Optimization of machine parameters to improve the quality of continuously cast slab

B Krishna Prabhu¹ and K R Udupa²
¹ Prof. Department of mechanical Engineering, Canara Engineering College, Mangalore S. Karnataka, India
² Prof. Department of Metallurgical & Materials Engineering, NITK Surathkal, Mangalore S. Karnataka India
E-mail: mechanical@canaraengineering.in

Abstract: Industries in general target to produce high quality tonnage steel at a lowest possible cost. On this count the technology of continuous casting (con-cast) is very promising. However, one of the serious quality problems that may arise in the con-cast slabs is the formation of cracks, on the surface and/or in the interior of the slabs. The cracks appearing on the surface get oxidized in air and therefore cannot be re-welded during rolling of the slab resulting into defective rolled plates. In this work, carried out at Bhilai Steel plant Bhilai (MP), machine parameters responsible for the formation of longitudinal surface cracks are studied. The objective of doing this exercise is to optimize these parameters to reduce the frequency of crack formation. Mould taper, age of the mould, pinch roll conditions and rigidity in fixing the pinch rolls are some of the parameters studied. The study concludes that, the existing level of 1.3% of mould taper is excessive and the optimum value is found to be 1.13%. From this study, the history of the machine after maintenance is optimized to 140 heats and the rigidity maintenance period for pinch rolls to 80 heats. It is proposed that the roll gap of the pinch rolls should be checked and rectified for every 65 heats.

Keywords: Continuous casting; Mould & Sub-mould; Pinch rolls; Longitudinal cracks; Quality.

1. Introduction
Continuous Casting is an improvement of conventional, batch type ingot casting. The process starts with pouring of liquid metal of necessary composition and super heat into tundish through the ladle. The metal then enters the water cooled copper mould, packed with dummy-bar. Prevention of sticking of the strand to the mould walls is achieved by continuous lubrication and oscillation of the mould. Primary cooling of the strand in the mould helps in developing a solid skin of sufficient thickness. Subsequent cooling down the machine involves direct spraying of water to the strand surface using water jets (secondary cooling). In a curve type con-cast machine, the strand is un-bent at around 700°C and moved ahead for further treatments [1].

One major quality problems that may arise in the con-cast slabs is the formation of cracks [2]. The cracks may appear anywhere on the surface or at the interior of the strands. The surface cracks, in particular, are nucleating, at high temperature, inside the mould and keeps growing, in the sub-mould region [3]. The tests conducted on high temperature mechanical properties of steel show that there are three distinct temperature ranges in which steel has low strength and/or ductility, and is therefore susceptible to cracking. These three temperature ranges are

- High temperature zone: ~1340°C to solidus temperature. The ductility to fracture of steel in this range of temperature is of the order of 0.2 to 0.3% [4]. The low strength and ductility seem to be due to the presence of liquid film in the inter-dendritic regions, which does not freeze until temperature is well below the solidus are reached [5, 6]. Adums [7] has measured phosphorus concentrations and found it to be in the range of 0.2 to 0.5% at the grain boundaries while phosphorus level of the matrix is only 0.02%.
• Intermediate temperature zone: 800 to 1200°C. The loss of ductility during cooling below 1200°C is mainly dependent on Mn/S ratio and thermal history of the steel [7]. Steels with Mn/S ratios above 60 are not embrittled because the Sulphur is tied to the stable phase as MnS, which precipitates in the matrix and not predominantly at the grain boundaries.

• Low temperature zone: 700 to 900°C. Less is known about this zone of low ductility. But there is general agreement that it is usually associated with the soluble aluminum in the steel and precipitation of AlN at the grain boundaries[8, 9].

The solidifying strand is exposed to all these temperature regions at one or the other levels of the machine. High temperature zone exists in the mould and sub-mould regions. Intermediate temperature zone is in the upper parts of pinch-roll sections and the low temperature zone is in the lower parts of the machine. Such a situation, demands proper design and maintenance of the machine for avoidance of the surface cracks. Optimization of the machine parameters may benefit in this regard [3].

2. Experimental work
The longitudinal surface crack is one of the major defects in con-cast slabs. An understanding of their formation, estimation of their magnitude and control of these defects are attempted in the present work. Information pertaining to longitudinal cracks comprising over 700 heats, involving 155(average) tons of hot metal in each heat, are collected. Following machine parameters are recorded from SMS-2, the slab casting shop.

a. Cast length  b. Casting speed  c. Metal level in the tundish  
d. Free O₂ in tundish  e. Free Al in tundish  f. Cutting nozzle jams in tundish  
g. Flux condition  h. Unbending temperature  i. Shrouding of ladle stream

In order to correlate machine parameters with the quality aspects of cast slab, following parameters are recorded from the inspection yard (table-1 and table-2).

a. Inspected Pieces  b. Accepted Pieces  c. Cracked Pieces  
d. Percentage Crack  e. Crack on top side  f. Crack on top side  
g. Crack on both sides and  h. Inspection type

| Table-1. Typical tabulation of mould parameters at con-cast shop (total > 700 heats) |
|-----------------|-----------------|-----------------|
| **Heat No.**    | **68959**       | **69709**       | **71411**       |
| Grade of Steel  | ASTM A36T₂      | IS2062 Grade BT₂| SAILMA 350HT T₁ |
| Ladle Temp (°C) | 1650            | 1570            | 1585             |
| Machine No.     | 2               | 3               | 1                |
| Machine Age     | 50              | 149             | 18               |
| Mould Life (Heats) | 14            | 16              | 18               |
| Sub-Mould Life  | 14              | 16              | 18               |
| Mould Taper (mm)| 8.5/9.0         | 9.0/9.0         | 8.0/8.0          |
| Tonnage (tones) | 115             | 110             | 112              |
| Other Remarks   | No. Lances -2   | No. Lances -2   | Meters cast – 52 |

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Following machine parameters are considered while optimizing con cast machine for longitudinal surface cracks (L/C):

a) Age of mould and sub-mould system  b) Mould taper  c) Pinch roll conditions  
d) Rigidity of pinch rolls  and  e) Wedge tightening period.

The machine parameters and corresponding quality aspects are correlated using slab tracking method. The results obtained are mentioned in the following section.

3. Results

The outcome of the analysis of slab tracking is put forth under four headings in this section.

3.1 Age of the mould and sub mould (5-roll) system

The influence of the mould parameter on the surface quality of the cast slab is displayed in figure 1.

Table-2. Typical tabulation of quality of slabs at inspection yard (total > 700 heats)

| Heat No.  | Pieces generated | Inspected Pieces | Accepted Pieces | Cracked Pieces | Top Side | Bottom Side | Top & Bottom | Percentage Crack | Inspection Type |
|-----------|------------------|------------------|-----------------|----------------|----------|-------------|-------------|-----------------|-----------------|
| 68959     | 15               | 13               | 14              | 09             | 1        | 5           | 3           | 59.7            | Spread          |
| 69709     | 13               | 13               | 13              | Nil            | Nil      | Nil         | Nil         | 0               | Stack           |
| 71411     | 20               | 20               | 20              | 15             | 11       | Nil         | 4           | 75              | Spread          |

Figure 1. Effect of machine age on L/C, (200*1500 mm slab)
The mould is changed at 36\textsuperscript{th}, with 5 roll on 75\textsuperscript{th} and 138\textsuperscript{th} heat in the machine. The subsequent decrease in the formation of the longitudinal cracks on the cast slab is evident in the figure 1. The figure is drawn for the slab with 200 * 1500mm dimension. Similar results are also observed in the case of slab caster casting slab of 250 * 1500mm (figure 2.). In this case, the mould and five roll sections are changed at 20\textsuperscript{th}, 64\textsuperscript{th}, 127\textsuperscript{th}, 188\textsuperscript{th}, 250\textsuperscript{th} and 315\textsuperscript{th} heat. Further, the roll gap of the pinch rolls was adjusted at 250\textsuperscript{th} heat that drastically reduced the level of crack formation.

![Figure 2. Effect of machine age on L/C, (250*1500 mm slab)](image)

3.2 Mould taper
The variation in the tendency of slabs to form longitudinal cracks as a function of mould taper (wide-edge taper) is shown in figure 3. The figure depicts an improvement in the slab quality with the decrease in mould taper from the initial value of 1.3%. Such an improvement is recorded till the mould wears and reduces the taper to 1.13%. It is also evident that further drop in taper increases the longitudinal cracks in the cast slabs. An average of 32 heats could be cast at this taper. Both these graphs are the results of data collected from over 40,000 tones of hot metal.

To verify the correctness of the results obtained, a trial mould with initial taper 1.13% is designed and experimented on the slab caster. This result is presented in the figure 4. An improvement in the surface quality is observed in the case of trial mould with respect to the regular mould with 1.33% initial taper. The figure depicts that after 32 heats, percent L/C increases further. Hence re-setting of the mould taper to 1.13% for every 32 heats may be advantageous. Further, at 1.13% taper, the wear out of copper from the mould plate is at its lowest.

3.3 Pinch roll conditions
The misalignment of the pinch rolls from the machine radius is found to be an important factor. Such a misalignment could be owing to prolonged casting without maintenance. Figure 1, shows that the lower and upper limit for crack formation increases as the machine gets aged. It could be observed that up to 25% of cast slabs are prone to for cracks in the initial one hundred heats. The occurrence increases over 30-65% once 100 heats are crossed. The lower limit increases above 50% after casting 125 heats.
Rigidity of the pinch rolls

The pinch roll segments are fitted rigidly to the ‘unit frame’ by using bolts or wedges. During the course of operation, progressive loosening of these wedges is observed. Tightening of wedges made at 160th heat (figure 1) clearly shows a decline in the percentage of crack occurrence. Further, the influence of this factor is clear in the figure 2. In this case, the wedges were tightened at 52nd and 315th heats. These figures infer that tightening of the wedges is effective up to about 80 heats.

Figure 1 indicates that the wedge tightening performed after 140 heats can only decrease the level of crack occurrence but not the frequency. In other words, more and more heats are susceptible for the crack formation after about 140 heats cast in the machine.

The roll gap adjusted after 140 heats seems not effective in reducing the cracking tendency of the slabs (figure 2). The roll gap adjusted at 127th heat resulted an increase in the crack level from 40% to 43%, and that at 250th heat from 55% to 66%. Such an increase is an indication for ineffective adjustments of roll gaps, when the pinch rolls are misaligned from the base radius.
4. Discussion

The morphological study on longitudinal cracks suggests that crack formation could be due to the existence of a “line of weakness” along with the “transverse tensile stresses” (figure 5). These conditions facilitate the initiation and the growth of the crack in the mould and pinch roll sections. The absence of any one of these conditions may fail to produce cracks on the slab surface. The cracks initiated in the mould, may propagate either in the mould or in the sub-mould and pinch roll sections [10].

4.1 Line of weakness

The steel chemistry along with the mode of solidification aspects may be responsible for the formation of line of weakness. The impurities in the steel like S, P and O\textsubscript{2} have a distribution coefficient (K\textsubscript{d}) less than unity. Solidification of steel with these elements involves micro segregation [11] of solute in the inter-dendritic regions. The presence of such a liquid film of solute makes columnar dendrites more susceptible to the formation of internal and surface cracks.

4.2 Transverse tensile stresses

From the initiation of the solidification of the skin at the mould till its completion, a continuously cast section is subjected to a complex history of thermal and mechanical stresses [12]. The friction between the oscillating mould and the surface of the shell causes axial stresses in the shell of the strand. These stresses are longitudinal tensile when the mould moves upward relative to the shell and compressive when the mould descends.

The ferrostatic pressure acting on the solidifying skin acts in a normal direction to that of frictional force. This generates stresses in the transverse plane as the shell cools and shrinks. The transverse stresses are the earliest to manifest in the mid face region where they are tensile in nature with the largest stresses appearing near the surface. Below the mould, the ferrostatic pressure can cause bulging of the wide face of slabs in the inter roll space of the pinch rolls. These stresses are tensile at the surface and compressive near the solidification front. Thermal stresses in and below the mould are generated by the change in the temperature gradients in the shell. They are normally tensile at the cooler surface due to contraction restrain caused by the adjacent hotter region [13].

4.3 Mould taper and age

The present investigation reveals that minimum crack level in the slab is observed at 1.13% taper of the mould. Both at lower and higher values of taper, the crack level are higher than that at 1.13% (figure 3). If the taper is higher to 1.13%, the reduction in the width of the slab is larger than that caused by the thermal shrinkage and hence the sides of the slab are compressed. Such a compressive force on the narrow face of the slab bends the wider face leading to the formation of air gap on the
wider face towards the side of the slab. The resultant drop in the local heat extraction due to the air gap formation causes a ‘hot spot’ on the wide face of the slab. This can give rise to the necessary stresses required for the formation of longitudinal crack. Such a crack occurs preferably at the one-third position from the end on the wide face [10].

On providing optimum taper for the mould the solidification contraction equals with the taper provided. The mould wear is very small under such a situation. If the taper is higher, the compression of the mould by the solidified surface strand increases the wear of the copper mould surface and the mould gets aged faster with better chances of formation of longitudinal cracks. As the mould gets aged further the wear in the mould surface reduces the taper below optimum value (<1.13%). The chances of formation of longitudinal crack increase, even under such a situation.

The study on the heat extraction by the mould [14, 15] showed that more than 50% of heat extraction by the mould takes place in the upper region of the mould. The lower portion of the mould, however, acts largely as supporting device for the solidifying shell. If the taper is below the optimum, the lower portion of the mould fails to support the strand, which is at high temperature zone (~1250°C). The bulging of the strand in the mould contributes to the necessary stress required for the crack to open up at the line of weakness.

4.4 Machine conditions

During the course of operation, the performance of the machine is found to deteriorate progressively. The causes could be roll misalignment and loose wedges. This causes an in the formation of longitudinal surface cracks. This clearly indicates the need for proper maintenance, in terms of wedge tightening, roll gap adjustment as well as re-alignment of the pinch rolls, on time.

5. Conclusions

Following conclusions could be drawn from the study on the quality aspects of the continuously cast slabs related to mould parameters.

- The common practice of using a mould taper of a value 1.3% to 1.33% is prone to form longitudinal cracks. The optimum taper for the mould could be 1.13%.
- Mould with taper 1.13% is also found to sustain for at least 30 heats undergoing minimum wear at the mould surface. Mould life of the copper mould, under the working condition, is around 50 heats. Beyond this value the percentage of slabs with longitudinal cracks increases. The mould can be changed at 50th heat than over 60th heats.
- The maximum number of heats cast after maintenance could be 140 heats.
- The wedge or bolt tightening could be regularly checked for every 80 heats.
- Roll gap adjustment period for pinch rolls could be about 65 heats.

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