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Reduction of transverse corner cracks in Tata Steel's Direct Sheet Plant in Ijmuiden

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In the thin slab casting and rolling plant in Tata Steel in IJmuiden, breakouts and quality issues occurred due to the occurrence of transverse corner cracks. Transverse corner cracks are thought to originate during the casting process and become apparent in the slab and in the hot rolled coil. In order to tackle the problem a multi-fold approach was used.
Analysis of breakout shells indicated an insufficient shell lubrication. Trials with adapted mould oscillation practice were conducted to control crack formation. The different mould oscillation practices did not result in improved corner crack performance. Mould measurements showed that the liquid mould slag layer was sometimes very thin. An alternative mould powder with reduced free carbon content was tested, leading to improved slag infiltration and a reduction in breakouts due to corner cracks.
In the product mix, both low carbon and high strength low alloyed (HSLA) steel grades show a large percentage of transverse corner cracks, making the solution direction difficult. A thermomechanical study was done to verify in what temperature range the onset of nitride and carbide precipitation occurred, which was linked to the crack sensitive temperature region in secondary cooling. With an FEM model, the slab temperatures in secondary cooling were calculated. It was shown that the cooling of the slab corners was too high, leading to cold corners in the bending points. Adaptations were made to the upper secondary cooling segment to reduce cooling of the corners, which resulted in hotter slab corners at caster exit.
Additional data analysis showed that next to casting parameters, also rolling mill parameters play a significant role in the corner crack performance. Especially the edger draft proved to be an important parameter. Successful trials were started with increased edger draft, which lead to improved corner crack performance.

KEYWORDS: THIN SLAB CASTING, TRANSVERSE CORNER CRACKS, BREAKOUTS, MOULD POWDER, MOULD OSCILLATOR, SECONDARY COOLING;

INTRODUCTION

The direct sheet plant

The thin slab casting and rolling facility of Tata Steel in IJmuiden, the Direct Sheet Plant (DSP), is used for the production of high strength low alloyed (HSLA), low carbon and electrical steel grades. Slab widths range between 1000 and 1560 mm and the operational casting speed is up to 6 m/min. The caster is a vertical and liquid bending type machine with a 1.1 m mould, followed by a seven-strand secondary cooling area. In the second segment, liquid core reduction is applied, squeezing the slab from 90 to 72 mm thickness [[1]].

The DSP suffers from the occurrence of transverse corner cracks. A main issue related to transverse corner cracks is the occurrence of breakouts. The cracks are for-

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med in the mould, causing a weak spot. Below the mould the as-formed shell of the weak spot ruptures, causing the breakout. An example of a transverse corner crack as found in a breakout shell is shown in Fig. 1 (right). It should be noted that this is a corner crack found on the cold slab, so it is not certain that this crack was also present during casting.

Another issue is the occurrence of edge cracks which manifest in hot rolled coils for both low carbon and HSLA steel grades. The percentage of edge cracks on hot rolled HSLA steels is obviously larger, but since low carbon steels are cast more often, the problems are in the same order of magnitude. An example of a transverse corner crack is shown in Fig. 1 (left). Edge cracks can clearly be detected by the Parsytec system of the rolling mill, and by combining Parsytec data in combination with operator inspection, the customer is shielded from receiving defective material. However, edge cracks cause a large financial burden due to downgrading and scrapping of material.

Fig.1 - Left: Edge crack as captured by the parsytec system in the hot strip mill in the DSP.
Right: Transverse corner crack as found on a breakout shell.

Origin of transverse corner cracks

Several mechanisms causing transverse corner cracks are proposed in literature. Brimacombe [[2]] comprehensively reviewed the stresses and strains in continuous casting that can give rise to cracks in the solidifying shell. Mechanical properties are affected by several factors, i.e. temperature, chemistry, microstructure, and thermal history.

One of the proposed mechanisms is that the cracks are formed in the mould during initial solidification of the steel shell [[3]]. In general, local process disturbances related to mould heat transfer and slag infiltration as well as the depth of the oscillation marks may result in the formation of weak spots and transverse corner cracks [[4]]. This could be attributed to the chemistry of the steel, where manganese-sulfides can be formed. Harada et al [[5]] present a thorough analysis of the formation of transverse cracks in conventional cast slabs in relation with manganese and sulfur content. The conclusion is that the cracks occur due to micro segregation of MnS in the oscillation mark. The degree of segregation was strongly affected by the depth of the oscillation mark. The MnS has a low melting point, making the grain structure in the oscillation mark weaker. It was advised to use slow cooling of the slab, a higher frequency and smaller stroke of the mould oscillation and avoid a Mn/S below 80.

In a continuous caster the steel is subjected to a combination of thermal and mechanical deformation. Mechanically induced stresses can be caused by mould friction, ferrostatic pressure, machine condition i.e. roll pressure and misalignment, bending and unbending, and bulging. Additionally, thermal stresses, like temperature gradients in the shell and shrinkage associated with cooling, may lead to mechanical deformation of the shell. Transverse corner cracks can also originate when the strand is subjected to mechanical deformation in the secondary cooling area in the temperature range of the ductility trough [[6]], especially when the slab is in the bending or unbending area.

The precipitation of carbonitrides in steels alloyed with Al, Nb, Ti, and V, influences the low ductility of steels in this temperature range. The carbides and nitrides precipitate at the grain boundaries, making the steel brittle and crack sensitive. As long as the corners of the slab remain outside the ductility trough, the occurrence of transverse corner cracks can be reduced. In literature, several authors have reported on the use of chamfered moulds (e.g. Rivaux et al [[7]]) in order to reduce cooling of the slab corners in the mould. In the DSP, a slightly curved narrow face plate is used, as described by Hibbeler et al [[8]]. During this study, trials were performed with straight narrow face copper plates, but they did not show an improvement in corner crack performance.

Adaptations in secondary cooling can be made. Modern casting machines are equipped with width-dependent secondary cooling [[9]]. When this is not installed, width dependent cooling can be achieved by changing the nozzles at the sides of the slab [[10], [11]]. This leads to hotter slab corners and thus a reduced occurrence of corner cracks. Isaev et al [[12]] indicate a clear dependence of the occurrence of transverse corner cracks on the slab width. They relate this to the over cooling of the slab edges when the width is too small, so they proposed a careful width dependent cooling.

It should be noted that the weak spots in the shell as formed in the mould could be made visible as cracks in the secondary cooling area since due the uneven solidification, thermal stresses may arise upon further cooling. This underlines the need for stable casting operations in the mould, especially at the meniscus.

Outline

In this paper we present steps taken to reduce the number of transverse corner cracks and breakouts. Not all approaches were successful, but for completeness they will be mentioned.

The first part is about the reduction of corner cracks formed in the mould due to lack of lubrication. This is done by investigating effects of mould oscillation and mould powder.

The second part is split in two, a part related to the chemistry and secondary cooling area in the caster and another part about the edger force in the rolling mill.

BREAKOUTS AND STRAND LUBRICATION

As mentioned in the introduction, several breakouts occurred due to the presence of transverse corner cracks. Inspection of breakout slabs also revealed the presence of small bleeders at the narrow faces of slabs. It is well known that bleeders can be caused by a (local) lack of slag infiltration during casting.

Measurements of the slag pool thickness (or liquid pool depth) in the mould of the DSP showed a thin slag layer with values between 2 and 5 mm. In particular the very low values around 2 mm or lower close to the narrow faces were thought to be insufficient for proper slag infiltration during casting. The measurements were done at casting speeds of 5.0 and 5.8 m/min.

It was concluded that the breakouts due to transverse corner cracks were related to processes in the mould and to a lesser extent to precipitation. Predominantly a lack of strand lubrication at the narrow faces of the mould, plays an important role in the occurrence of breakouts. Improving strand lubrication could be realized by increasing the liquid slag layer thickness. In principle this would also be helpful in controlling the occurrence of transverse corner cracks in the hot rolled product [[5],[13]].

Mould powder

The presence of free carbon in mould powder (C_{free}) is the dominant factor influencing powder melting. Free carbon is added to the mould powder in order to control the melting rate during casting. Lowering the free carbon content in mould powder will result in increasing the melting rate and finally in the formation of a thicker liquid slag layer during casting [[14]]. It is reported that a thicker slag layer in the mould can be a cause of more rim formation during casting - in particular at the corner areas and in combination with meniscus fluctuations [[13],[14]]. Besides, a thicker slag layer can result in some increase of slag entrapment during casting [[15]].

It was found that the free carbon content always shows values of 3.8 or 3.9 wt.%. The supplier was asked to decrease the free carbon content to 3.2 wt.% using the same free carbon sources and maintaining the same mould powder components and hence the same powder and slag properties.

Plant trials with the adapted version of the standard mould

powder were done at all casting speeds and casting widths with special attention for the process and product performance. Based on mould measurements, the average slag layer thickness increased with 18%.
After the introduction of the adapted version of the mould powder, no breakouts due to transverse corner cracks occurred. Furthermore, coil inspection showed a significant decrease of edge cracks. No effects were found on other casting process parameters like strand friction, powder consumption and bulging of the strand. The only parameter changing slightly is the presence of non-metallic inclusions in the strip due to slag entrapment. Occasionally, some more rim formation was observed, which can be explained by the fact that the liquid pool is thicker, and more slag may quench on the mould copper plates.
Currently, the adapted mould powder with a reduced free carbon content is used as standard mould powder for low carbon and HSLA steel grades at all casting speeds and casting widths. Special attention is given to the control of rim formation during casting. This can be done by controlling the mould level fluctuations.
Mould oscillation
Parallel to the work on strand lubrication and mould powder, plant trials were done on changing the setting of the mould oscillator. Some authors [[5]] report that the presence of transverse corner cracks can be reduced with increasing oscillation frequency and with decreasing stroke of the oscillator. It should be noted, however, that this is reported for conventional slab casting with mould oscillation frequencies in the order of 100 cpm and with strokes above 5 mm.
Trials were performed with maximum oscillation frequencies between 350 min^{-1} and 370 min^{-1} and the stroke was between 3 and 4.5 mm. No significant differences in corner crack performance were observed.

EDGE CRACKS REDUCTION BY IMPROVING THE SECONDARY COOLING STRATEGY

It was observed that the HSLA steel grades suffer from a higher amount of transverse corner cracks than the low carbon steels. Also, it was observed that the low carbon steels suffer from transverse corner cracks at high casting speeds, while for some of the HSLA's, the casting speed seemed to have no effect.

Chemistry

Thermodynamic calculations have been performed with the Thermo-Calc package, using the TCFE9 database. The grades considered are niobium and vanadium containing HSLA's and plain low carbon steels.
While cooling down, the low carbon steel starts fully liquid and then forms a fully ferritic phase. Around 1400oC, the material has a transformation to the austenitic phase, which remains until the steel is cooled down to 900oC. At 900oC, the transformation to the ferritic phase follows and below 700oC, a cementite phase starts to appear (seen as pearlite in combination with the ferrite phase in the microstructure). This pearlite phase is brittle and possibly crack sensitive, but as it appears at much lower temperatures than the ones considered during continuous casting, no problems should be expected.
The HSLA steels cast at the DSP contain niobium and vanadium. Upon cooling, these grades also follow a full transformation to ferrite and then to austenite around 1450oC. Different from the low carbon steel is that pre-cipitation of vanadium carbonitrides V(C,N) and niobium carbonitrides Nb(C,N) takes place, making the steel less ductile and more brittle. The fact that a multiple precipitation appears in this steel, is consistent with the theory that some micro-alloyed steels have two ductility troughs [[17]]. According to the steel grade specifica-tions, the vanadium can be in a range with a minimum, maximum and aim concentration. Thermo-Calc calcu-lations were performed to verify the influence of vanadium and nitrogen concentration on the onset temperature for precipitation. Fig. 2 shows the influence of the vanadium content on the temperature of onset of precipitation of vanadium-nitrides. It is clear that for higher vanadium contents, the onset of precipitation is at a higher temperature. This temperature is reached higher in the secondary cooling area, making the steel more prone to cracking.

Secondary cooling

Data analysis showed more transverse corner cracks for smaller width slabs. This is thought to be due to the cooling intensity at the corner areas, as also stated by Isaev [[12]]. In the cooling segments, flat spray nozzles are used for slab cooling. When a smaller width slab is cast, the spray nozzles have an impact on the narrow face, overcooling the corners (Fig. 3). Modern thin slab casting machines are usually equipped with a width dependent secondary cooling system, but in the design of the DSP, this is not incorporated.

Trials were done with adaptation of the outer spraying nozzles in nine spray bars in the upper segment in the secondary cooling area. The outer two nozzles were replaced by nozzles with a 35% lower flow rate than the original nozzles. The adapted spray nozzles are indicated by the green spray nozzles in Fig. 3. This approach is comparable to the one described in reference [[10]].

Fig. 3 shows the configuration of the spray nozzles in the secondary cooling area in the caster. It is seen that when the slab width is smaller than 1350 mm, the spray nozzle angle is such that it impacts the narrow face of the slab, leading to over cooling of the corners of the slab.

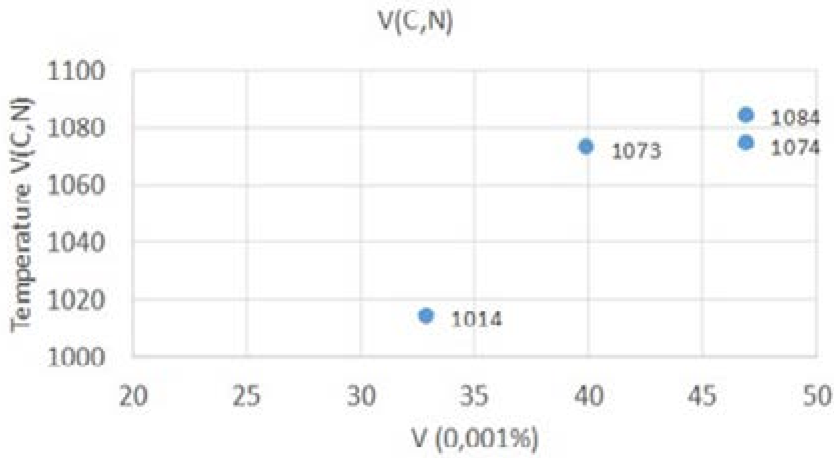

Fig.2 - Onset of precipitation temperatures for different vanadium contents in the HSLA steel grade.

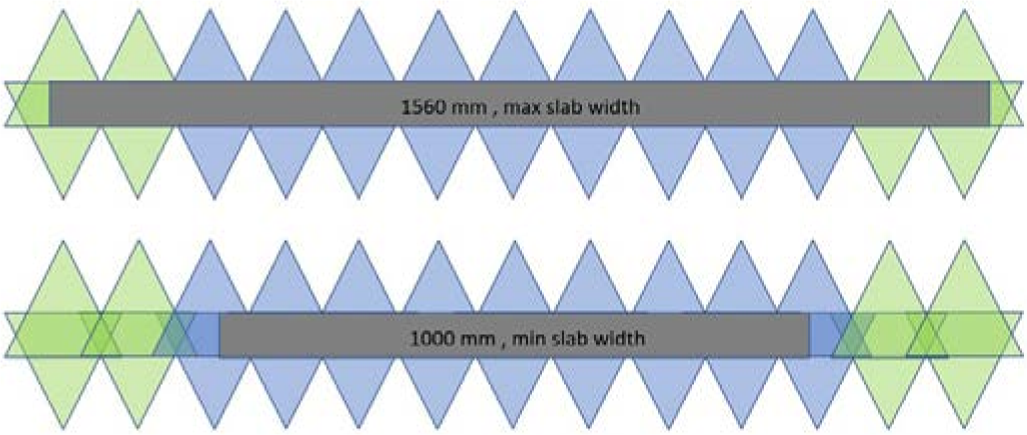

Fig.3 - Spray nozzle configuration for narrow and broad slabs in the secondary cooling area. The outer two (in green) spray nozzles were replaced in the plant trials for spray nozzles with a 35% lower flow rate than the original nozzles.

Model calculations

Model calculations, using the inhouse developed 3D finite element model Slab3D [[16]], were performed to verify the impact of the adaptation in secondary cooling on the slab temperature. This was done to verify whether the slab corners would go through the bending areas in the caster during the ductility trough. Fig. 4 shows the corner temperature of the slab for cast widths of 1.1, 1.3 and 1.5 m. The red line shows the temperatures for the original spray nozzle configuration and the green line shows the results for the adapted spray nozzle configuration. It is seen that when the slab width is 1.1 m, there is no significant difference in slab temperatures, as expected, since the adapted spray nozzles are not impacting the slab surface. For 1.3 and 1.5 m slab width, a significant increase in slab corner temperature is seen with the adapted spray nozzles configuration, especially between 1.5 and 5 m from meniscus. Further down the secondary cooling zone, the temperatures equalize. For the adapted spray nozzle configuration the corner temperatures are about 10 – 20oC higher at the end of the casting section.

Plant trials

Trials were performed with the adapted top segment in the secondary cooling area. At the end of the secondary cooling area, 16 meters from the meniscus, a line scan temperature measurement is available. Fig. 5 shows the average slab surface temperature as measured by the line scan for a trial with casting speed of 5.7 m/min and cast width of 1450 mm. As predicted by the model calculations, temperature differences between the original and trial situations are small, but a clearly higher slab corner temperature is measured during the trials. The transverse corner crack performance with the adapted secondary cooling segment is significantly improved for low carbon steels.

A positive side effect of the adapted spray cooling is that also bulging of the slab was reduced. This can be explained since the flow to the slab is redistributed such that the cooling in the middle of the slab is increased while the cooling at the edges is decreased. This makes the shell in the middle of the slab stronger and more bulging resistant.

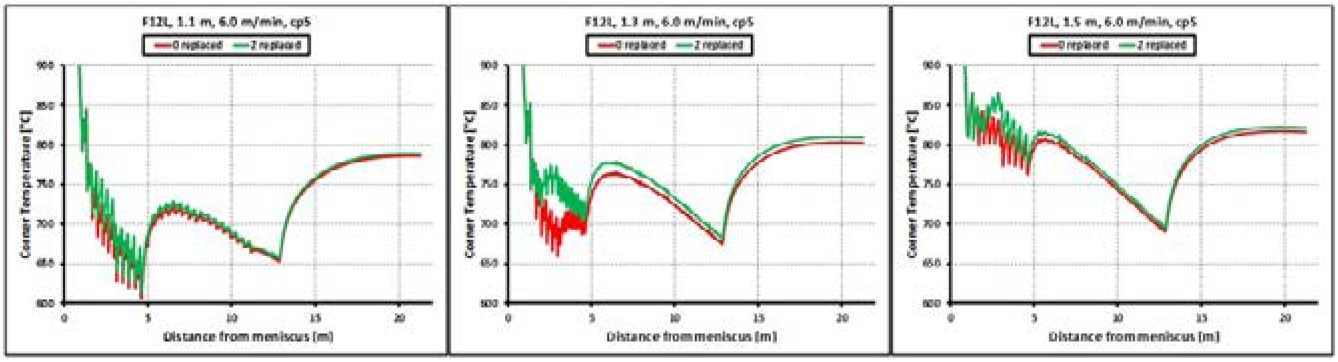

Fig.4 - Model calculations of the temperature at the slab corners for the original spray nozzle configuration (red) and for the configuration where the outer three spray nozzles at the first secondary cooling segment were replaced by nozzles with a 35% lower water flow rate.

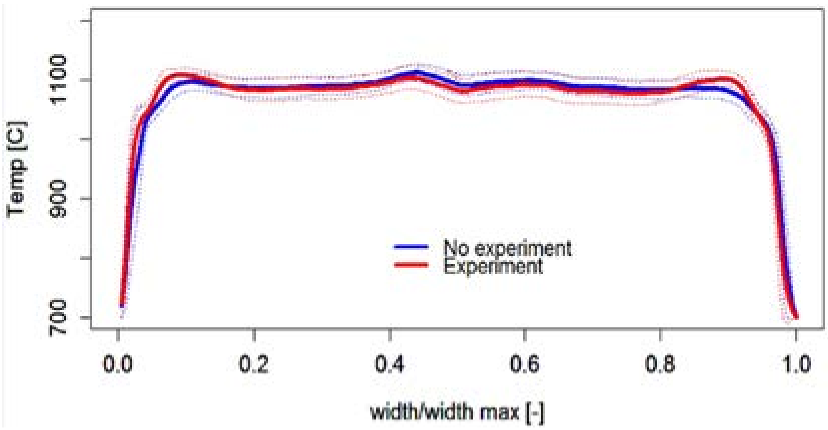

Fig.5 - Slab temperature as measured at 16 m from meniscus. Result for low carbon steel, cast at 1450 mm slab width and at 5.7 m/min. The red line indicates the result for the trial with adapted spray nozzles and the blue line indicates the result for the original spray nozzle configuration. The dotted lines indicate the temperature at plus and minus one standard deviation.

EDGE CRACKS REDUCTION BY OPTIMIZING THE EDGER FORCE IN THE ROLLING MILL

Data analysis

A random forest data analysis was performed to detect the main parameters influencing the occurrence of edge cracks[1] in the hot rolled material. Since the plant consists of both a continuous thin slab caster and a rolling mill, also the rolling mill parameters were considered. The rolling area consists of two roughing and five finishing stands. In front of the roughing stands an edger is installed which exerts a force on the narrow sides of the slab. It was observed that the edger force of the rolling mill had a significant correlation with the occurrence of edge cracks: With a lower edger force more edge cracks occurred (Fig. 6). Trials were done with increasing the edger draft in order to exert a higher edger force and the trial results show that indeed a causality can be found between edger force and edge crack performance. In this chapter, the effect of the edger force and a possible mechanism for reducing the edge cracks will be elaborated on.

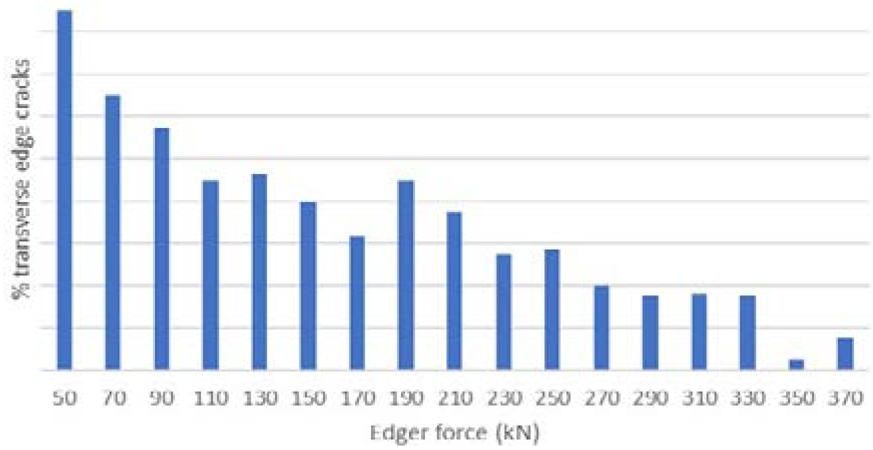

Fig.6 - Distribution of transverse corner cracks with varying edger force. Data analysis on coils in the period from January 2017 to June 2019 clearly shows the dependence of edge crack formation on edger force.

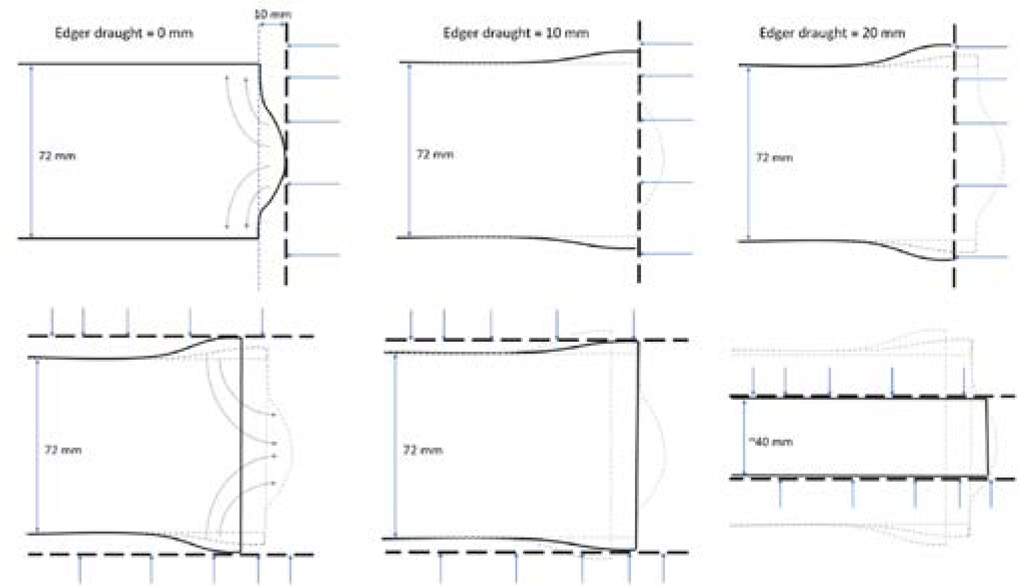

Fig.7 -Top row: From left to right, the edger pushes on the narrow face with a draft of 0, 10 or 20 mm. Note that the narrow sides of the slab always bulge outward by 10 mm due to the liquid core reduction of the caster. Due to the inward pressure of the edger force, the broad face close to the slab edge bulges, forming a dog bone. Bottom row: From left to right, the action of the first roughing stand is depicted. First the dog bone is pushed back, causing the re-widening of the slab until it almost reaches the original width. Then further rolling action reduces the slab thickness to roughly 30 mm.

[1] *Note the change in terminology: In the milling area we refer to edge cracks whereas in the casting area we refer to transverse corner cracks.*

Proposed mechanism of edge crack reduction

The edger is set to a certain draft, which is the value with which the slab width is decreased. When the edger draft is larger, subsequently the edger force is larger. However, since the slab width to thickness ratio is large (14 < W/T <22) the effect of the edger on the final width of the coil is minimal. This is in contrast to the working of the edger for conventional slabs with 4 < W/T < 10, in which the edger is used for width control. In practice at the DSP it is observed that an edger draft of 10 mm results in a decrease of width at the end of the rolling mill of 2 – 3 mm.

Fig. 7 shows the stages the slab narrow face goes through when the edger draft is applied (top row) and when the roughing action is applied (bottom row). When the edger pushes on the narrow face, a dog-bone deformation takes place where the broad face thickness near the slab corner increases. It is hypothesised that with the edger pushing on the narrow face, weak spots in the form of micro cracks are decreased in size. These smaller micro-cracks lead to reduced local stress build up, making the material less prone to cracking. In the first roughing stand, the dog bone is pushed outward, but also deformation in the length is established, reducing stresses in the strip edges and hence reducing the sensitivity to edge cracks, this is a fully three dimensional process, schematically indicated as a 2D image in Fig. 7. After the first roughing stand, the dog bone has vanished, bringing back the width of the strip to its original width. The rougher reduces the thickness to ~30 mm.

CONCLUSIONS

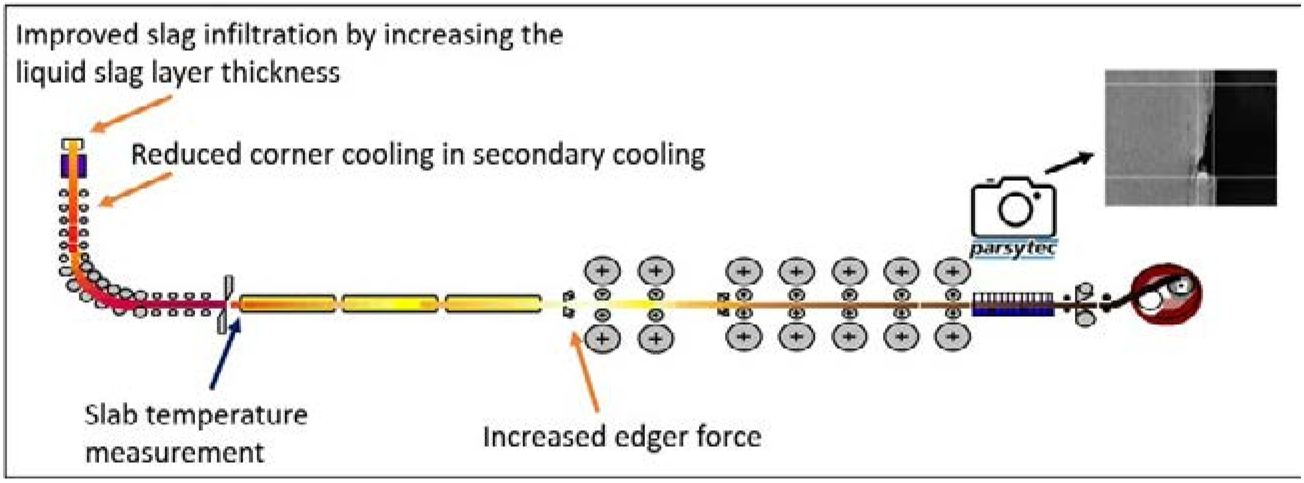

Fig.8 - Schematics of the integrated approach for reduction of transverse corner cracks in Tata Steel's Direct Sheet Plant.

In order to reduce transverse corner cracks in Tata Steel's Direct Sheet Plant in IJmuiden, an integral approach was followed to determine the most significant parameters influencing the transverse corner crack performance. This is visually illustrated in Fig. 8. Significant parameters were found in the casting as well as in the rolling area of the machine, making it necessary to incorporate both aspects in the analysis. Below, the most important findings are summarized:

- To reduce breakouts due to transverse corner cracks, a sufficiently thick liquid slag layer thickness in the mould is needed in order to provide enough liquid slag for infiltration between the mould and the solidifying shell. The liquid slag layer thickness was increased by reducing the free carbon content in the mould powder. Note that the rest of the mould powder chemistry was kept the same. Besides, a reduction in the occurrence of edge cracks was obtained by increasing the slag layer thickness. The mould oscillator setting was also tested, but did not have a dominant effect on the edge crack performance.

Process parameters that significantly affect the occurrence of edge cracks are

- Slab width: More transverse corner cracks for small width slabs. A reduced corner cooling in the secondary cooling area is shown to help reduce the occurrence of transverse corner cracks.
- Chemistry: More transverse corner cracks were observed for HSLA steel grades. A correlation was found between the vanadium content in the steel and the occurrence of transverse corner cracks. Also, the amount of sulfur in the steel was positively correlated to corner cracks.
- Edger force of the rolling mill: A lower edger force correlates with more transverse corner cracks. A mechanism for reduction of transverse corner cracks due to the edger action was proposed.

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