Research Status and Control Measures of Transverse Cracks for Micro-alloyed Continuous Casting Billet

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Abstract. The transverse cracks of the micro-alloyed steel continuous casting billet seriously damage the quality of the continuous casting billet and cause great losses to the enterprise. The influence of the hot ductility, microstructure, and micro-alloying elements on transverse crack was discussed, which has been researched in-depth at home and abroad. Through a great deal of studies, various control measures of transverse crack are proposed, such as secondary cooling technology, chamfering mold, refining the surface structure of the casting slab, and double phase transformation process. However, the transverse cracks have not been fundamentally solved. Therefore, the formation mechanism and control measures of the transverse crack are summarized for providing with the idea of eliminating transverse crack.

1. Introduction
Micro-alloyed steel is widely used in various engineering structural steels and is the main product in the modern steel industry[1]. The main feature of micro-alloyed steel is the addition of micro-alloying elements such as niobium, vanadium and titanium to the steel in order to control the formation of related carbonitride to regulate the recrystallization behavior of deformed austenite and prevent grain growth, and to produce precipitation strengthening and grain refinement in matrix, thereby increasing the strength and toughness of the steel.

However, due to the addition of micro-alloying elements, the crack sensitivity of the billet increases, and surface transverse crack and corner crack are formed in most cases, which makes the billet have a high defect rate after rolling and prejudices the production schedule and cost. Therefore, how to optimize the continuous casting process and micro-alloying elements addition, and reduce the transverse crack of continuous casting billet is an urgent problem for domestic and foreign enterprises.

2. Factors of the Transverse Cracks Formation
In the continuous casting process, as the molten steel is injected into the crystallizer and solidifies to form a shell, the billet is subjected to various stresses such as phase transformation stress, molten steel static pressure, thermal stress and mechanical stress. When the stress is greater than the critical stress that the slab can withstand, the solidified shell of the slab will crack. Therefore, the factors of the slab crack are numerous, and most of them are the combined effects of multiple factors.
2.1. Influence of the Hot Ductility on the Transverse Cracks

Suzuki et al. proposed and improved the mechanism of three brittle zones[2-4]. B. Mintz et al.[5-9] conducted many detailed and in-depth studies of the relationship between the third brittle zone and the transverse crack. The reason for forming the ductility trough below the Ae3 temperature is that the strain-induced pro-eutectoid ferrite precipitates along the austenite grain boundary, causing stress concentration around the MnS; moreover, the ductility trough is caused by the grain boundary slip above Ae3 temperature. On the high temperature side of the ductility trough, plastic recovery occurs due to dynamic recrystallization, but the precipitation of micro-alloyed carbonitride hinders dynamic recrystallization of steel, especially Nb (C, N), and widens the ductility trough of steel containing Nb. On the low temperature side of the ductility trough, plastic recovery is dependent on the formation of a large amount of ferrite in the grain boundaries and grains. In case the proportion of ferrite in the austenite-ferrite two-phase region is higher than 45% during straightening stage, the ductility of the slab can be effectively improved and the formation of transverse cracks can be reduced.

2.2. Influence of the Microstructure on the Transverse Cracks

As early as 1974, Rain et al. [10] proposed that the formation and development of transverse cracks in continuous casting billets are always accompanied by coarse austenite grains. Tsai et al. [11] found that in the event the austenite grain diameter is larger than 1 mm, the probability of transverse cracks in continuous casting billet is almost 100%. Mainly due to the different grains orientation on both sides of the grain boundary, the dislocation structure is very complicated, and the difficulty of crack passing through the grain boundary is correspondingly larger. Therefore, the finer the grain size, the larger grain boundary area will be, and the hindrances provided by the grain boundary are more during the expansion process of cracks [12-14].

When the surface temperature of the slab is cooled to below the transformation temperature of austenite to ferrite, the pro-eutectoid ferrite has sufficient time to precipitate along the austenite at a slow cooling rate, and continuously connected into pieces, thus forming film-like pro-eutectoid ferrite with a thickness of about 10 to 25 μm[15]. The film-like pro-eutectoid ferrite can cause the continuity of the matrix to be destroyed under high temperature conditions, and the strength of the ferrite is only about one quarter of the austenite strength, therefore the stress of the continuous casting billet during straightening segment is easy to concentrate on relatively soft ferrite and film-like pro-eutectoid ferrite[16]. As the stress acting on the ferrite is greater than the ultimate stress that it can withstand, tiny pores are formed in the ferrite. Under the constant action of various stresses, the tiny pores will gradually grow, leading to grain boundaries slip, and finally transverse cracks extending along the austenite grain boundary form on the surface of the slab[17].

2.3. Influence of the Microalloy elements on the Transverse Cracks

Alloying elements such as Nb, V and Ti in micro-alloyed steels are forming elements of strong carbides, nitrides, and carbonitrides[18-20]. In the continuous casting process, as the temperature of the slab decreasing, the elements such as Nb, V and Ti in the solid solution react easily with the C and N elements to form stable carbides, nitrides or carbonitrides that precipitate in a chain form on the austenite grain boundary. The bonding force between the austenite grains reduces, and the slip between the grain boundaries is hindered, so that the stress concentration of the slab is easily formed at the grain boundary during deformation of the slab, which is also the reason that the crack generates along the grain boundary.

3. Control Measures of the Transverse Cracks

A large number of researchers have studied the control methods of transverse cracks in continuous casting billet. Based on the mechanism of transverse cracking formation, by controlling the parameters of continuous casting process, the microstructure and precipitation phase of the continuous casting billet are adjusted to reduce the transverse cracks of the continuous casting billet.
3.1. Secondary Cooling Technology
The secondary cooling technology is important for reducing transverse cracks. During bending or straightening process in the third brittle zone (600-900°C), transverse cracks form easily. In contrast, bending or straightening at a temperature higher or lower than third brittle zone, the formation of the transverse cracks can be minimized. Zhu Guosen et al.[21] used the cooling method of blocking the edge nozzle or the edge of the reinforcing plate to improve the transverse crack of the slab. Sun Yanhui et al.[22] believed that the surface of the continuous casting slab unevenly cooled, which produces \( \gamma \rightarrow \alpha \rightarrow \gamma \) repeated phase transformation, accompanied by various micro-alloyed carbonitrides precipitated at the grain boundary, eventually leading to transverse cracks of continuous casting billet under the action of straightening stress. By controlling the amount of water with secondary cooling technology, the weak cooling is used to ensure the uniform transverse cooling rate of the slab and avoid the brittle temperature zone to control the surface cracks. He Dongfeng et al.[23] proposed a secondary cooling middle-scope water spray spraying technology, by which the slab surface temperature became more uniform and the third brittle zone is avoided, compared to secondary cooling wide-scope water spraying by which the surface temperature gradient was too large to separate from the third brittle zone. A large number of studies[22-26] have shown that through the secondary cooling technology, rapid cooling or slow cooling, avoiding the brittle zone of the slab, can effectively reduce the generation of transverse cracks in the continuous casting billet, which has been widely used.

3.2. Chamfering Mold
Some studies have shown that[27,28], the uneven heat transfer in the corner of the slab, exacerbates the internal thermal cracking caused by the thermal shrinkage of the slab shell in the mold. Liu Yang[29] and Wang Wenjun[30] compared the right angle and chamfer mold by two-dimensional mathematical simulation and actual production, and pointed out that the chamfer mold can increase the corner temperature of the slab by 70°C during bending and straightening, thereby reducing the thermal stress in this area. Yang Chunzheng[31] mainly studied the temperature, thermal stress and mechanical stress distribution of the billet during straightening under different chamfer lengths and angles. Much progress has been made in the study of the geometrical characteristics of the mold corners. The practice shows that the chamfering mold can reduce the corner crack of the micro-alloyed billet to 1.6%[30], but this defect cannot be eliminated.

3.3. Refining the Surface Structure of the Casting Slab
In 2003, Sumitomo Metal[32] published the SSC (surface structure control) cooling mode to eliminate the corner transverse cracks by controlling the structure and precipitation at the surface and corner. After cooling by SSC and testing, the value of reduction in area has exceeded 60% under various temperature conditions. The hot ductility of the slab has been significantly improved, and the third brittle zone has basically disappeared. The reason why the SSC cooling can improve the hot ductility of the steel is as follows. On the one hand, the size and distribution of the precipitation can be improved by SSC. The precipitations uniformly distribute in the grain boundaries and the grains, and the size of the precipitations are larger. On the other hand, the microstructure of the cast slab can be improved. The intergranular ferrite almost disappears, thereby cracks and expansion along the grain boundary can be avoided, and the corner transverse cracks are fundamentally eliminated.

3.4. Double Phase Transformation Process
The refinement of the original austenite grains in the second cooling stage is another way to solve the transverse cracks. For the hypoeutectoid steel, the double phase transformation method controlled by thermal cycles (ie, transformation of austenite to ferrite can be realized by rapid cooling, and ferrite transforms into austenite by reheating ferrite) can achieve austenite grain refinement. The researches of Lee et al.[33] show that after the samples are heated to 1300°C and rapidly cooled to 600°C and then back to 1100°C to make the sample cyclic transformation, austenite grain size decreases from 88
μm to 33 μm. Du Chenwei et al.[34] calculated the temperature field and cooling rate especially for surface center and corner along the casting direction based on the two-dimensional heat transfer and solidification model of slab continuous casting, and studied the influence of temperature distribution and cooling rate distribution on the surface transverse cracks. The results show that, before straightening segment the temperatures of the surface and corner are always in the range of 700-900°C, resulting in there is enough time for Ni (C, N) and AlN precipitating. In addition, as the temperature reduces to 800°C, the film-like pro-eutectoid ferrite becomes the mainly reason of the deterioration of the hot ductility at the cooling rate of 0.1-0.5°C/s. However, Li Yunfeng[35] believed that the existing continuous casting machines are difficult to achieve the double phase transformation process, and the control process is cumbersome.

4. Conclusions
The formation mechanism and control methods of the surface transverse cracks of the continuous casting billet have reviewed based on many studies of researchers. The transverse cracks of continuous casting billet is mainly caused by microstructure and precipitation phase. The design of secondary cooling technology and chamfering model structure is widely used, which is relatively the most effective and lowest cost. However, it cannot fundamentally eliminate the surface transverse cracks. Therefore, the mechanism and control methods of the generation of transverse cracks requires further study.

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