Solidifying shell waviness during continuous casting of AHSS slabs

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Solidifying shell waviness during continuous casting of AHSS slabs

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Abstract. Transverse cracking of continuously cast products has been encountered at almost every caster operation. Enormous efforts have been carried out in the past aiming at identifying the cause and reducing the problem, especially on steel grades with peritectic chemistries. So far, however, there is still no cost-effective solution with good trade-off for internal quality and productivity. In this study, a new cracking formation mechanism is proposed based on observations of equally spaced crack pattern and the undulation (shell thinning pattern) observed on the inside and/or outside (surface depression) of the breakout shell with similar spacing. This wavy solidification shell forms at initial solidification stage and induces the local shell thinning and reheating which in turn causes the local "Blown grains" inside the solidification shell. As observed on slab surfaces, these blown grains are closely related to transverse cracking problem.

1. Introduction

Enormous efforts have been made to understand the cause of transverse surface cracking in continuously cast products[1]. For steel grades with peritectic chemistries, the problem is normally worse than other grade groups at a typical conventional caster. The basic guidance for resolving the transverse cracking problem is to avoid the hot ductility trough caused by the combination of weak ferrite film and large amount of tiny precipitates formed on austenite grain boundaries (AGB) during cooling to around bending and/or unbending temperature of cast product surface[2]. Slab surface cooling strategies and steel chemistry designs can be applied to avoid and/or to elevate the ductility trough. The secondary guidance is to reduce the depth of oscillation marks which behave like notch for crack initiation. Many studies have shown that transverse cracks initiate at the base of oscillation marks[3]. The third guidance relates to the reducing stress on slab surface in the casting machine. Mold lubrication and caster machine alignment become important[4]. With these guidelines in hands, casting operations around the world are able to reduce the occurrence of the transverse cracking in cast products.

Recently, a new group of steel grades called Advanced High Strength Steels (AHSS) are developed and heavily commercialized due to demands for weight reduction in cars and machineries[5]. Because of special chemistry design (2-3%Mn, 2-3%Si and 1 to 2%Al - unfortunately most of them are peritectic in nature during solidification) and heavy alloying to achieve certain mechanical properties, transverse cracking issue has re-appeared at casters making AHSS grades. Although these cracks in AHSS slabs have similar characteristics to the cracks in traditional HSLA and peritectic steel grades, there are unique features associated with the cracks in AHSS grades. This paper descripts the similarity and uniqueness of the transverse cracks in AHSS slabs and tries to propose a new formation mechanism of transverse cracking based on observations of these cracks.

2. Equal spacing of transverse cracking

One of the unique features of transverse cracking in AHSS at one of the ArcelorMittal USA curved mold conventional slab casters is the equal spacing between these cracks. Due to the difficulties of viewing these cracks on as-cast slabs with width of 1.3 m and thickness of 0.24 m, the slab top surface has to be lightly scarfed by hand scarfing, grinding or machine milling to reveal them. One example of a hand scarfed slab surface with multiple transverse cracks is shown on the left in Fig.1 after sand blasting treatment in the area of slab quarter width. The scarfing can normally remove a layer of steel in about 2-3 mm thickness from the as-cast surface, which means these cracks are more than 3 mm deep. The interesting observation here is the roughly equal space at about 32 mm between those cracks. When this slab was made, the casting speed was at 1050 mm/min. This gives the timing interval between cracks at 1.8 s. It should be pointed that the mold oscillation frequency was 120/min, i.e., the timing between cracks is roughly 4 times of the mold oscillation cycle.

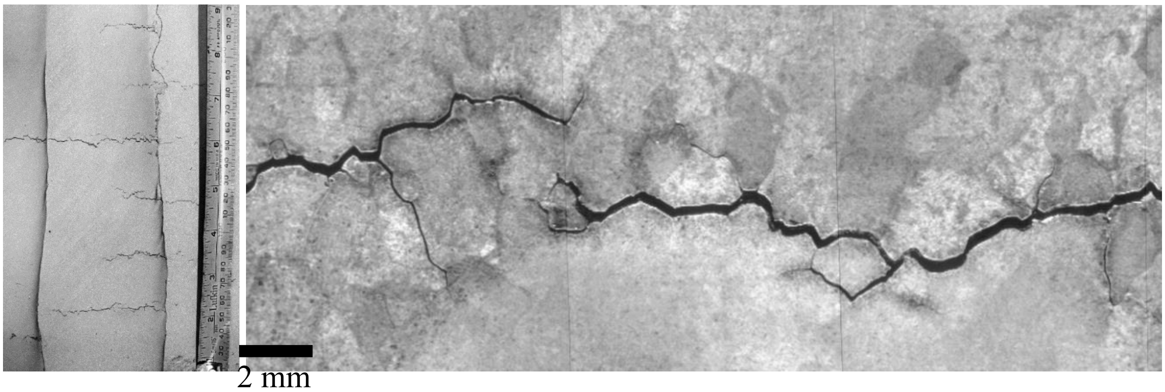

Fig.1 Equally spaced transverse crack exposed after lightly hand scarfed (left) and micro analysis of the crack showing "Blown grain" structure alone ferrite film on prior AGBs (right).

The micro-structure after polishing and etching one of these cracks by removing 2 mm from scarfed surface (to avoid torch heat affected zone) is given on the right in Fig.1. There are two significant features about these cracks. The first one is that the cracks follow ferrite film formed on the prior AGB. The second is the large size of these prior austenite grains in the range from 1 to 5 mm. This is in agreement with the "Blown grain" concept[6] which was proposed to explain severe transverse cracking due to reduced cracking path resistance.

Another example on the left in Fig.2 demonstrates transverse cracks at an equal spacing of about 48 mm in average in the area 150 to 250 mm from the slab corner. These cracks were discovered after surface milling of 2 mm depth applied on an as-cast slab top surface and they disappeared after the slab was milled down to 6 mm deep. At 1100 mm/min casting speed, the time interval between two adjacent cracks is 2.6 s, which is longer than the case in Fig.1. The magnified picture of one of these cracks on the right also showed "Blown grain" characteristics.

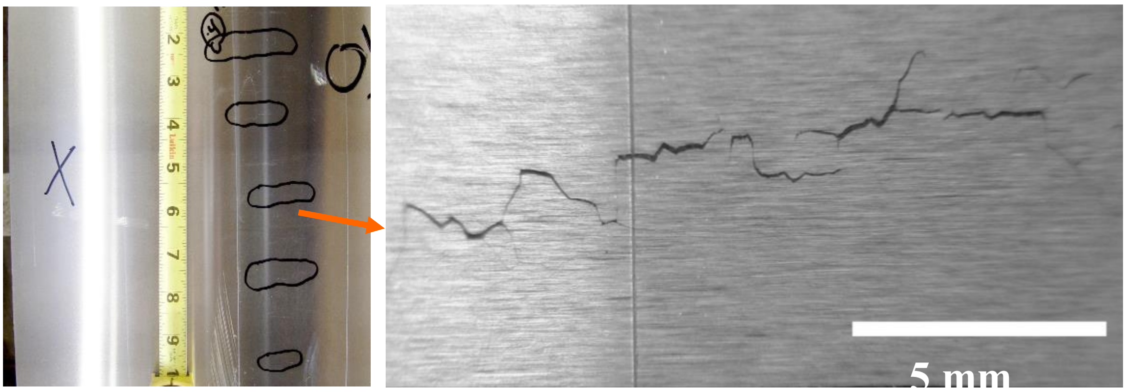

Fig.2 Transverse crack exposed after surface milled as-cast slab surface showing "Blown grain" feature.

One more example was found at the slab off-corner area as shown in Fig.3 after 2 mm surface milling and applied dye penetration to expose the cracks for better visualization. The bigger and darker the red dye shadow gets, the deeper and severer the crack is. These so-called off-corner transverse cracks were common for normal peritectic grades. The different in this AHSS slab case is that the most severe ones pointed by the black arrows demonstrate roughly equal spacing feature. The spacing is between 25 to 50 mm and lighter cracks are seen in between. Although the spacing is smaller compared with previous 2 cases, it is still significantly longer than the molds oscillation stroke.

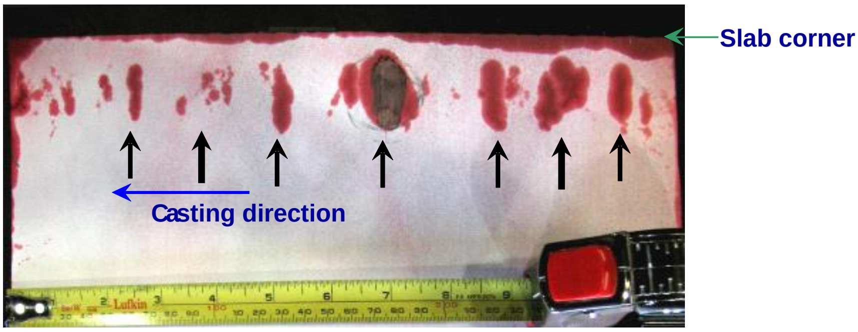

Fig.3 Transverse off-corner crack exposed after dye penetration at 2 mm from as-cast slab surface.

The detailed micro-etching of the off-corner area with cracks is given in Fig.4. This figure demonstrates the close correlation between blown grain to the transverse cracking problem. The larger prior austenite grains (blown grain) appears in a 30 mm zone which is 18 mm away from the slab corner and the severe cracks are only found in this zone. The neighboring areas on both sides of this blown grain zone have much smaller grain size and the cracks stop right at the transition lines from blown grains to fine grains.

It is common to find off-corner gutter formation in slabs close to the blown grain zone in Fig.4. The gutter is believed to form in the upper mold area when the slab corners rotate due to two-dimension heat and stress development near the corner area. Because of lack of heat removal in the gutter area, the temperature rebound will occur, which is potentially the reason for quick grain growth.

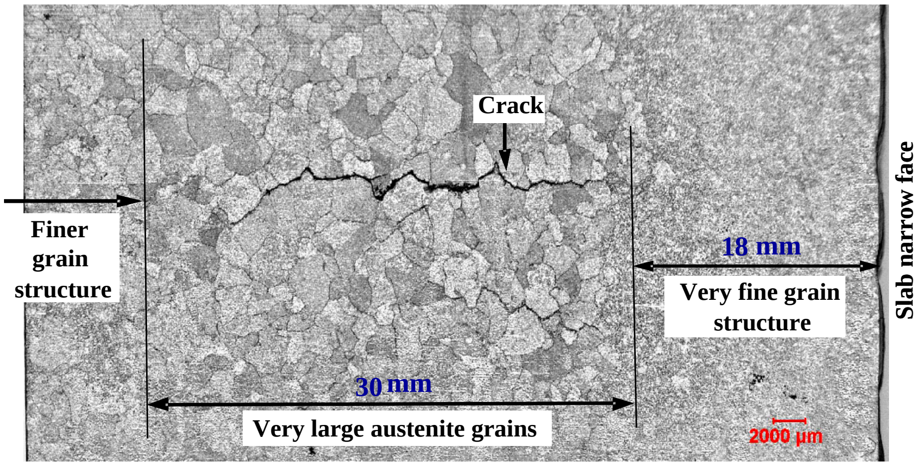

Fig.4 Transverse off-corner crack exposed after dye penetration at 2 mm from as-cast slab surface.

3. Equal spacing of transverse depressions

Transverse depression with equal spacing has been observed frequently on peritectic AHSS steel grades during continuous casting. An example is given in Fig.5 for an AHSS slab broad surface (BF) on the left from caster A and slab narrow face (NF) on the right from caster B. The spacing in-between these transverse depressions are roughly at 75 mm in average on the BF case and 70 mm on the NF case. It becomes clear that the equal spacing depression phenomenon is not caster dependent because when the similar AHSS grades are cast on different casters, the slab surfaces have very similar topographic featured depressions with very similar spacing distance when the casting speed is similar. With the use of laser line scan surface profile along the casting direction applied at 8 locations across the thickness to the narrow face of an AHSS slab from Caster C, the spacing in-between the measured big valleys (transverse depressions) can be determined at about 75 mm in average (See Fig.6).

Fig.5 Transverse depression on as-cast AHSS slab surface at an equal spacing (Left – BF and Right – NF).

The worst depression can be as deep as 4 mm while the oscillation mark depth (small peak-valley cycles along each colored line) is about 0.5 mm in average. After surface milling and dye penetration of the slab as-cast surface, severe transverse cracks were typically found almost exclusively aligned with the deepest oscillation mark inside the big valleys (transverse depressions). Micro-examination of these severe cracks shows the same blown grain features as mentioned above.

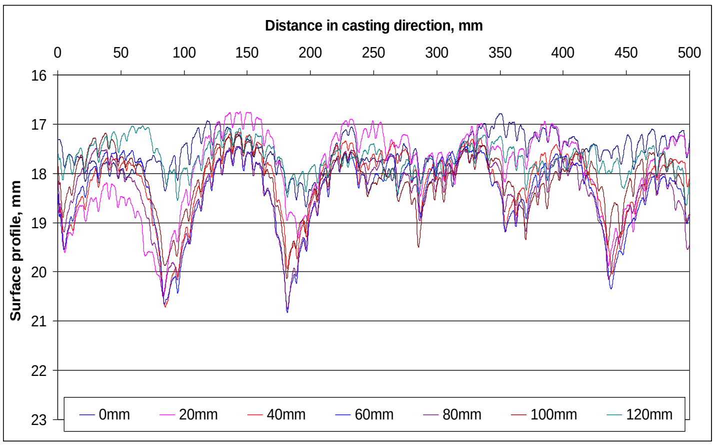

Fig.6 Transverse depression on as-cast AHSS slab narrow face at an equal spacing.

4. Equal spacing of shell thinning spots

Local thinning of the solidification shell during continuous casting has been often reported in the past. The direct result of shell thinning can be breakout of liquid steel. Strong liquid steel jet concentrating at a local area of the shell is often blamed for local thin shell in a larger area. For instance, when one of the SEN ports is clogged while most of the steel flow comes out from the other port. Inadequate mold flux feeding into the mold-shell gap at a local area or shell buckling due to inadequate taper setting can cause longitudinal local shell thinning, resulting in longitudinal cracks.
However, by carefully examine the breakout shells of an AHSS steel grade with peritectic chemistry, it was often found that a transverse shell thinning phenomenon exists at a roughly equal spacing along casting direction of the shell.

An example is shown in Fig.7 with 3D laser scan to obtain the breakout shell thickness profile. From this color map, it becomes obvious that the shell thinning in transverse direction (green horizontal lines in yellow area and yellow horizontal lines in red area) is well developed through the entire length of the shell inside the mold and the distance in-between the thinning lines is about the same, ~ 100 mm. Visual examination of the shell outside surface reveals transverse depressions very similar to the BF case in Fig.5 while the shell inside surface also shows smoother valleys mirroring the outside depressions. This can be seen on the cross-section image of the shell on the right in Fig.7.

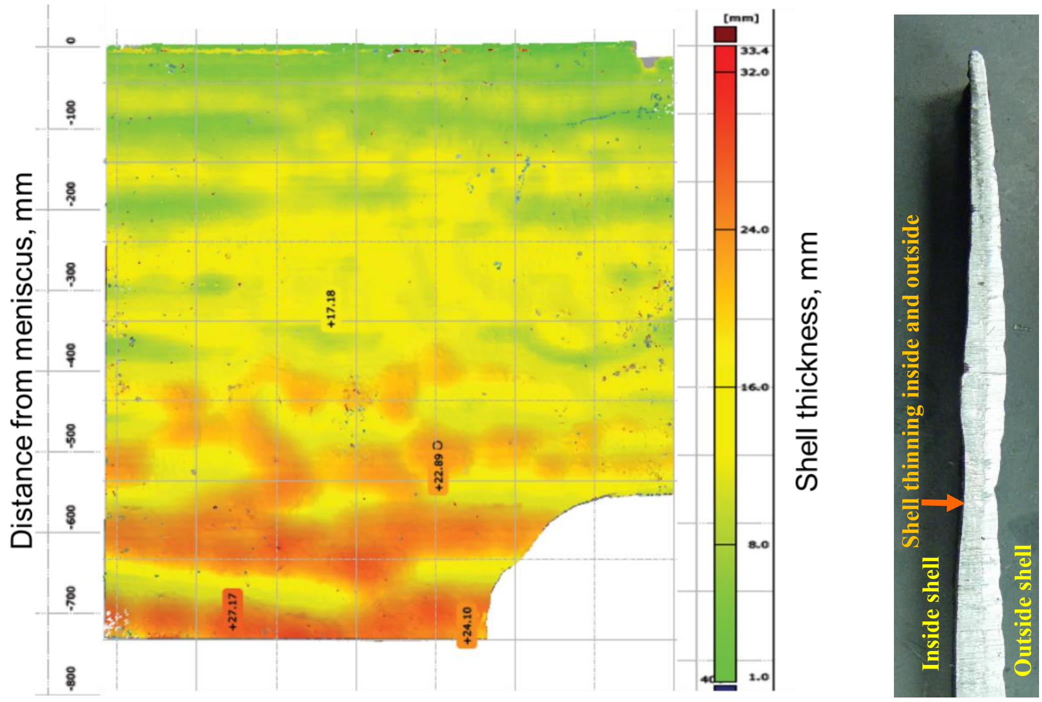

Fig.7 Shell thinning phenomenon on a breakout AHSS slab.

Actual measurements on shell thickness along the shell length direction were done on another breakout shell of an AHSS grade. The deviation of the measured data from the calculated theoretical shell thickness values at solidification coefficient of 28 is shown in Fig.8 for example. The severity of the shell thinning increases as the shell travels deeper in the mold and the maximum shell thinning can be as high as 12 mm from the expected value of a normal solidifying shell at 700 mm depth.

The important information in Fig.8 is that the shell thinning spots are at a roughly equal distance. The average spacing is about 63.5 mm. Under the casting condition when the breakout occurred, the time interval between the thinning spots is calculated at 4 seconds.

5. New concept for transverse crack formation in AHSS slab surface

Based on the above observations on the phenomena of transverse surface cracking at equal spacing, transverse depressions at equal spacing and the transverse shell thinning at equal spacing, all three are closely related for AHSS grades especially with peritectic chemistry from conventional slab casting process. In summary, the observed spacing distance between these defects is from 30 to 100 mm depending on steel grades and the casting time interval between these defects is in the range of 2.5 to 5 seconds depending on casting speed. After examining all other possibilities in casting process, none can be found that relates to a cycling pattern at a frequency of 0.2 to 0.4 Hz. It should be mentioned that the spacing distance or time interval only differs slightly at different casters as long as the casting conditions are similar. For conventional caster, the mold oscillation frequency is typically around 2 Hz and the caster roller pitch and roller periphery translate to roughly 0.06 Hz. The observed shell thinning cycling frequency of 0.2 to 0.4 Hz lies in between the two intrinsic mechanical cycling frequency of the casting machine. Therefore, this mid-frequency cycling phenomenon in 0.2 to 0.4 Hz is caster independent whereas reflects the nature of the initial solidification of the AHSS chemistry.

It is most likely that the solidification of steel gets into a rhythm to allow synchronized solidification shrinkage to occur and the cycling volume change of the liquid steel then results in a cyclic mold level disturbance. Hence, this mid-frequency mold level disturbance causes a transverse depression cycling pattern in the shell at initial solidification moment. At the depressed area, the shell temperature rebounds due to low local heat extraction from the mold, causing the shell to remelt partially from inside. This creates a wavy pattern in the shell at a roughly equal spacing.

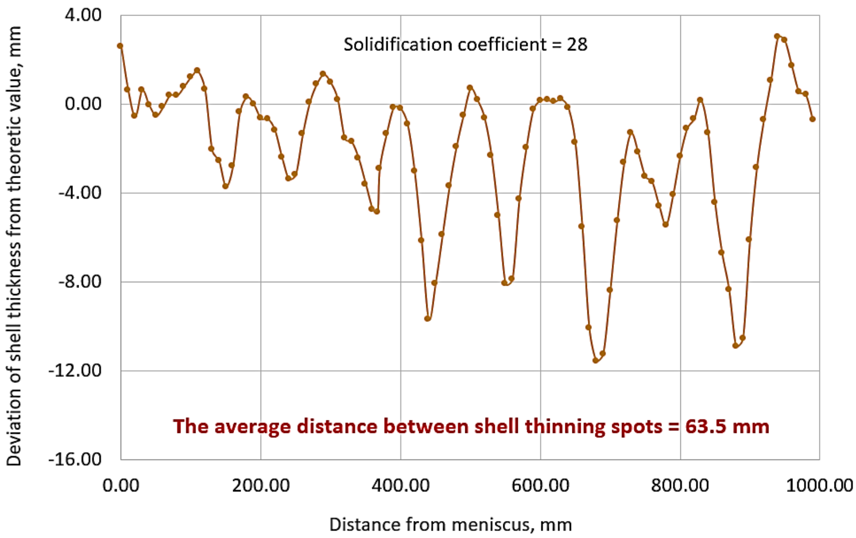

Fig.8 Shell thickness deviation from theoretical calculation along shell length.

For lean alloyed AHSS grades with lower high temperature strength, the shell at the local depressed area with thinner thickness and higher temperature can be pushed out against mold by static pressure at lower part of the mold. As a result, although the wave pattern exists at the inside of the shell, the as-cast slab surface depression on the outside of the shell can be barely observed. For rich alloyed AHSS grades which has much higher strength at high temperatures, the local thin shell cannot be easily bended out, and hence the surface depressions stay on the as-cast slab surface. In both cases, the local shell thinning effect exists which becomes much hotter than surrounding areas. This will cause local delta ferrite and/or austenite grains to grow much larger, so called "blown grains" (larger delta ferrite grains will induce larger austenite grains). This blown grains in turn will cause transverse cracks at bending and unbending process during casting.

According to this new concept, the reason for the mid frequency disturbance in the casting process needs to be fully understood. This will extend our knowledge on transverse cracking formation and develop countermeasures accordingly.

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