facility).

Replay mode In combination with the offline DSC, replay mode can be used to simulate a cast already made. This makes it possible to trace the cause of quality problems, allow specific sampling in transition areas or determine the cause of temperature variations between computation and measurement.

PREPARATION OF SOFT REDUCTION BILLET TEST PIECES

As shown in *Figure 7* there is a direct relationship between the CMD and the size of the cavity which remains at the strand centre after cooling. Two methods are employed to determine the diameter of the remaining cavity, and the results are compared. One section (length 600mm) of the non-deformed billet is vertically split at the centre, the split face is ground, photos are taken and the maximum extension of the cavity band is determined. The same cut piece is then radiographed in order to search for further cavities in the strand centre which are not visible in the micrograph.

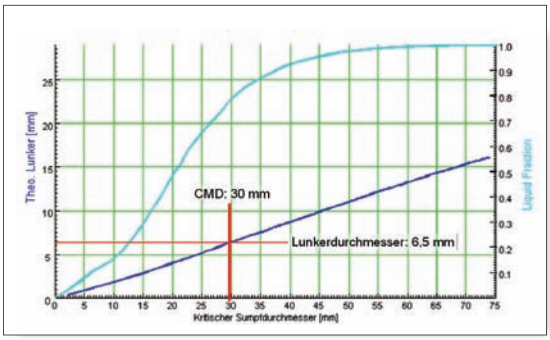

Fig.7 **Relationship between critical mushy diameter and size of the remaining cavities**

ESTABLISHING THE CMD

To determine the influence which the various casting parameters have on the position of the CMD and hence on the start of soft reduction, a few computations have been made using the DSC offline model. It has been found that in addition to the casting speed and cooling water flow rate, the temperature of the steel in the tundish and the steel composition need to be taken into account when planning tests during regular casting operation. *Table 1* shows how these parameters affect the position of the CMD. The material used in the model was a 0.45% C steel (C45). The \`Change\` column indicates the extent of the respective change in position of the CMD for the variation indicated.

Casting parameters	Basic value	Variation	Change in CMD position
Casting speed	4 m/min	+0.1 m/min	+ 585 mm
Secondary water	100%	+ 10%	- 458 mm
Tundish temperature	33 K above T liq	+ 20 K	+ 526 mm
Carbon content	0.46%	+ 0.04%	+ 299 mm
CMD	30 mm	+ 2 mm	- 355 mm

Table 1 **Influence of casting parameters on the position of the CMD**

Apart from the influencing factors which may be preset or can be measured, the size of the CMD is important when selecting suitable soft reduction parameters. While the other factors primarily influence the position of the CMD, its size additionally affects the extent of the reductions needed to compensate the difference in volume between the remaining liquid and strand shell. For example, an increase in the CMD from 30 to 40mm may lead to the total reduction required to fully reduce the central cavity having to be raised from 7.5mm to 15.5mm.

Figure 8 shows the results of both examinations. The left part of the figure is a false-colour representation of the central area of the longitudinally cut samples. The cavities are marked red. Note that the distribution of cavities seems to be non-uniform. The right part of the figure shows the radiograph of the same longitudinally cut sample at the same scale. The cavities here appear darker and, although at some points, there is conformity between the quantity and distribution of cavities in both figures, overall, the radiograph shows many more cavities which are more uniformly distributed than in the micrograph.

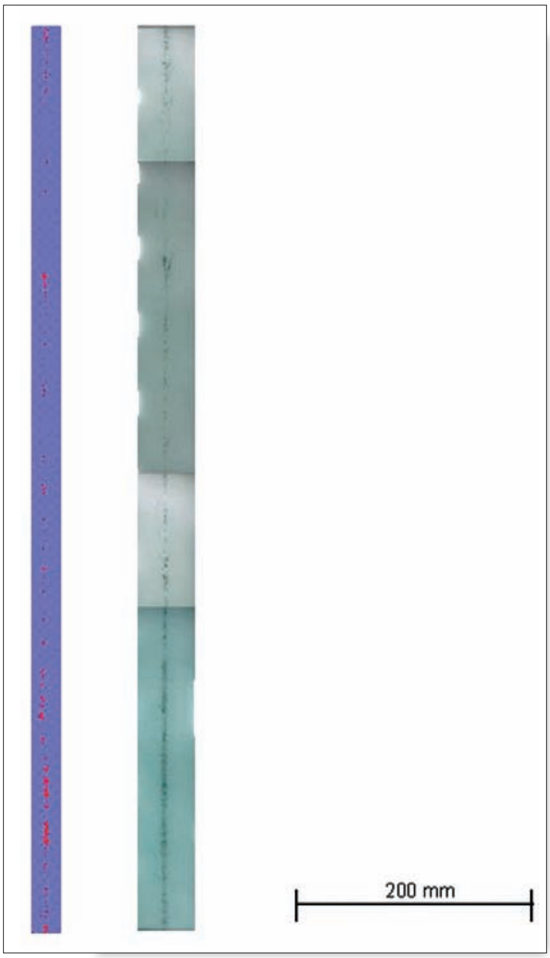

Fig.8 Expansion and distribution of the cavities at the strand centre;

From these examinations it may be concluded that the density and distribution of the cavities at the strand centre remains relatively constant over the cast length. The position of the porosity band may vary slightly, which is why not all cavities are visible in micrographs. However, it is clear that both methods may be employed to establish the same extension of the cavity band vertically to the casting direction. In this example it is around 6.5mm and results in a CMD of 30mm.

PLANNING AND IMPLEMENTATION OF TESTS

In line with the above considerations, the individual reductions chosen for testing were so large that the different changes in volume of the remaining liquid and strand shell are just about balanced with each thickness reduction and the ensuing cavities are re-compressed. This is to prevent the remaining liquid that has been segregated by the ensuing negative pressure from being drawn into the cavities, resulting in segregation. However, not all the deformation applied to the strand from the outside becomes effective as volume reduction inside the strand. Depending on the status of solidification, the temperature curve in the strand shell and the strength conditions, the effective proportion of deformation may vary.

Since it has been found in past tests that small deviations from the scheduled process parameters lead to an unacceptably high displacement of the CMD, the exact height and position of the soft reduction were not calculated by the DSC offline model until just before the start of testing. The test was conducted using C45 as material for the model. A cast with an increased sulphur content was deliberately chosen in order to more clearly show the segregation and cracking behaviour of the test billets via sulphur prints.

The procedure for making test pieces with several stepped reductions was as outlined above. Upon reaching stable conditions, the rolls of the pinch-roll segment are set to the calculated soft reductions. These positions were maintained for about one billet length. All the rollers involved in soft reduction as well as all subsequent rollers were then opened simultaneously. The billet produced with stepped reduction was singled out for further examination downstream of the torch cutter. This operation was repeated immediately afterwards without interrupting casting, with the preset reductions divided by two. In total two billets with different total reductions were available for further tests.

EVALUATION OF SAMPLES

The exact dimensions of the two billets were taken, some areas cut out and sulphur prints made. Table 2 summarises the soft reduction established for both test billets and the set points.

	Billet 1		Billet 2	
	Set point mm	Actual mm	Set point mm	Actual mm
Roll 6	0.3	0.4	0.15	0.5
Roll 7	2.2	1.7	1.1	0.8
Roll 8	2.6	3.4	1.3	1.9
Roll 9	5.7	5.8	2.85	2.9
Total	**10.8**	**11.3**	**5.4**	**6.1**

Table 2 Set points and actual values at the various reduction stages

It is noticeable that the actual reductions deviate by up to 0.8mm from the planned figures. The cause was found to be to a variable amount of wear of the pinch rolls.

Figures 9a and 9b shows sulphur prints (longitudinal) of the two billets examined at those positions at which the deformation steps took place. It is clear that the total reductions applied resulted in inner cracks in both cases. However, the intensity and number of cracks and also the place at which the cracks arose are different in each billet. In *figure 9a*, the second reduction (roller 7: 1.7mm) resulted in the production of inner cracks, whereas in *figure 9b* no cracks were found at a reduction of 0.8mm. Cracks only occur after the third reduction at roller 8 in billet number 2.

Because of these cracks, no further statements can be made on the desired effect which soft reduction has on segregations (V-segregation, centre segregation). After soft reduction no V-segregation can be detected on the

Fig.9a, Fig.9b Billet sulphur prints

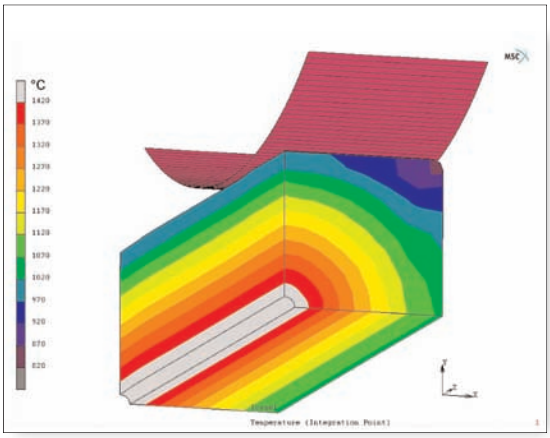

Fig.10 Temperature distribution in the strand shell just before final solidification

sulphur prints and the internal cracks account for a considerable share in the segregated remaining liquid. Thus application of soft reduction has resulted in the complete disappearance of cavities.

Based on these findings, the thermal and mechanical loads of the strand shell were modelled with the help of FEM in order to arrive at a statement on the admissible load limits in soft reduction. *Figure 10* shows the temperature distribution in a 1/4 segment of the strand just before final solidification, as calculated by the DSC software. These temperatures as well as the related mechanical properties of the material were used to calculate the strain arising at the solid/liquid phase boundary (fs = 1) due to deformation.

In *Figure 11* the relationship between the applied deformation and the calculated strain at the phase boundary in the casting direction is plotted. The diagram clearly shows a direct dependence between the amount of deformation and the strain at the phase boundary, which occurs irrespective of the position of the load, and is hence not determined by the thickness of the strand shell. The FEM calculations also show that the axial ▷

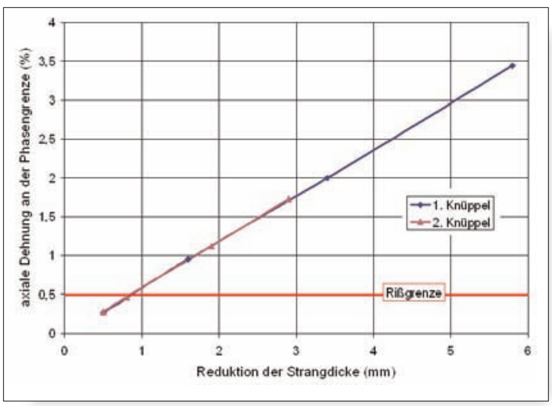

Fig.11 Relationship between deformation and strain at the phase boundary

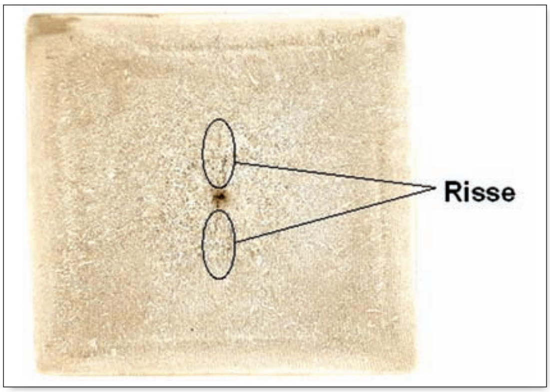

Fig.12 Transverse sulphur prints

strains along the whole phase boundary are roughly equal in size. Superimposed tensile strains transverse to the casting direction additionally occur below the roller, causing the inner cracks to arise preferably in this area *(see Figure 12)*.

With these results a load limit can now be defined which, if exceeded, leads to cracks at the phase boundary. The critical strain `$\varepsilon$` thus established for this material is about 0.5%, and is therefore in agreement with figures which are specified in the literature for similar steel grades. Critical strain for the cross section of 150 x 150mm is reached at a thickness reduction of 0.8mm. This number can now be used for planning and performing further soft reduction tests.

SUMMARY

A new process was tested on the continuous billet caster S0 at Saarstahl to assess the effect of soft reduction on strand internal quality. The process simultaneously lifts all the necessary rollers off the billet both in the soft reduction area, and below it. The stepped sections thus produced are cut into pieces and subjected to metallographic examination.

The following was found:

- The process used to make a test piece of stepped thickness is well suited to optimising soft reduction and it substantially reduces the expense of testing.
- The tests and accompanying temperature and solidification calculations made with the DSC software have shown that because of the influence which casting parameters such as the casting speed, steel temperature, spray water temperature and steel composition have on the position of the critical mushy diameter, they need to be taken into account. Smaller size billets especially can be produced with good results only if a solidification calculation is made and strand cooling is adapted according to the results of the simulation concurrent with soft reduction.
- The options which soft reduction offers to reduce segregation at the strand centre are limited by the ductility of the strand shell at the liquid/solid phase boundary. Because overloads to the strand shell produce internal cracks at the solidification front, the various deformation steps are not allowed to exceed a maximum amount. The respective limit value can be established by tests and calculations.
- FEM computations have shown that an optimised mould shape with cambers at the top and bottom will improve the effect of soft reduction whilst decreasing the load acting on the strand shell and the risk of internal cracks.

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