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Defects of the steel billet in continuous casting

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Abstract

In continuous casting process, defects of the steel billet (e.g. crack, pinhole, blowhole, central shrinkage, slag entrapment and appearance deviation, etc.) negatively affect the quality and the yield of rolled products. This research has been carried out to investigate some defects which often occurred in Vietnamese steel plants. The experimental work was conducted in an industrial 4-strands continuous casting machine with the billet's cross-section of 130×130 mm^2. The position, generating cause identification of these defects and proper measures have been discussed. A change in the steel compositions and the water distribution during secondary cooling was applied to improve the steel billet quality It has shown that the billet defects have greatly decreased and the quality of billet has obviously increased.

1. Introduction

Steel continuous casting is now very popular to produce semi-finished products (slabs, blooms or billet) in the most suitable cross-section for further shaping [1-4]. Improving the steel quality and the steelmaking process has been a target of metallurgical engineers and steelmaking companies in a demanding market for better products at highly competitive price [5-9]. According to research of Kong, prediction of quality of each continuous casting product and the assessment were essential for increasing the yield of rolled product and improving the production management cost [9]. It is knowing that high quality steel can only be obtained if the continuous casting steel has not any defects which relate to appearance, form, dimensions, internal or surficial, chemical or mechanical deviations. A defect is always the result of multiple interacting causes which are dependent on variation of the operating parameters [9-12]. Sahoo reported that the reasons may include the phase transformation, heat transfer within the mold, the cooling water sprays, friction between strand and mold, mechanical effects due to misalignment of the casting machine, and straightening strains [13]. Several defects may be found on the same billet, meanwhile, a specific defect (e.g. appearance) may have one or more different causes. Apparently, different defects may have one or more common causes. Much research has been conducted to detect the reasons of occurrence and to prevent or remove these defects [14-17]. For example, Matjaz reviewed the hot brittleness of automotive panel in the peritectic range and found that copper and tin penetrated along the grains boundaries and weakened the grains cohesion and induced surface cracking; the original defect came from defect of the steel billet [14]. Dinesh proposed a method to check the surface defect, root causes of the defect; and solutions were recommended for each case [17]. Since secondary cooling control is an important factor in the continuous steel casting process, simulation and modeling of this issue have been published in the literatures [18-23]. A mathematical model of the heat transfers and solidification was developed for a continuous casting of round billet and calibrated with superficial temperature measurements in the industrial plant, then the water flux density distribution of flat jet and full cone jet nozzles along the secondary cooling zone was determined experimentally [10]. A finite-element model has been developed to simulate the temperature, shape, and stress of the steel shell which moved down inside the mold in a state of generalized plane strain at the casting speed [12]. Meanwhile, Ma has optimized the secondary cooling water distribution by using finite volume method to solve a mathematical heat transfer model at the casting speed of 1.9 m·min^{-1}, and the billet defects strongly decreased [2]. Han established a secondary cooling strategy of transverse non-uniform water flux and compared with the uniform cooling strategy using mathematical modeling; found that the latter case contributed to reducing internal cracks of the billet and the first one was beneficial for surface quality and central segregation [3].

In Vietnam, all kinds of steel bars are produced from the continuous casting billets which sometime have cracks or other defects. These imperfect billets result in a reduction of mechanical properties and surficial quality of the rolled product. Thus, many efforts have been made to enhance quality of the steel products and to fulfill the increased requirements of the customers. Although a lot of works have been done to study on this issue, clarification of the defects and the effective solutions are still important for the industrial scale. In this paper, typical defects of the billet which often occurred in Vietnamese steel plants (namely crack, pinhole, central shrinkage, etc.) were

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identified, and the causes of formation were elucidated in the basis of the published references. Some preventing solutions, e.g. adjusting the steel composition and distribution of secondary cooling water, have been applied to reduce the rate of defect billets.

2. Experiment

The industrial experiments were carried out over several months in a steel plant. The continuous casting machine had four strands and was capable of producing billets of 130×130 mm^2 of cross-section. The observed billets were taken from the same strand, of which curvature was 9 m. The primary cooling of the liquid steel took place in the mold and the secondary cooling carried out in the water spray chamber which had four controlling zones (0, 1, 2 and 3) as illustrated in Figure 1. After going out from the chamber, the billet was straightened and cut in different lengths.

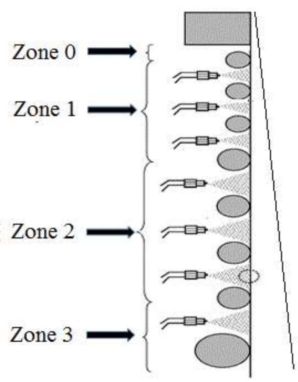

Figure 1. Secondary cooling zones in steel continuous casting.

The casting speed was controlled as 2.6 m·min^{-1} depending on the steel grade and temperature of the melts. Temperature of liquid steel in the tundish was measured in the range 1540-1550°C. During observation period, chemical compositions of the steel billet were shown in Table 1. The specimens were taken from various melts which compositions were consistent with the standard. Type of the defects was detected by checking the macrostructure, and remarked for evaluating the fraction of the defective billets. For a doubtful billet, grinding the surface was used to make the defects clearly. The water flow and distribution of the secondary cooling zone was experimentally changed to investigate improvement of billet quality.

3. Results and discussion

It is important to know the frequent occurrence, origin and position of defects in the steel billet. The determination must include the recording and analysis of general information by using an easy method. For instance, the defects of the billet surface or the cross-section can be seen with naked eye and a better view of these defects is obtained when the observation area is cleaned of scale by means of sand blasting or shot blasting [17]. Some typical defects appeared during the solidification and cooling in the present continuous steel caster have been pointed out and discussed as below.

Pinhole is a surface defect occurred in the billets, shows up in a longitudinal way in the center of the face. During rolling, the pinholes are elongated; and depending on the reduction, they can be seen on the final product or the practically disappear. If being present in abundance or have a large size, pinholes may originate defects in the rolled products. Their distribution on the billet surface depends on the phenomena that originated its formation. According to findings of Jorge, the pinholes were accommodated longitudinally along the center of a billet face, while the surface closer to the corner showed some friction related defects [1]. The pinholes formation has been associated with gas development by pyrolysis of lubricating oil, and the presence of oxygen dissolved in the steel. So, it would be safe to work in the lower range of oil rate and good deoxidation of the liquid steel to avoid the pinhole formation.

In the experimental time, opening cracks were sometime found on the billet surface shown in Figure 2 with variable length and depth, which may extend on the entire billet. The cracks were not always straight, but interrupted and further continued in zigzag. Taking into account the direction on which they were formed, the cracks could be longitudinal, transverse or star types. Although inspection of billets does not always detect, transverse cracks which form in the mold or during secondary cooling may cause a serious defect in the rolled products known as V defects on the surface [17]. In the present study, the cracks were observed only in the corner belonging to the inner radius due to tensile stress related to the sticking and the straightening of the billet. This problem can become worsened by deep oscillation marks, or when the corner temperature was in low ductility range. A good approach to solve the problem is to set proper secondary cooling to avoid the dangerous temperature range in the corners during strengthening [10].

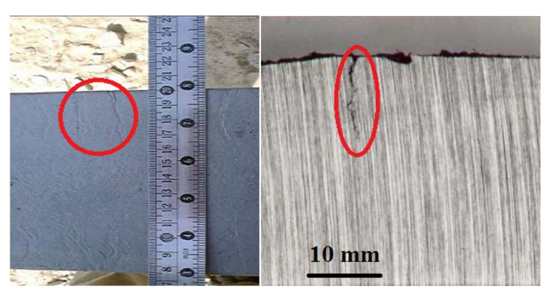

Figure 2. Surface cracks of the steel billet (left) and depth of the crack (right).

Table 1. Chemical compositions of steel billets.

	C	Si	Mn	P, S
Grade 1	0.20-0.25	0.25-0.30	0.85-0.90	≤ 0.03
Grade 2	0.26-0.29	0.18-0.23	0.70-0.75	≤ 0.03
Grade 3	0.10-0.14	0.15-0.20	0.45-0.50	≤ 0.03

Rhomboidal billet, which usually present off-corner cracks in the obtuse corners (Figure 3), is an old problem of steel continuous casting, even for new casters. Depending on the level of rhomboid, the off-corner cracks may continue through the diagonal, after the path where the columnar grains meet. This fact suggests a link between the formation mechanisms of rhomboidal cross-section and off-corner cracks [11]. During preheating the billet, rhomboidal cross-section may bring a problem in billet movement, particularly in push furnaces. As occurs with other inner cracks, these cracks usually stay as a weak point in the structure of the rolled products. Originated in the mold, probably in the first centimeters solidified, and linked to steel solidification features and mold heat transfer, the problem has been generally attributed to non-uniform cooling in the mold. Strategies to overcome the problem vary from plant to plant and even in the same caster under different operational situations.

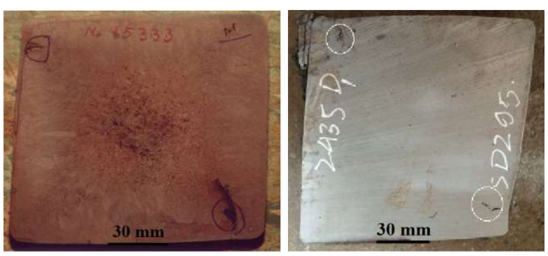

Figure 3. Rhomboidal cross-section and off-corner cracks (in the circles) of the billet.

Central crack and porosity shown in Figure 4 is an inner inhomogeneity of the continuous cast strand and can sometimes be accompanied by shrinkage, both caused by the same factors. Clearly, the micro-shrinkage concentrated in a central hollow of the cross-section as the result of steel shrinkage on passing from the liquid into solid state. These defects appear because of the high casting temperature, the high rate of solidification and by the strongly secondary cooling. It is accepted that the fluctuation of casting speed has a great influence on the billets quality, e.g. reduction of the casting speed is benefit for decreasing the central porosity. Sahoo concluded that central shrinkage and number of central crack were significantly reduced using the electromagnetic stirrer (EMS) installed along the casting strand, and the billet quality was improved [24].

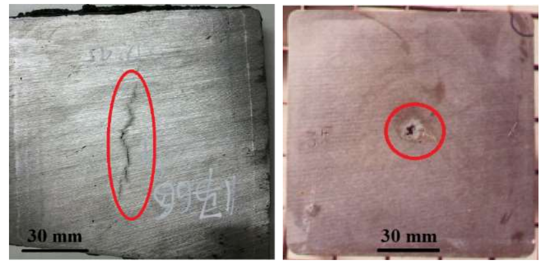

Figure 4. Central crack and porosity on cross-section of the billet.

The quality of the steel in the continuous casting is directly related to the temperature variation during the solidification process [25]. A low-ductility temperature region also exists between 750 and 850°C, which is usually associated with formation of inter granular/ columnar crack along austenite grain boundaries. Examples of inter columnar cracks were shown in Figure 5, in which the cracks were present near the first solidified shell of the billet. During the solidification of steel, the trace elements (e.g. copper, tin) and other impurities (e.g. sulphur, phosphor) concentrated in the last liquid phase and were pushed towards the inter dendritic regions, where they facilitated the formation of cracks or caused brittleness of the steel when the steel was exposed to shrinkage stress [13,14]. This type of crack results in the surface tears, i.e. surface cracks on hot rolled products. So, it needs to be careful about inter columnar cracks and the solution in controlling the impurities as well as the depression at the austenitic temperature.

Figure 5. Inter columnar crack (in the black circle) on cross-section of the billet.

In the period of survey, the defective billets were classified to determine the fraction as plotted in Figure 6. Clearly, rhomboidal defect which caused the off-corner crack occurred at the biggest fraction. This type of defect strongly affected to the rolling process, resulting in reducing the metallic yield and the productivity of casting machine. As discussed above, there were many factors affecting the formation of the rhomboidal cross-section and the off-corner crack but only the compositions of the steel grade and the secondary cooling regime were concerned and analyzed.

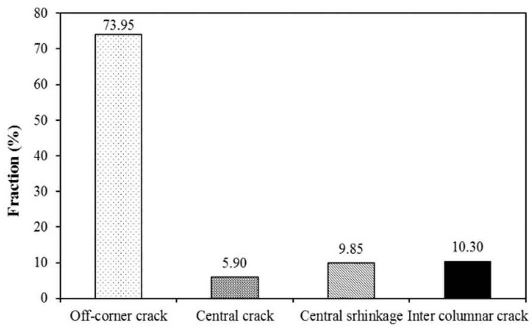

Figure 6. Fraction of the defective billets classified by the defect type.

Billet of the grade 3 had the biggest fraction of off-corner crack (Figure 7). This was attributed to the C content of 0.10-0.14 %, which was thought to be a sensitive range for cracking occurence as found by Manjohme *et al.* [26]. Once varied thickness of the solidified shell was easily formed, the inhomegenuous solidification of the strand surfaces occurred; and the cross-section of the billet became rhomboidal. Otherwise, a higher Mn content in the other steel grades was also a positive factor for improving the fluidity of liquid steels and preventing formation of the rhomboidal defect; resulting in the same thickness of the shell. When formation of a thin shell in the mold in two opposite corners and a thick shell in the other two occurred, the section became to an off-square shape during first stage of secondary cooling. Due to the faster temperature decrease where the shell was thicker (due to enhanced heat transfer) and shrinkage was not uniform, giving to an acute angle in the colder corners and obtuse angle in the hotter corners.

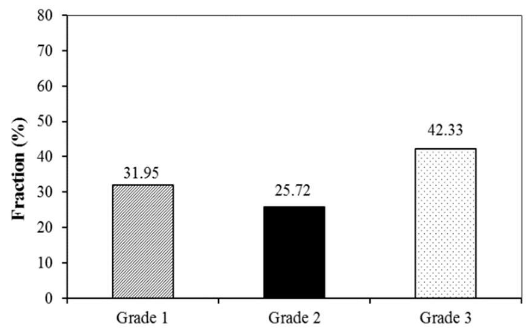

Figure 7. Fraction of the billets having off-corner crack versus the steel grade.

Table 2. Effect of the secondary cooling on cracking defects of the steel (grade 3)

Experimental conditions in 2nd cooling			Fraction of cracked billet (%)
Water flow ($m^3 \cdot h^{-1}$)	**Number of heats**	**Water distribution (%)**	
95	3	Zone 0 : 30 Zone 1 : 40 Zone 2 & 3: 30	14.41
	5	Zone 0 : 40 Zone 1 : 35 Zone 2 & 3: 25	10.29
	5	Zone 0 : 40 Zone 1 : 30 Zone 2 & 3: 30	11
105	5	Zone 0 : 30 Zone 1 : 40 Zone 2 & 3: 30	7.84
	7	Zone 0 : 40 Zone 1 : 35 Zone 2 & 3: 25	5.93
	5	Zone 0 : 40 Zone 1 : 30 Zone 2 & 3: 30	6.42
115	2	Zone 0 : 30 Zone 1 : 40 Zone 2 & 3: 30	7.94
	3	Zone 0 : 40 Zone 1 : 35 Zone 2 & 3: 25	9.62
	5	Zone 0 : 40 Zone 1 : 30 Zone 2 & 3: 30	10

It was believed that these defects were attributed to the non-uniformity of the heat transfer of the billet in the secondary cooling. The research showed that the water distribution was not uniform in both longitudinal and angular directions owing to the unevenness of the spray and to the curvature effect of the billet [25]. This non-uniformity caused an important variation on the heat transfer coefficients and superficial temperature of the billet, especially in the first cooling zones where the temperature was higher. Thus, the water flux has the largest effect on heat transfer coefficient in the temperature range. From this research, a full comprehension of the formation mechanism was still lacking; the mechanisms proposed in the discussion gave partial explanation for the occurrence of the defect. Since the local water flux density along the secondary cooling zone varied, the heat flux and heat transfer coefficient varied locally as well [21,22]. In order to eliminate internal cracks and other defects, the secondary cooling water distribution must be controlled so that the surface temperature of steel billet is kept in the desired range. There are several strategies of secondary cooling water distribution [2]. In this work, manual control method was carried out according to the experience of the operators and obtained results of the references. Based on confirmation of Huang, the surface temperature of continuous casting in water spraying zone was a key factor for production control [19]. Therefore, the billet surface temperature of the present caster was controlled at about 950°C at the straightening area by adjusting the secondary cooling condition (corresponding to the 105 $m^3 \cdot h^{-1}$). The water flow and distribution in the specific zones of the secondary cooling were adjusted as shown in Table 2. Low water flow (95 $m^3 \cdot h^{-1}$) caused the high surface temperature at the straightening area (965°C in average), so it would be a reason for formation of the internal cracking including off-corner crack; meanwhile, high value (115 $m^3 \cdot h^{-1}$) caused the low surface temperature (940°C in average), so it would trend to occur the cross-section distorce and thermal stress inside the billet. The result indicated that the water flow of 105 $m^3 \cdot h^{-1}$ and the water distribution of 40-35-25% were most suitable when the fraction of cracked defect was only 5.93%. For this experimental condition, other problems such as bulging, breaking, etc. of the strand were not occurred.

4. Conclusions

In continuous casting, defect of the steel billet is one of the important factors affecting the rolling products quality. This study was conducted to investigate defects of the billet of 130×130 mm^2 (e.g. central shrinkage, rhomboidal cross-section, inter columnar crack which often occurred in Vietnamese steel plant), as well as to investigate the cause and measure for prevention. In consistent with other research papers, it was acknowledging that the defects and cracks formation were highly dependent on the temperature distribution and cooling regime of the casting strand. For the present caster, rhomboidal billets and off-corner crack were found to be the largest fraction of the defects during production. Chemical compositions of the melt and the secondary cooling regime were important factors for these defects formation. Beside a higher Mn content was suggested, the water flow of 105 $m^3 \cdot h^{-1}$ and a distribution of 40-35-25% in the secondary cooling region were used to decrease the defect of billet. However, not always the solutions adopted in one caster could be applicable to others because of the varied conditions of casting speed, mold design, operating practice and configuration of secondary cooling.

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