

## Experimental study of the continuous casting slab solidification microstructure by the dendrite etching method

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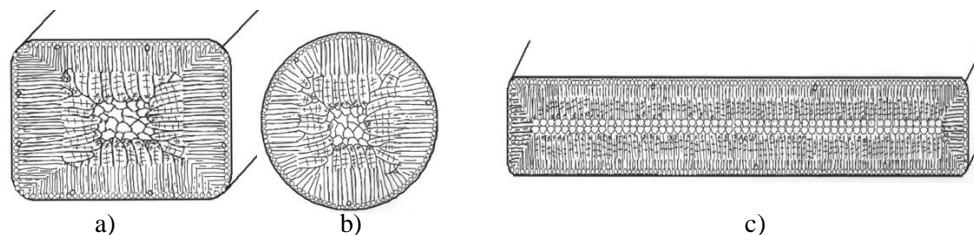
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**Abstract.** The relationship between the microstructure of the continuous casting slab (CCS) and quality defects of the steel products, as well as evolution and characteristics of the fine equiaxed, columnar, equiaxed zones and crossed dendrites of CCS were systematically investigated in this study. Different microstructures of various CCS samples were revealed. The dendrite etching method was proved to be quite efficient for the analysis of solidified morphologies, which are essential to estimate the material characteristics, especially the CCS microstructure defects.

### 1. Introduction

Quality of the continuous casting slab (CCS) is closely related to its solidification microstructure and it has a direct influence on defects of the steel product. By releasing the superheat, latent heat and sensible heat during the cooling process down to the room temperature, the typical solidification microstructure of CCS is usually composed of: (i) fine equiaxed grains, (ii) columnar grains, (iii) equiaxed grains, and (iv) crossed dendrite, as shown schematically in figure 1. With respect to the blooms and heavy slab, crossed dendrite as the transition zone can be observed between the columnar and equiaxed region, while crossed dendrite is rarely found in the billets and thin slab due to the fast cooling rate.



**Figure 1.** Schematic diagram of solidification microstructure of continuous casting: a) rectangular bloom; b) round billet; c) blank

The measurements of the deflective angles of the columnar grains and distances of the secondary dendrite are important for characterization of the solidification microstructure. In this respect, very instrumental is the dendrite etching of the solidification microstructure, which is based on the recommendations of Chinese standard GB/T 226-2015, whereas the assessment of the solidification microstructure accords to the methods given by GB/T 24178-2009.

In general, five macro-examination methods including sulfur print, hot etching, electrolytic etching, cold etching, and dendrite etching can be used to the macro-examination. Among these, the dendrite etching method is applicable for characterization of the solidification microstructure, which is further illustrated by several examples.

## **2. The relationship between the solidification microstructure and defects.**

The solidification microstructure especial the distribution and abundance of various regions of CCS is of great concern due to their important effect on the defects of the steel products.

### *2.1 The relation between solidification structure and defect of continuous casting*

The situation that the fine equiaxed region is too thin or inhomogeneous, especially the strong columnar grains below the surface depression, and absence of the chilled zone [1], may lead to the formation of surface longitudinal crack in the CCS and even to catastrophic failure. The strong columnar grains generally aggravate the central segregation of the CCS, thus deteriorating the properties of steel products. For example, low content of equiaxed grains in the strong columnar region of CCS may lead to an increase in the inhomogeneity and degree of deformation to effect the seamless steel tube internal buckling.

The high abundance of the equiaxed region, where the equiaxed grains are embedded into each other and firmly combined, implies a better processability to ensure isotropic mechanical properties. On the contrary, intense columnar grains with a parallel orientation to each other exhibit the intergranular segregation, banded structure, and anisotropy [2], therefore deteriorating the transversal mechanical properties and tenacity.

### *2.2 Influence of the solidification condition on the microstructure of CCS*

It is generally believed that microstructure of CCS significantly depends on the solidification conditions. However, for the continuous casting process the latter are hard to be monitored and can be alternatively assessed and modified, according to the identified CCS microstructure patterns

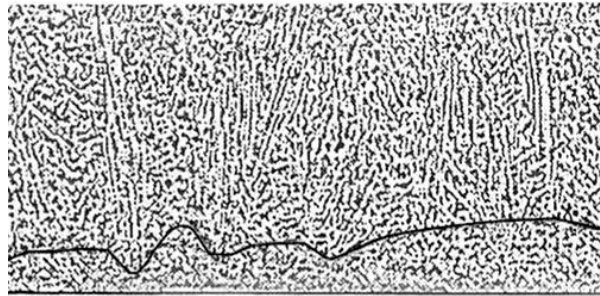
## **3. Solidification microstructure of CCS**

### *3.1 Fine equiaxed grains*

During the solidification process, the fine equiaxed grains crystallize firstly at the wall of the mold and contribute to the surface of CCS. This region is fine, dense, and anisotropic, while its thickness is usually inhomogeneous and has a size of about 2-8 mm. In addition, the composition of the fine equiaxed region is similar to that of the liquid steel.

The fine microstructure of the fine equiaxed zone [3] is ascribed to the fact that nucleation rate much exceeds the growth rate because of very high cooling rate ( $100^{\circ}\text{C/s}$ ) caused by the strong endothermic and heat dissipation effects of the copper wall at the mold meniscus. As illustrated in figure 2, the fine equiaxed zone is located between the lower edge and the black line of CCS, above which the fine columnar zone can be observed.

The thickness of the fine equiaxed zone is mainly controlled by the liquid steel superheat: higher temperature corresponds to larger thickness and vice versa. In addition, the thickness of the fine equiaxed zone is also controlled by the cooling ability of the mold and the casting speed.



**Figure 2.** Micro-equiaxed and micro-columnar crystals in the transverse section of 300mm x 1650mm blank from 16Mn steel.

### 3.2 Columnar crystal

The columnar grains are actually composed of a primary dendrite, secondary dendrite, tertiary dendrite, and multiple dendrites. These dendrites generally grow in parallel to the same direction and have a pillar-like morphology [4]. The columnar zone distributes between the fine equiaxed zone and the equiaxed zone (central region).

Most of the columnar grains are formed in the secondary cooling zone where the intense cooling of water or vapor gives rise to a temperature gradient vertical to the surface of CCS and inhibits the grain growth parallel to the surface, and thus columnar grains vertical to the surface are achieved, as displayed in figure 3.



**Figure 3.** Micrograph of columnar crystal of the secondary cooling zone in transverse section of 380 mm x 280 mm rectangular bloom of steel 20.

Fine columnar grains with the absence of branch and deflection can be observed in the region near the fine equiaxed zone (chill zone), which is attributed to the high gradient of temperature. Then, the number of columnar grains decreases, and multiple dendrites develop. Finally, the columnar grains become thicker, and the section morphology changes from simple to complicated one.

At the center and lower parts of the mold, air gaps appear due to shrinkage and separation of the billet shell from the mold. Herein, the thermal resistance increases, heat transfer slows down, and the heat flux flows along the direction perpendicular to the mold wall, and the fine columnar grains begin to grow. Therefore, the fine equiaxed grains are formed only on the mold top. To prevent distortion and breakout of CCS in the mold lower part, the billet shell thickness should reach a certain size (usually over 8-10 mm for a small billet and 15-25mm for bloom and heavy slabs).

### 3.3 Equiaxed grain

The equiaxed zone locating at the center of CCS presents various morphologies such as round, oval, polygon and strip-like grains and is anisotropic. At the later stage of the columnar grains, a decrease of both the thermal transfer rate and temperature gradient caused by the increase in thickness of the shell stops the growth of the columnar grains and also the crystallization of the residual liquid steel. At the same time, some dissociative nucleus and broken dendrites are brought into the residual liquid, which decreases the temperature and becomes the new nucleus for solidification and promotes the formation of the central equiaxed zone. The central equiaxed grains are coarse for the low thermal transfer and adequate grain growth, as illustrated in Figure 4.



**Figure 4.** Equiaxed grain band: horizontal area of 300mm×1650 mm blank from medium carbon steel (0.23% W(C)).

### 3.4 Cross dendrite

Heat transfer and a decrease in vertical temperature gradient during the later stage of the solidification process result in the formation of the crossed dendrites, which limits the directional growth of the columnar grains. Furthermore, some broken dendrites with various growth orientations also promote the crossed dendrites. A typical morphology of the crossed dendrites can be seen in figure 5. The crossed dendrites, which are located between the columnar and central equiaxed grains, can be often observed in the bloom, heavy slab or billet with high alloying contents, but seldom in thin slabs and small billets.

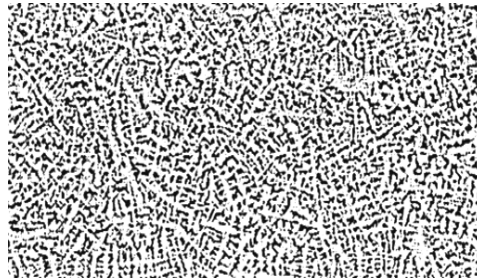
The crossed dendrites with no directional distribution are beneficent for the isotropy in steel products. The crossed dendrites embed with each other and distribute uniformly thus act in a similar manner as equiaxed grains do. So according to GB/T 24178-2009, the method for the assessment of microstructure for the crossed dendrites should be identical to the one used for equiaxed grains.

In general, a fine equiaxed zone exists at the surface of CCS: the center is the equiaxed zone, and columnar grains are located between the center and the surface. The crossed dendrites are located in the middle of the columnar and central equiaxed grains or the trigonum of the blooms.

As to heavy slabs or blooms produced by the arc continuous caster, the columnar grains at the inner arc side are obviously longer than that at the outer arc side, although the cooling intensity is similar. Besides, the equiaxed and crossed dendrite zones on the inner arc side are both thinner than those on the outer arc side. The phenomenon is ascribed to the fact that growth of columnar grains is limited by some dissociative nuclei and broken dendrites brought into the outer arc side under the effect of gravity. Those broken dendrites can act as



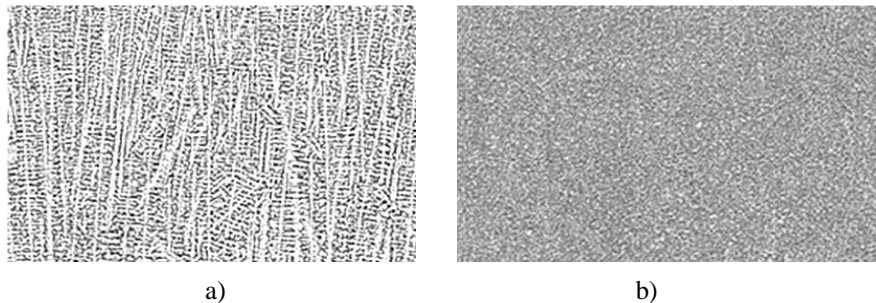
nuclei of crossed dendrites, and thus make them stronger.



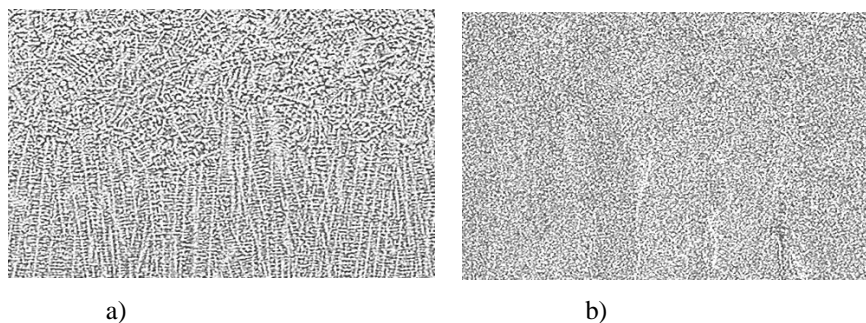
**Figure 5.** Cross dendrite (horizontal area) of 230mm×1650mm blank of Q235B steel.

#### 4. Examples of different solidification microstructures

##### 4.1 Comparison of the morphologies by different etching methods



**Figure 6.** Casting slab solidification structures (horizontal area) for 180 mm×1200 mm blank 510L steel: a) Dendrite etching (with the solidification microstructure and secondary dendrite details); b) Cold etching (with no solidification microstructure details).

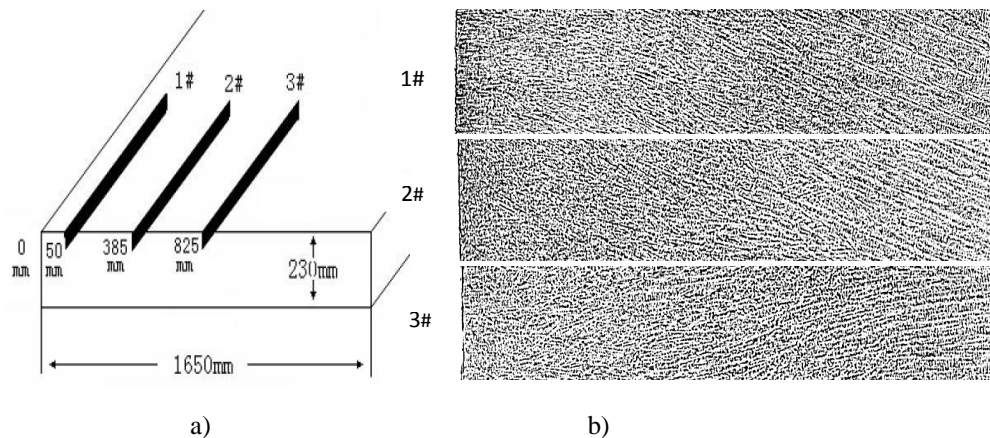


**Figure 7.** Casting slab solidification structures (horizontal area) for 180 mm×1200 mm blank Q345B steel: a) Dendrite etching with detailed morphologies of the crossed dendrites (upper half) and columnar grains (lower part) and the secondary dendrite; b) Cold etching (with no solidification microstructure details).

##### 4.2 Analyses of solidification microstructures

*4.2.1. Deflection of the column crystal.* The inclination/deflective angle of the columnar grains, which are mainly influenced by flow velocity of the liquid steel can be used to derive

the flow condition, and modify shape of the submerged nozzle, insertion depth, size, and angle of the side hole, and thus check the CCS purity and availability of inclusions [6]. There is a deflective angle of  $20^\circ$  between the columnar grains and vertical direction of the CCS surface (heat flow) direction) in #1 and #2 samples, as can be seen in figure 8(b). However, no deflection is observed in the central part of #3 sample, except for the liquid flow edge.



**Figure 8.** Continuous casting slab column crystal's dendrite etching picture [5] for 230mm×1650mm blank of medium carbon steel ((0.15%W(C),0.38%W(Si),1.34%W(Mn), 0.013%W(P), 0.017%W(S) at casting temperature of 1542°C and casting speed of 0.79m/min: a) Surface of the inner arc side of SSC with positions of samples #1, #2, and #3 samples; b) Column crystal inclination angles (vertical area) for #1, #2, and #3 samples.

**4.2.2. Measurement of the secondary dendrite distances.** It has been reported that the cooling rates in different locations of CCS during solidification are hard to be measured. However, the cooling rate  $\varepsilon$  (K/S) can be calculated by the following empirical equation that  $\lambda_2 = a\varepsilon^n$  [7], where  $\lambda_2$  is the secondary dendrite distance,  $a = 109.2$ , and  $n = 0.44$ .

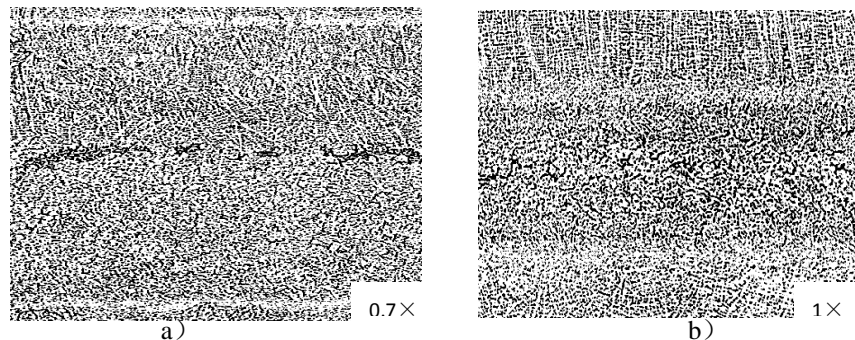


**Figure 9.** Micrograph of the secondary dendrite in the transverse section of medium carbon steel (0.16%W(C)) in 230mm×1650mm blank.

It is also necessary to analyze the central segregation based on the secondary dendrite distance as is shown in figure 9. When the cooling rate is low, an increase in the secondary dendrite distance leads to a dramatic elevation of permeability, promotes the mother liquid enriched with the solute elements flowing into the center of CCS, and thus aggravates the central segregation. However, this does not occur at high cooling rates. This effect is more

pronounced for billets of high-carbon steel (150mm×150mm), where low central segregation and fine grains can be obtained when the secondary dendrite distance is suppressed.

4.2.3. *Determining the electromagnetic stirring effect (S-EMS) at secondary cooling zone.* Figure 10a) depicts the phenomena of sinking equiaxed grains with a poor S-EMS, where the central segregation is assessed as grade 2, while figure 10b) shows a symmetrical distribution of equiaxed grains for a good S-EMS, and the central segregation is assumed to be of grade 1.



**Figure 10.** Assessment of the metallurgical effect of S-EMS in transverse section of the medium carbon steel: a) 300mm×1650mm blank; b) 230mm×1650mm blank.

## 5. Conclusions

Continuous casting is an accelerated process of steel production, for which the quality control of steel products in terms of their solidification microstructure is crucial. Abundant metallurgical data can be obtained during the continuous casting process by assessing the solidification microstructure. It is proved in this study that the dendrite etching method is instrumental to examine the solidified morphologies and estimate the material characteristics, especially the defects of the CCS microstructure, and then modify/optimize the casting technology for the particular practical purposes.

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