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A REVIEW OF DEFECTS IN BEAM BLANK CASTING AND THE MEASURES PROPOSED FOR THEIR ELIMINATION*

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Resumo

Neste trabalho se leva a cabo uma revisão da literatura sobre defeitos em *beam blanks*. O foco é no mecanismo de formação e as soluções propostas para diminuir sua ocorrência. Os defeitos superficiais incluidos são as trincas longitudinais e transversais, bleeding, pinholes e escória. Os defeitos internos levados em conta são os blowholes, as trincas centrais e as trincas nas pontas das abas. A revisão incluie as técnicas utilizadas para pesquisar os defeitos: caracterização metalográfica, CFD, modelagem termodinâmica e termomecânica, etc. As medidas adotadas estãorelacionadas a mudanças no sistema de lingotamento (por exemplo o design da vâlvula submersa), design do molde, mudanças e regulação do resfriamento secundário, suporte dos veios.

Palavras-chave: Lingotamento contínuo; Beam blakns; Defeitos; Solidificação.

A REVIEW OF DEFECTS IN BEAM BLANK CASTING AND THE MEASURES PROPOSED FOR THEIR ELIMINATION

Abstract

In this paper a thorough review of the literature on defects in beam blanks is carried out. The focus is on the formation mechanism and the solutions proposed to decrease their occurrence. Surface defects included are longitudinal cracks and transverse cracks, bleeding, pinholes and slag entrapment. Internal defects are blowholes and solidification cracks (web and wing end). The review includes the techniques used to investigate the defects: metallographical characterizations, CFD, thermodynamical and thermomechanical modelling, etc. The measures taken have to do with changes in casting system (i.e. SEN design), mold design, secondary cooling modifications and regulation, strand support.

Keywords: Continuous casting; Beam blanks; Defects; Solidification.

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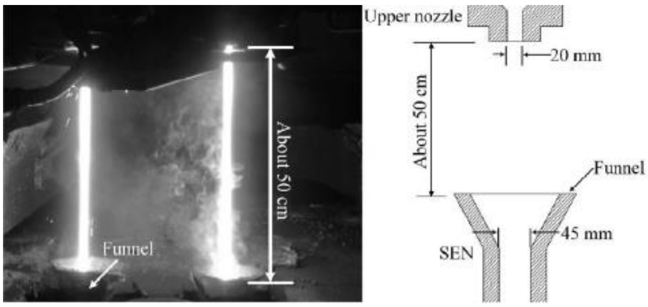
1 INTRODUÇÃO

Beam blank casting is a mature process born in 1968 [1]. Around 60 casters has been installed since. In this paper a thorough review of the literature on defects in beam blanks is carried out. The focus is on the formation mechanism and the solutions proposed to decrease their occurrence. Surface defects included are longitudinal cracks and transverse cracks. Internal defects are blowholes and solidification cracks. The review includes the techniques used to investigate the defects: metallographical characterizations, CFD, thermodynamical and thermomechanical modelling, etc. The measures taken have to do with changes in casting system (i.e. SEN design), mold design, secondary cooling modifications and regulation, strand support.

Casting of beam blanks may be carried out with open casting, semisubmerged casting and submerged casting. The three casting possibilities are presented in Figure 1. Each one has advantages and drawbacks (table 1).
Open casting tends to concentrate in the smaller sizes. Usually two metering nozzles are used for a given strand, although use of one has been practiced, too. Automatic nozzle changer has been developed for open beam blank casting [2]. Deoxidation is with Si and Mn, at times completed with aluminum injection in the mold. The quality issues mentioned in table 1 conspire against open casting, despite of its inherent simplicity and productivity.
Semi- submerged casting is the most used casting mode, as it combines the advantages of the other two casting ways. Here two funnels conduct the liquid steel flow to the mold, allowing for casting powder addition. Straight, vertical entrance to the mold is usually carried out, although lateral ports has been tested [3]. Stopper or slide gate / SEN casting is the choice when the beam blank dimension is large and Al killed steel grades have to be cast. Due to the space constraints, one SEN casting has been tested [4, 5].



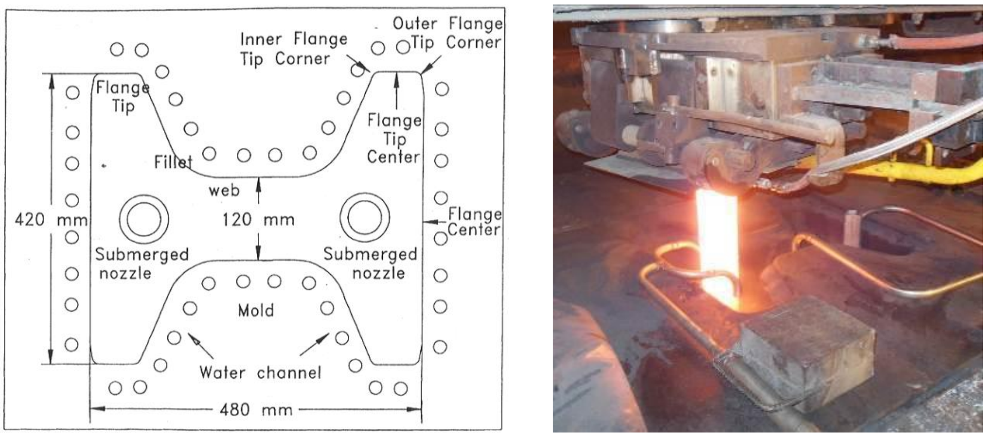


Figure 1. Top: open nozzle casting; Middle: semi submerged casting; Bottom left: Submerged casting, two SEN [6]; Bottom right: one SEN [4].

Table 1. Advantages and drawbacks of the three casting modes.

Casting type	Advantages	Drawbacks
Open casting	Low cost: No need for SEN and casting powder High productivity: possibility of automatic metering nozzle change	Splashing: cold drops Reoxidation: macroinclusions, trapped scum Oil lubrication: Pin holes; risk of cracks due to higher heat transfer Al-killed steel not feasible
Semi submerged casting	Less splashing Less reoxidation Less pin-holes More control of heat transfer	Higher cost (funnel and casting powder)
Submerged casting	No splashing: no cold drops No reoxidation: no macroinclusions Casting of Al-killed steels Higher control of heat transfer (less risk of cracking)	Higher cost (Stopper rod/ slide gate, SEN and casting powder) Lower productivity (limited by SEN life)

Molds for beam blanks may be tubular, as is usual for square billets or made of four plates, as for slabs (Figure 2). Usually, tubular molds tend to be preferred for the small and medium sections. Plate molds have two narrow and two wide faces [7].

Figure 2. Molds for beam blanks. Left: Tubular mold. Right: Four plates mold.

An alternative has been devised for using plate mold in a mold jacket designed for tubular molds (Figure 3). This is applied to intermediate sections.

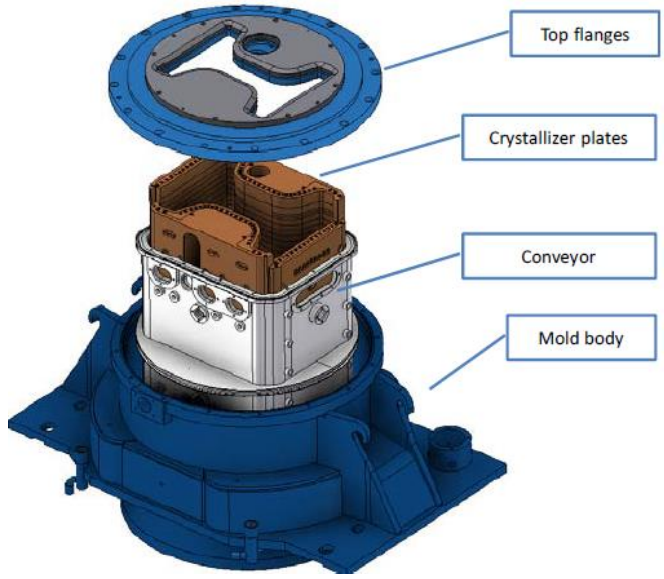


Figure 3. Devise for using plate mold in a mold jacket for tubular mold.

Typically, plate molds are cooled with holes (and spacers within the holes) for the wide faces, and slots for the narrow faces, Figure 4.

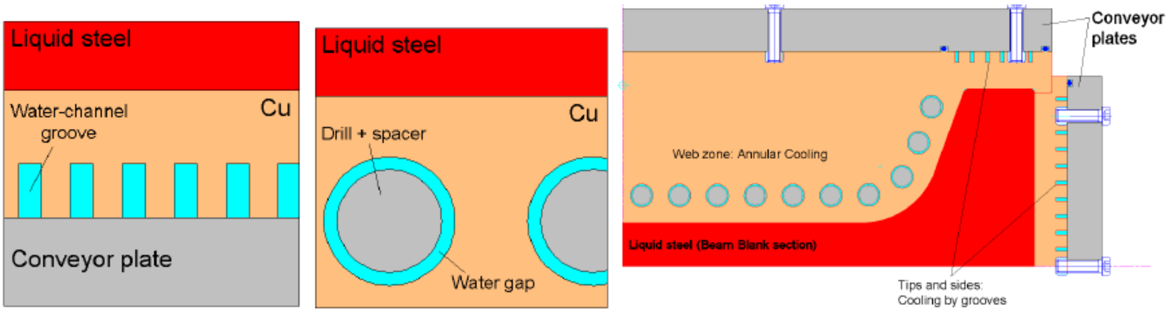


Figure 4. Typical design of narrow and wide mold plates.

Plate molds have the following features

- more alternative to manage water cooling: slots, holes with spacer, full hole, distance between holes, distance to hot face.
- More rigidity of the assembly
- Stability of transverse geometry of cooling channels
- Easy achievement of different taper modes
- Higher cost

Due to the complexities associated with the particular transverse section of the beam blanks, fluid flow and thermo mechanical modeling has been used extensively, with much more intensity than for billet casting [8-11].

2 SURFACE DEFECTS

Surface defects in beam blanks are much like in billets, but have some specificities. Between surface defects we can name:
Pinholes
Bleeding
Scum / casting powder entrapment

Longitudinal facial cracks

2.1 Pinholes. This defect occurs mainly for casting with metering nozzle with oil lubrication. May be deleterious for the final product if they are concentrated in a particular zone (“nest”); they are deep enough as to not disappear in the reheating furnace or if in the first rolling steps the materials has free spreading (it is not contained) somewhere [12]. They are almost scale-free in the beam blank, but then in the reheating furnace the become filled with scale (Figure 5).

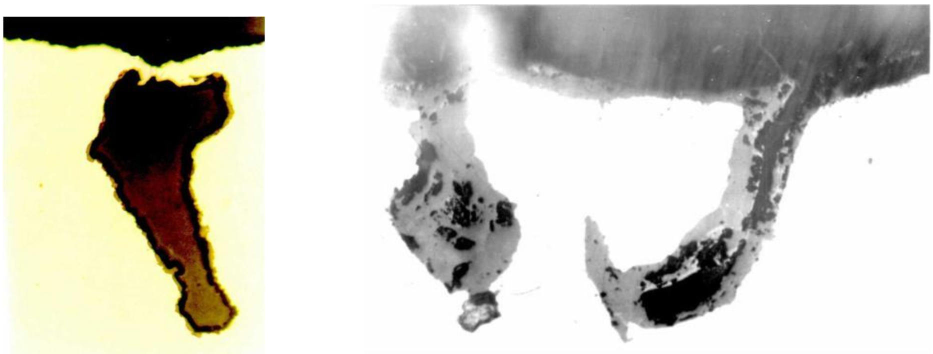


Figure 5. Left: pinhole in as cast billet, just with a thin scale film. Right: pinhole in reheated billet, filled with scale. Polished samples, no etching.

Some of possible causes for pinholing are moisture in the oil (or moisture pick-up in the oil circuit); too high oil rate; inhomogeneous distribution; too thick oil slot gap (more than 0.5 mm); partial obstruction of oil slot gap by splashing; sudden variations in steel mold level; use of pulsing bomb; lack of deoxidation. The use of electromagnetic stirring may help in pinhole elimination.
Blowholes are discussed separately, under the heading Internal Defects.

2.2 Bleeding. As in billets, this defect occurs when small strand breakout takes place, healing immediately, without metal loss. An example of this defect in a beam blank is presented in Figure 6. They may be attributed to the effect of annular strain in hot zones, or sticking. The mechanism in oil casting has been described as presented in Figure 7.

Figure 6. 670 mm wide beam blank with bleeding in the inner surface of the wing [11].

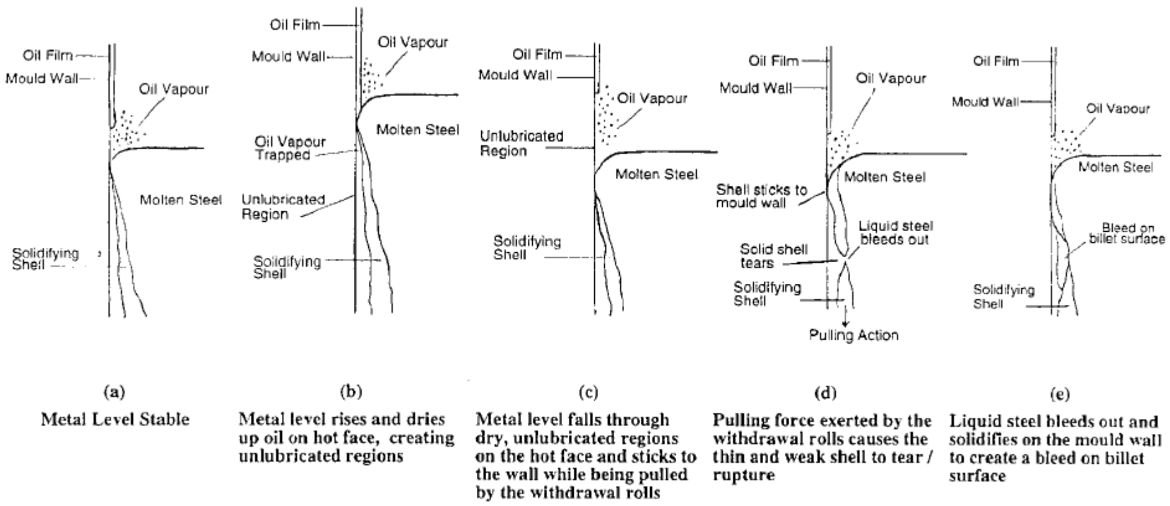


Figure 7. Mechanism for bleeding formation in oil casting.

2.3 Trapped scum / casting powder. Scum forms during open casting due to thorough reoxidation of the liquid steel in contact with air and oxidizing slag. This scum is usually a liquid manganese silicate. If silicon content is too high (due to a low Mn/Si ratio), silica precipitation occurs, bringing about higher viscosity and the risk of scum entrapment in the surface of the beam blank, and in extreme cases, strand breakout. Another way to promote higher viscosity is through aluminum wire injection in the mold, whenever it is excessive or it is not in the right point. Both situations are summarized in Figure 8, on the SiO_2-MnO-Al_2O_3 ternary diagram.

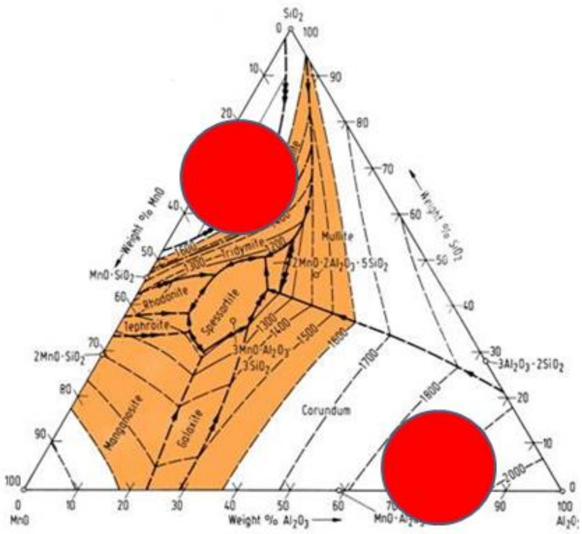
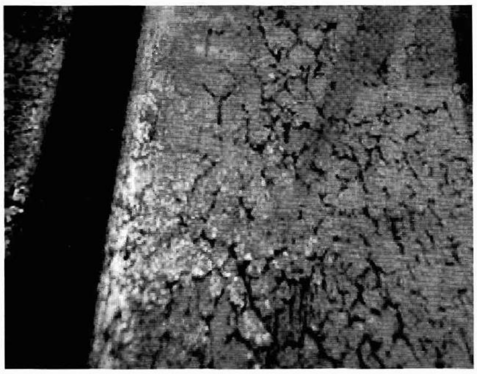


Figure 8. Red circles: regions with risk of precipitation of a solid phase (silica, due to low Mn/Si ratio, or alumina, due to imperfect aluminum wire injection), for scum formation at meniscus level in open casting.

Somewhat similar phenomena may occur with casting powder (with funnel or SEN). Higher viscosity may occur in this case through alumina pick-up, or reduction reactions between elements in the steel and oxides in the casting powder (for example, dissolved titanium reacting with silica in the slag). Casting powder entrapment is enhanced through turbulence: excessive electromagnetic stirring, small SEN / funnel submersion.

2. 4 Network cracks. These cracks, related with a high copper content in the steel, are common to other semis produced in meltshops operating with high scrap charge. In zones where the gap between strand and mold becomes large, the grain size increases and if copper content is high, give place to such cracks. In Figure 9 (left), the effect of these cracks on the rolled H-beam is shown, at Dragon Steel Corporation. At that plant, the copper specification is <0.15%. To achieve this, high hot metal charge is used in the EAF, its content depending on the other scrap types being charged (Figure 9, right).



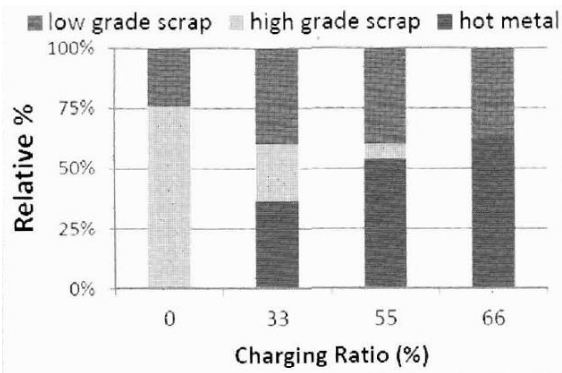


Figure 9. Left: effect of network cracks in beam blank surface on rolled H beam at Dragon Steel Corporation.

2.5 Longitudinal facial cracks. This defect is fairly common for beam blanks. Formed in the mold, it has certain similitudes with longitudinal cracks in slabs and blooms (figure 10). When observed in the rolled product, its metallographic features are the presence of internal oxidation (as polished, no etching), decarburization (etching with Nital 2%) and oxygen penetration (hot etching with alkaline sodic chromate). Influencing factors are the chemistry of the liquid steel, the properties of the casting powder, deviations of caster radius caused by mold oscillation, flow rate and temperature of primary cooling water and secondary cooling flow rate.

Figure 10. 1050 mm wide beam blank. Longitudinal crack between web and fillet [11].

Steel chemistry. From early times, the influence of sulphur content on longitudinal cracks is well known (Figure 11). Another steel chemistry-related factor is the carbon content. Peritectic transformation need to be avoided. Many experiences point to their influence on longitudinal cracking as is well known from slab casting. For instance, POSCO specialists reviewed these cracks for scarfed beam blanks corresponding to 2,000 heats [15]. They found that the more sensible chemistry range was 0.12 – 0.13% carbon, corresponding to steel suffering peritectic transformation. Stahlwerke Thüringen recommended years ago C 0.08% max., with

Mn 0.60% min. to obtain the required mechanical strength [16]. Recently, the criteria to calculate the range of carbon content for which peritectic reaction occurs has been revisited, using thermodynamic commercial codes like FactSage and ThermoCalc.

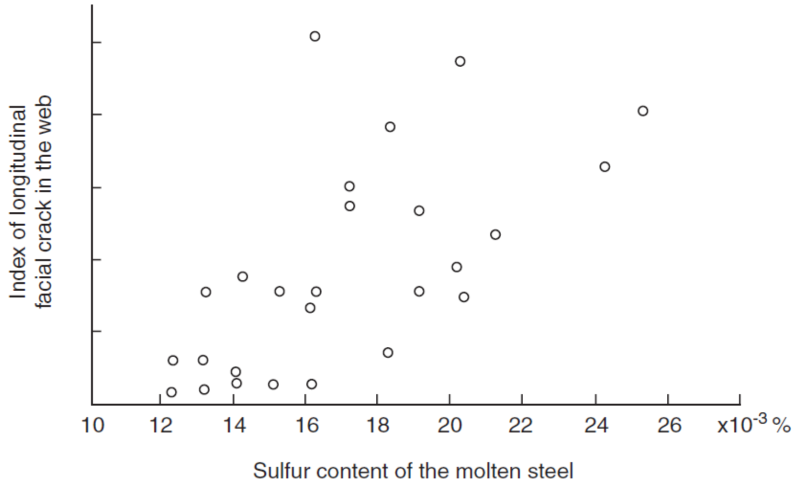


Figure 11. Influence of sulphur content in liquid steel on index of longitudinal facial cracks in the beam blank web [14].

Regarding residuals, their presence seems not to affect very much the presence of longitudinal facial cracks. Stahlwerke Thüringen report no quality problems with Cu 0.35% and Cr or Ni 0,20%; the same with 0.030% Zn and 0.04% Sn.

Casting powder. The influence of casting powder for funnel or SEN casting on longitudinal crack formation s well established. For instance, high basicity – low viscosity mold fluxes gave good results in casting of small beam blanks at low speed (<1 m/min), at Stahlwerke Thüringen [17], figure 12. A “soft” cooling at meniscus level was obtained with that flux. The lower capacity for infiltration and lubrication was partially compensated by the low viscosity.
For another set of conditions, JFE Steel Mitsushima found the opposite situation: low viscosity giving place to longitudinal cracks (among other reasons).

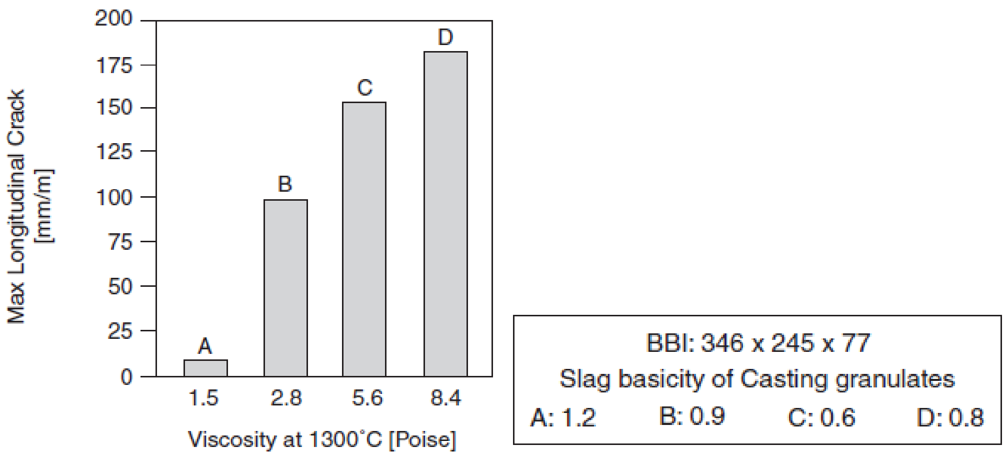


Figure 12. Tests with different mold fluxes at Stahlwerke Thüringen, for a small beam blank cast at low speed (less than 1 m/min), to check influence on longitudinal facial crack formation.

In cold zones of the meniscus (for instance, close to the nozzle), casting powder may reach the limit of its performance and give place to surface cracks (Figure 13).

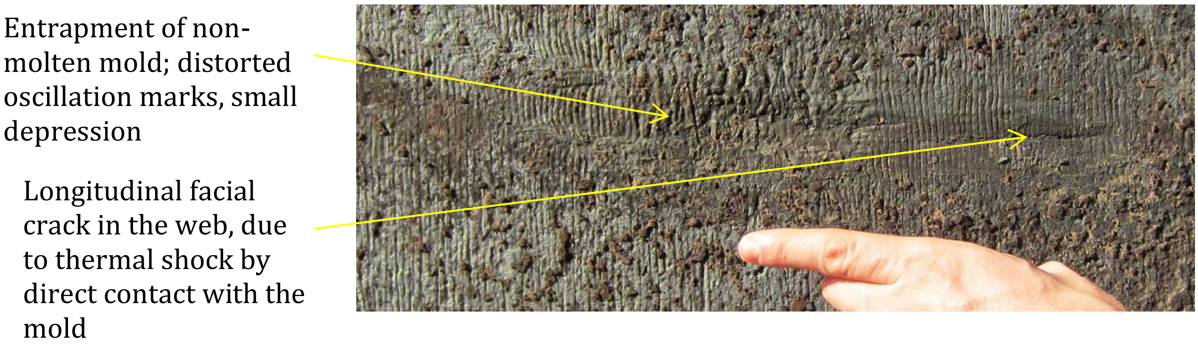


Figure 13. Longitudinal facial crack and casting powder entrapment in a 1050 mm wide beam blank [11].

Casting speed. The afore mentioned research by Posco revealed the there is a lineal relationship. As the casting speed increases, the solidifying shell is thinner, heat flow increases, and strain is larger, giving more cracks as a result.
Secondary cooling. An increase in secondary cooling intensity brings about a proneness to longitudinal crack formation. An experience at Kawasaki Steel (now JFE Steel) shows this relation ship taking into account the already discussed effect of sulphur, too (Figure 14).

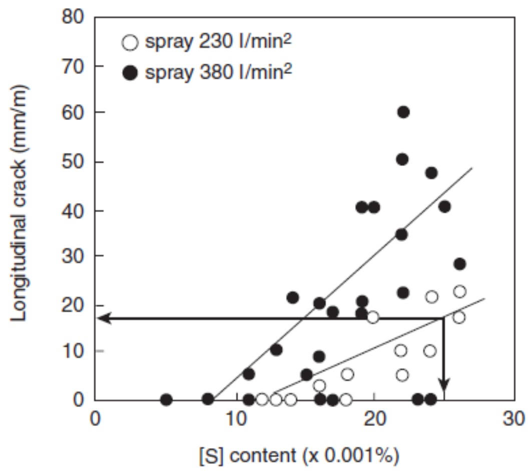


Figure 14. Effect of sulphur on longitudinal crack formation, for different secondary cooling flow rates [18].

Extensive use of mathematical modeling has been carried out to solve this defect. For example, Jin Yi Iron and Steel modeled an optimization of secondary cooling to avoid these cracks, using ANSYS for the thermo mechanical model and MATLAB for parameter optimization [19]. Maanshan Steel did a very thorough modeling of secondary cooling with the same purpose, taking into account all the mechanisms involved in heat transfer (Figure 15) [20].

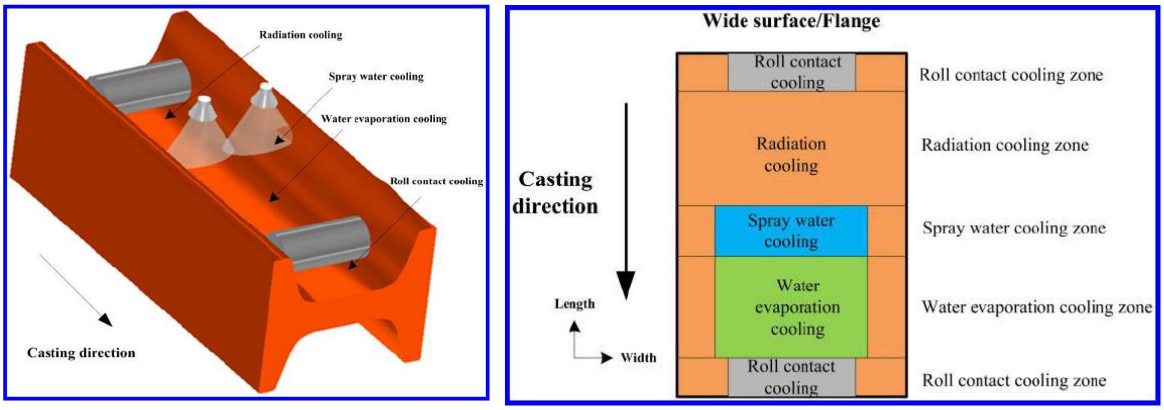


Figure 15. Mechanisms for heat transfer taken into account by Maanshan Iron & Steel in the mathematical modeling of secondary cooling to find ways to avoid longitudinal facial cracks.

In Table 2 these experiences are summarized. The corrective actions may be divided as follows:
Metallurgy: Low sulphur; avoid peritectic transformation
Mold flux: high basicity and even heat transfer
Mold design: To avoid longitudinal cracks in the shoulder
Secondary cooling: less water, mostly for the first segments; better transverse distribution

Table 2. Summary of published experiences for longitudinal facial cracks in beam blanks.

Company/Plant	Year	Corrective actions	Comments
JFE Steel Mizushima	1975	Decrease sulphur; increase mold flux viscosity; improve mold alignment	
JFE Steel Mizushima	1981	Decrease sulphur; adequate mold flux; minimize mold misalignment; adequate primary cooling; soft secondary cooling in first segments; better distribution of sprays in transverse section	
Stahlwerke Thüringen	1998	High basicity low viscosity casting powder	For small sections
JFE Steel Fukuyama	1996	Decrease sulphur; decrease secondary cooling flow rate	
Stahlwerke Thüringen	1997	C<0.08% (Mn 0.60 to ensure mechanical properties)	
Posco	2002	Avoid 0.12-0.13% C; lower casting speed	2000 beam blanks scarfed; 490 x 420 x 140 mm
Stahlwerke Thüringen	2002	Avoid 0.12% C	
Jinyi Iron & Steel	2013	Lower water flow rate in all secondary cooling segments	For high ductility at straightening
Maanshan Steel	2014	More secondary water to fillet; less to wing ends and web center. -10% segment 1; -7% segment 2	

3 INTERNAL DEFECTS

The inner defects in beam blanks have similitude to some extent with defects in billets. The following defects will be discussed:
Blowholes
Web central crack
Inner crack in wing end

3.1 Blowholes. These defects are localize close to the surface, with a direction perpendicular to the surface. They can be seen in the oxycutting, if there occurrence is important. Depending on the root cause, they may be concentrated in the first heat of the sequence or in some given heat, or all along the sequence [12].
The blowholes depart close to the beam blank surface, when there is enough gas segregation to the interdendritic spaces. They come to an end when somewhere below the meniscus, the ferrostatic pressure is higher than the gas pressure (Figure 16).

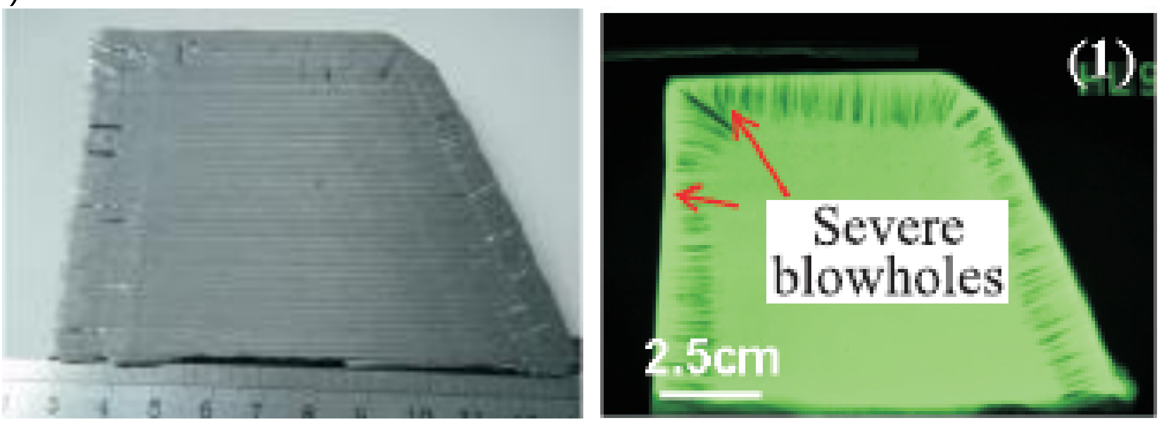


Figure 16. Aspect of blowholes in a beam blank. Left: machined transverse cut. Right: radiography [21].

Blowholes are attributed to an excess of gases dissolved in the steel (oxygen, nitrogen, hydrogen), enough to produce a bubble. This phenomena has been modeled since the early times of continuous casting. From the point of view of deoxidation, for Mn-Si killed steels there is a compromise between the risk of clogging (if deoxidation is too strong) and the risk of blowholes, as shown in figure 17.

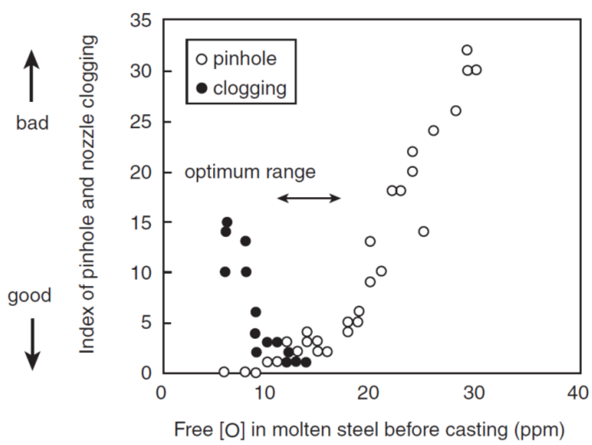


Figure 17. Optimum deoxidation range to minimize blowholes and nozzle clogging, for Mn-Si killed steel beam blanks, according to [18].

Some typical industrial cases of heats with blowhole occurrence, mostly for open casting, are as follows:

- High oxygen: Heats sent to the caster with deoxidation not finished, due to coordination problems of complications derived from furnace slag carry-over
- High oxygen and nitrogen: sequence start
- High hydrogen: moisture in new lining of ladle or tundish
- High nitrogen: ladle with long treatment, when nitrogen is used for stirring

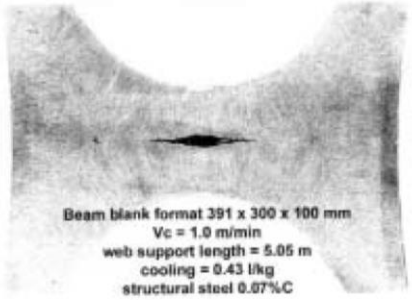
Dragon Steel Corporation reported a case of blowholes in beam blanks cast with metering nozzle [21]. The deoxidation practice included an 80 kg Al addition during tapping, and 40 kg CaFe to get O<10 ppm. Oxygen was injected in the tundish if steel temperature was too low. The beam blanks were scarfed for inspection (Figure 18).

Figure 18. Scarfing for blowhole detection at Dragon Steel Corporation.

After thorough study of ladle furnace and continuous casting variables, it was concluded that high moisture in tundish repair refractory material was responsible for the problem [22].

3.2 Web central crack. This defect is equivalent to centerline segregation in slabs. Not enough support length and/or insufficient secondary cooling have a consequence the bulging of the beam blank and in severe cases, an internal opening in the web (Figure 19, left). High central segregation and crack formation may appear in the rolled product. Tools to avoid central cracking are the roll checker and the equipment for segment alignment.

The Mitzushima plant of the then Kawasaki Steel reported a case of web central cracks for its caster of 12.5 m radius, casting with funnel beam blanks of 400 x 460 x 120 mm and 287 x 560 x 120 mm. There was an influence of sulphur content and casting speed (Figure 19, right). The problem was solved with intensive spray cooling on the web portion, and strict maintenance of roll gap.



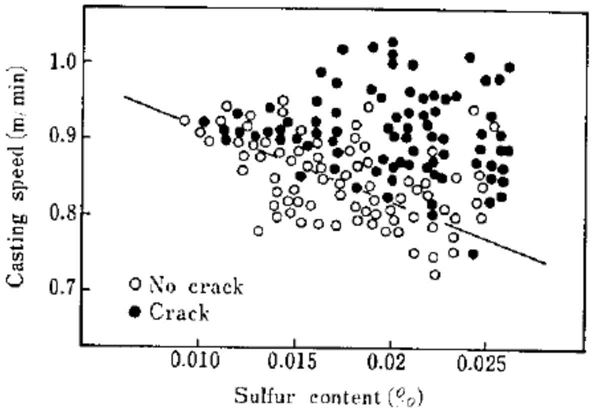


Figure 19. Left: Central web crack. Right: Influence of sulphur content and casting speed on web crack formation.

3.3 Inner crack in wing end. This particular defect has been studied because it gave place to strand breakouts. An improvement plan was carried out at JFE Steel Kurashiki to get rid of the problem. The approach included several studies (Table 3). The aspect of cracks in normal heats had certain features in common with off-corner cracks in billets and slabs (Figure 20).

Table 3. Studies to understand the wing end cracking at JFE Steel Kurashiki.

Study	Objective
Observation of breakout boxes	Research solidification in the mold and the cause for the breakouts
Solidification macrostructure	Clarify mechanism of formation of inner cracks in wing end
Sulphur addition test	Measurement of shell thickness in normal operation
Mold temperature measurement	Estimation of heat flow in several parts of the mold

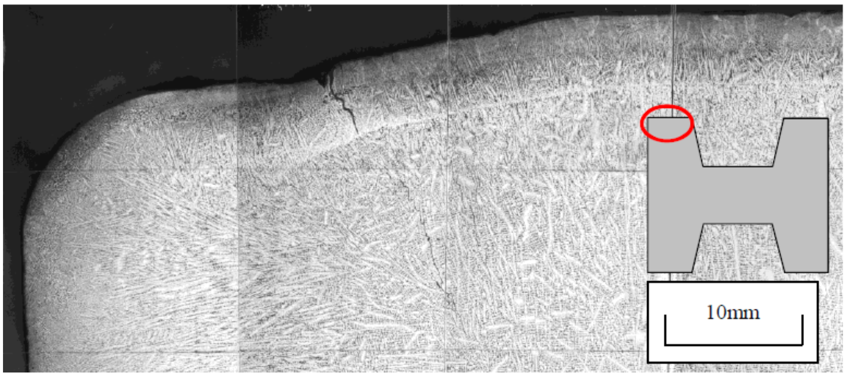


Figure 20. Wing end cracking in beam blanks of a normal heat (no breakout) and JFE Steel Kurashiki.

The problem was solved through an optimization of mold taper in the ends of the wing.

4. CONCLUSIONS

Beam blank casting is an established process with a 50 years history. Nevertheless, it is not free of surface and inner defects. Some of them share features with billet defects; other has more to do with slab defects. The complex shape induce specific solidification defects. The occurrence of defects requires carrying out improvement plans to make minimal. Defect characterization is important. Simulation may help to elucidate the formation mechanism and to suggest corrective measures.

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