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Solidification mechanisms occurring in horizontal continuous casting. part 5: Mechanisms of solidification

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ABSTRACT

After having described, in the previous parts of this work, the external particularities of the organic or metallic pieces solidified in the 'cold' and 'hot' simulation devices, and the microstructural ones in the obtained SG and white cast iron pieces, as well as the real-time development of first skin and its kinetics, this final part will give a microscopic description of the mechanisms which allow the development of the dynamic skin. This description, extrapolated from what is known for vertical continuous casting with presence of a meniscus, will allow explaining all the particular features observed on the organic and metallic pieces solidified in the two simulation apparatus, as well as of course the ones appearing on surface of the steel half products industrially fabricated in horizontal continuous casting.

KEYWORDS

Continuous casting;
Cast iron;
First skin;
Solidification mechanisms.

INTRODUCTION

In the four previous parts of this work, the preliminary results obtained in terms of direct observation allowed a 'cold' simulation apparatus and surface aspects of both the organic pieces solidified in the above-mentioned apparatus and the cast iron tubes solidified in the 'hot' simulation apparatus, evidencing a double growth of the first skin: a dynamic one from the extracted piece solidified at the preceding cycle, and a static one directly on the denuded cooled wall or mould. The examination of the cross-section samples of cast iron tube's part led to additional post-solidification information at the microstructure scale: special orientation of some phases or compounds notably, in relation with the observation location in the dynamic skin or in the static skin. Furthermore, kinetic data, averaged or more detailed were obtained by exploiting the spaces between circumferential marks and by using a grooved mould especially machined, showing for example that the longitudinal growth rate of the dynamic skin may be limited in case of extraction speeds high enough. All these data were capitalized with the objective of understanding the microscopic phenomena which allow the formation of periodic marks even when there is no free meniscus.

This In this final part, all these observations will lead to extrapolate the mechanisms known from several decades in the case of vertical continuous casting[1-8] to propose models completing the first proposed descriptions[9-12].

EXPERIMENTAL

The results obtained for, one the one hand with the 'cold' apparatus, and on the other hand with the 'hot' apparatus, were compiled together: qualitative observations, real-time for transparent organic compounds[13] or post-experience for cast iron tubes[14], microstructure evolution along the static and dynamic skin in the cross-section prepared from the solidified cast iron samples[15] and kinetic data about the dynamic skin development from the extremities of solidified pieces[16]. All these data will be explained after having presented the microscopic models.

RESULTS AND DISCUSSION

Rapid recall of the mechanism of natural wrinckles' formation in vertical continuous casting

In vertical continuous casting a free meniscus exists at {semi-solidified molten steel, mould + gas, upper molten slag}-three point close to the mould, since the molten steel did not wet the mould from which it is in addition partly separated by molten slag (Figure 1). At each extraction cycle the partly solidified meniscus – called "horn" – bents to the mould and when contact a new meniscus forms. Because of the contact solidification accelerates again, leading to a new horn. At the same time a wrinckle is formed. This scenario is repeated periodically,

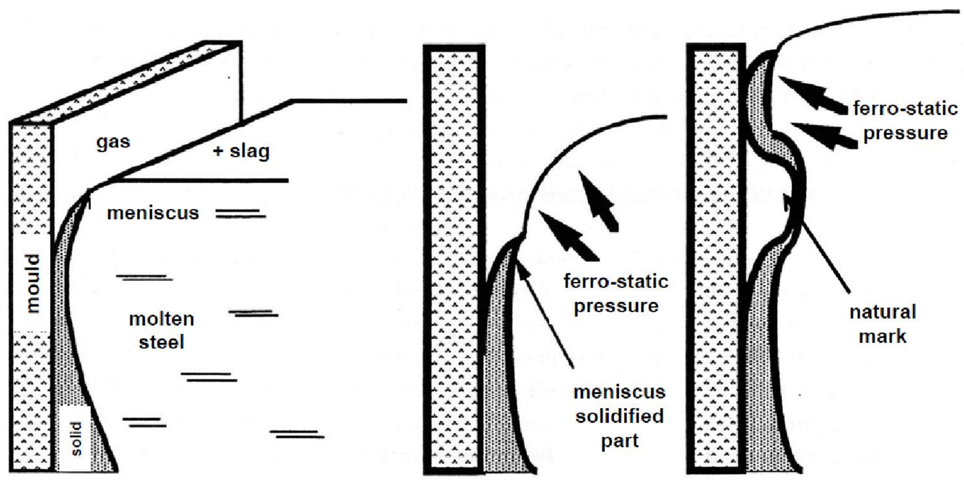

Figure 1 : Mechanism of the natural marks' formation in vertical continuous casting (with partly solidification of the free meniscus)

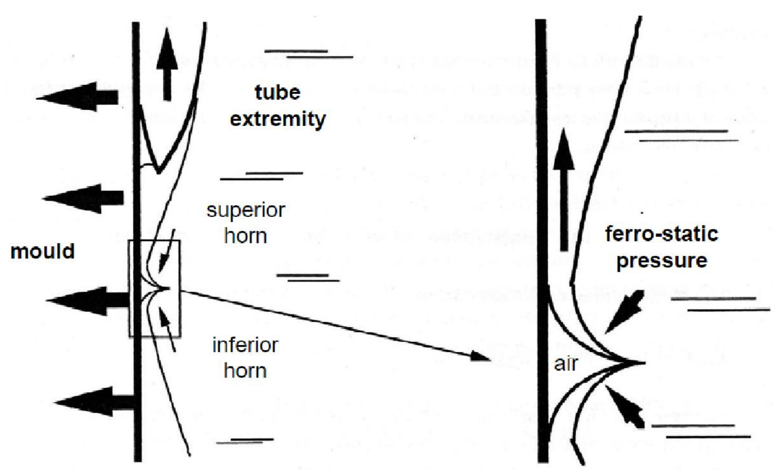

Figure 2 : Mechanism proposed for the development of the dynamic skin and for the static skin too

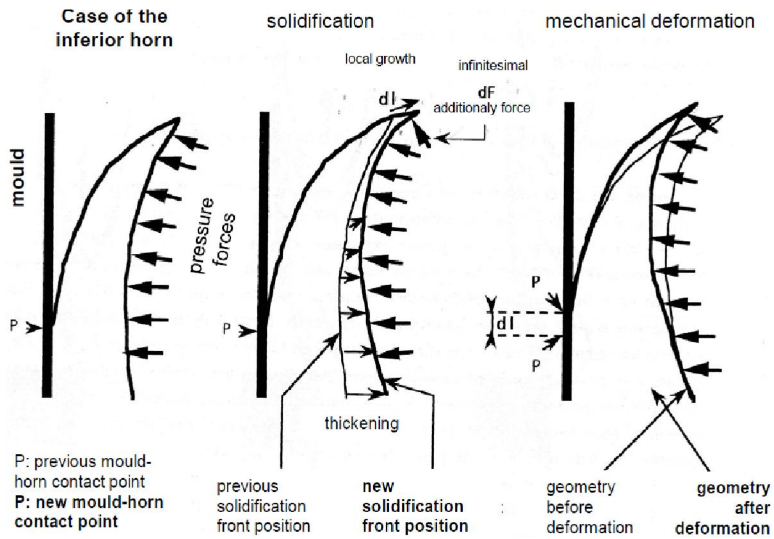

Figure 3 : Decomposition of the different phenomena – solidification and deformation – for clearer explaining mechanism, here in the case of the static skin

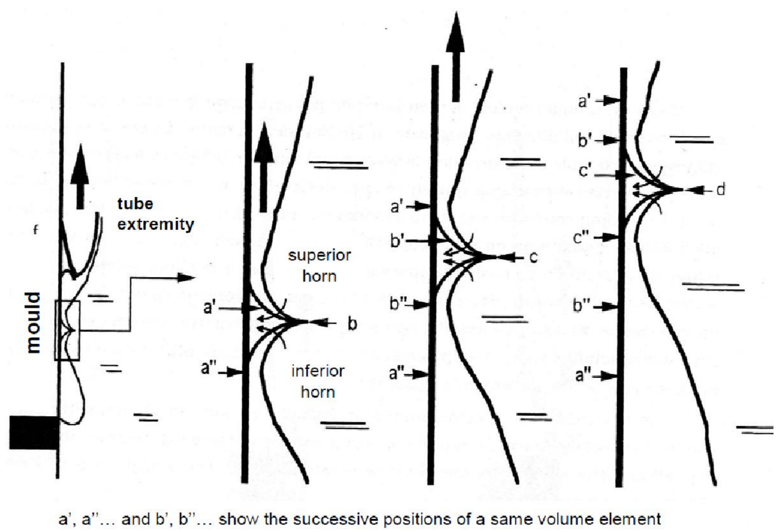

Figure 4 : Progress of the development of the dynamic and static skins by continuous bending of the two horns

with as results successive wrinckles more or less regularly spaced.

Proposed mechanism of solidification of the dynamic and static skins in absence of free meniscus – case of high extraction speeds ('hot' simulation apparatus with normal extraction speed)

In the case studied here, horizontal continuous casting for example, one can speculate that the extremities of the two parts of the first skin are also composed of horns: a superior horn at the extremity of the dynamic skin and an inferior horn at the static skin' one. The longitudinal developments of the dynamic skin and of the static skin are supposed resulting from a continuous bending of the superior horn for the dynamic skin and, in some cases, also of the inferior skin for the static one (Figure 2).

This continuous bending results from coupled solidification growth and horn's deformation, both continuous and kinetically equilibrated, phenomena presented decomposed in Figure 3 while the resulting progress of development of the two skins is schematically illustrated in Figure 4. For higher extraction speeds horns are faster continuously bent and their extremities are thus closer to the cooling mould, this allowing a faster solidification rate at their extremtities allowing a new steady state growth (Figure 5).

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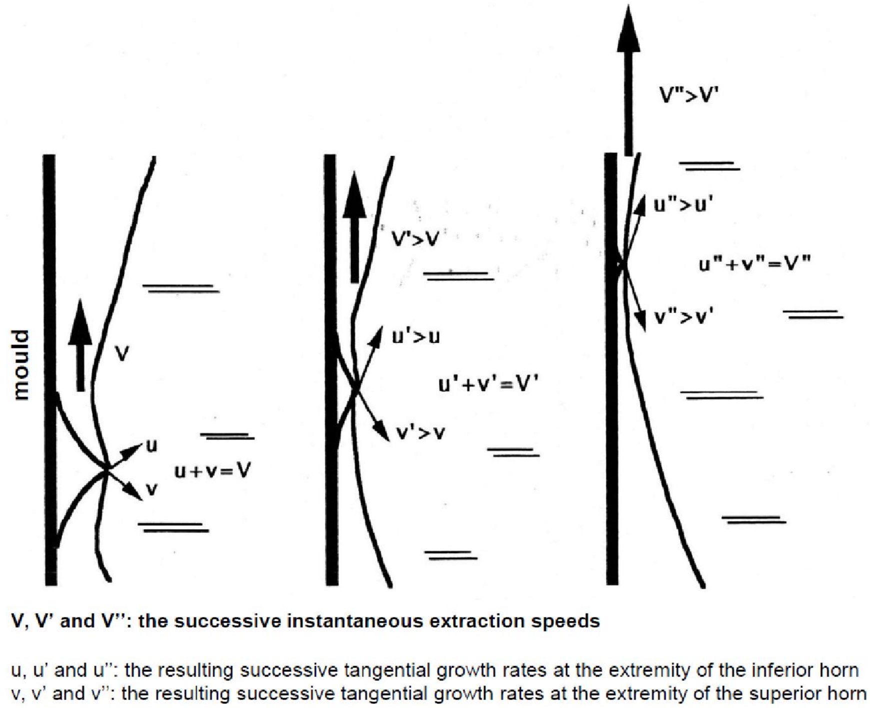

Figure 5 : Higher extraction speed leading to accelerated bending and solidification rate at the horns' extremities

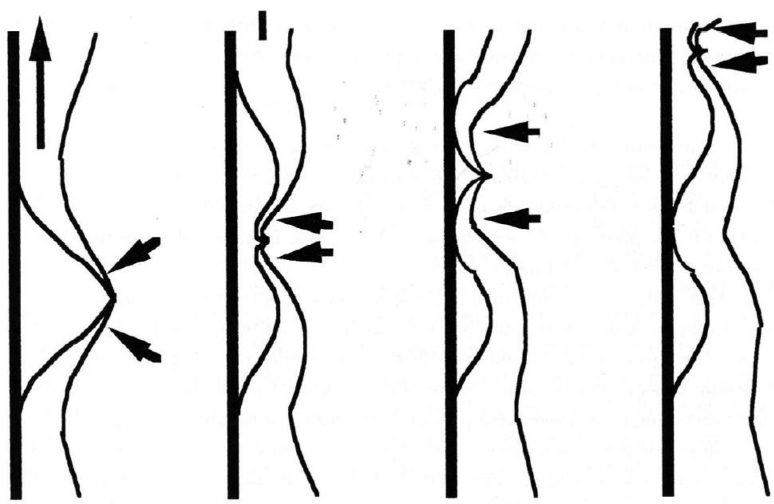

Figure 6 : Slow extractions inducing thicker and more resistant horns which bend only in their extremities with as result the formation of wrinckles on the external sides of the dynamic skin and of the static skin

Proposed mechanism of solidification of the dynamic and static skins in absence of free meniscus – case of high extraction speeds ('hot' simulation apparatus with low extraction speed, 'cold' apparatus, and horizontal continuous casting of steel)

When the extraction rate is low more time is available for solidification at each time. Thus, the horns are then longer, thicker and their solidified part colder. They are consequently more resistant to deformation and only their finest parts bend. This is true both for the static skin and the dynamic skin. The repeated bending followed by accelerated solidification leads to the wrinckles on the external sides of the dynamic skin and of the static skin (Figure 6). This is here the mechanisms explaining the formation of the natural marks in vertical continuous casting which govern here the development of two opposite skins, the external sides of which present series of periodic wrinckles. For higher extraction speeds but remaining low enough to still centre (and the centre zones are much far from the mould this considerably limiting the solidification rate!).

If the origin of the wrinckles[14] on both sides of the junction marks is now clear, the geometry of this junction marks is also easy to explain: the shapes of the two horns when the tubes stopped (then low speed and consequently transition to final discontinuous bending): depending on the bending state of these ones several geometries may be encountered when observed on cross-sections[15]. Concerning the joint's marks as observed in cross section, the first of their two main geometries simply results from the first discontinuous bending of the superior horn at start-

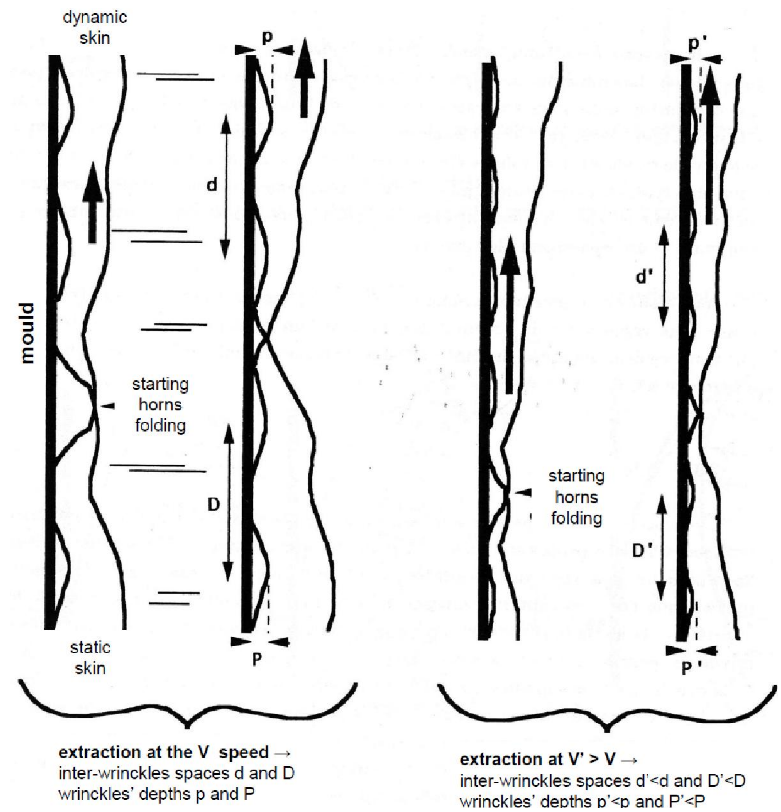

Figure 7 : Decreases in wrinckles' depth and in inter-wrinckles' spaces resulting from higher extraction speed

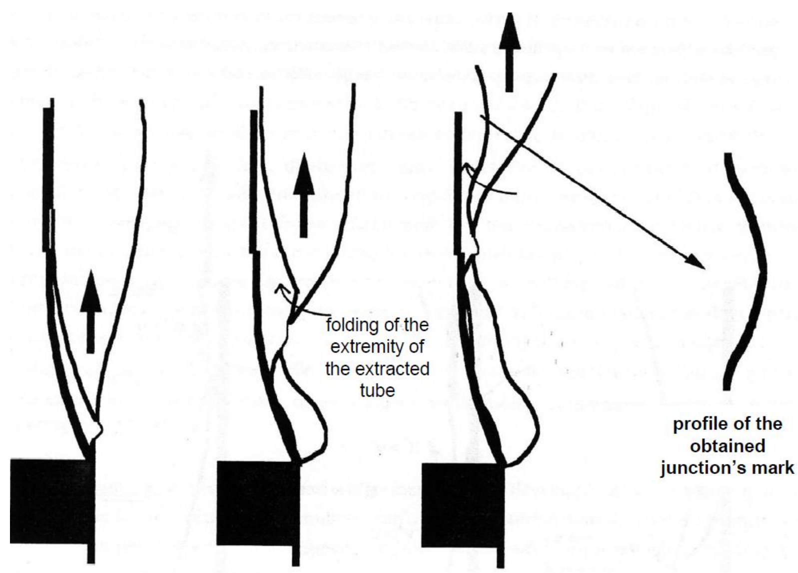

Figure 8 : Origin of one of the two main cross-sectional geometries of the joint's mark

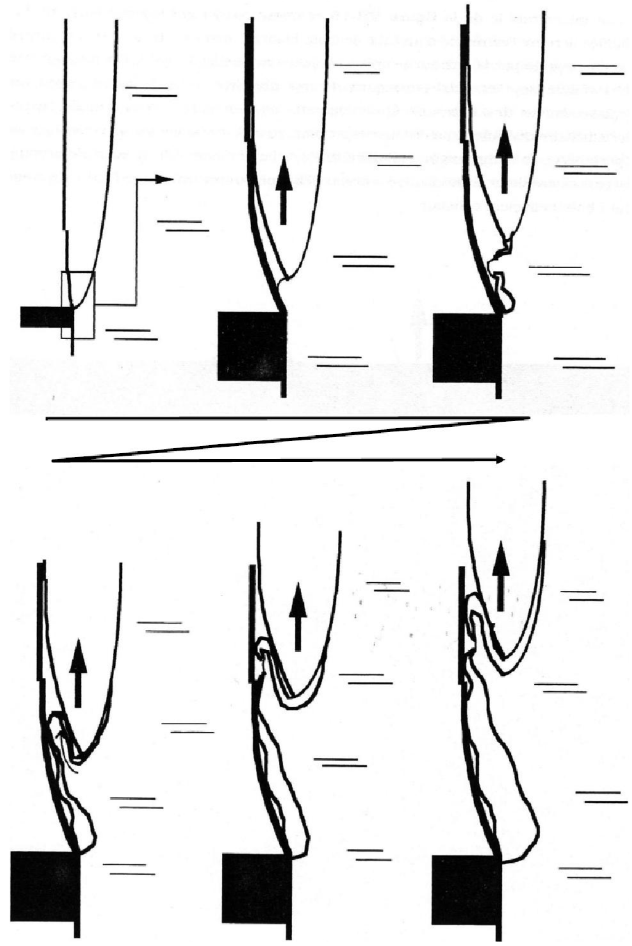

Figure 9 : Origin of the other main cross-sectional geometries of the joint's mark

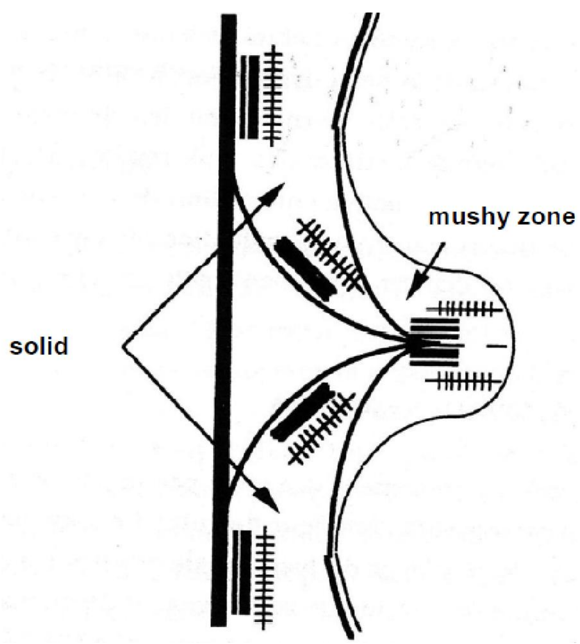

Figure 10 : Origin of the particular microstructure orientation distribution along the first skin between two consecutive joint's marks

allow the formation of wrinckles, the depth of the later and the average spaces which separate them both decrease (Figure 7) since horns have less time to thicken and then they are less resistant against deformation under the metallostatic pressure. Indeed, in such conditions they are less long and they bend more frequently.

General commentaries

Thus, what took place during the extraction of the tube at low speed is the same phenomenon as in vertical continuous casting. Here this one acts two times, as there is a mirror in which the image of the dynamic skin is the image of the static skin. Thanks to the 'hot' apparatus which allowed higher extraction speeds one saw that this discontinuous progress of the two skins may becoming continuous, what should be probably also the case for vertical continuous casting of steel if higher speeds were possible (in the industrial case time is necessary to solidify the half-products from their surface to their

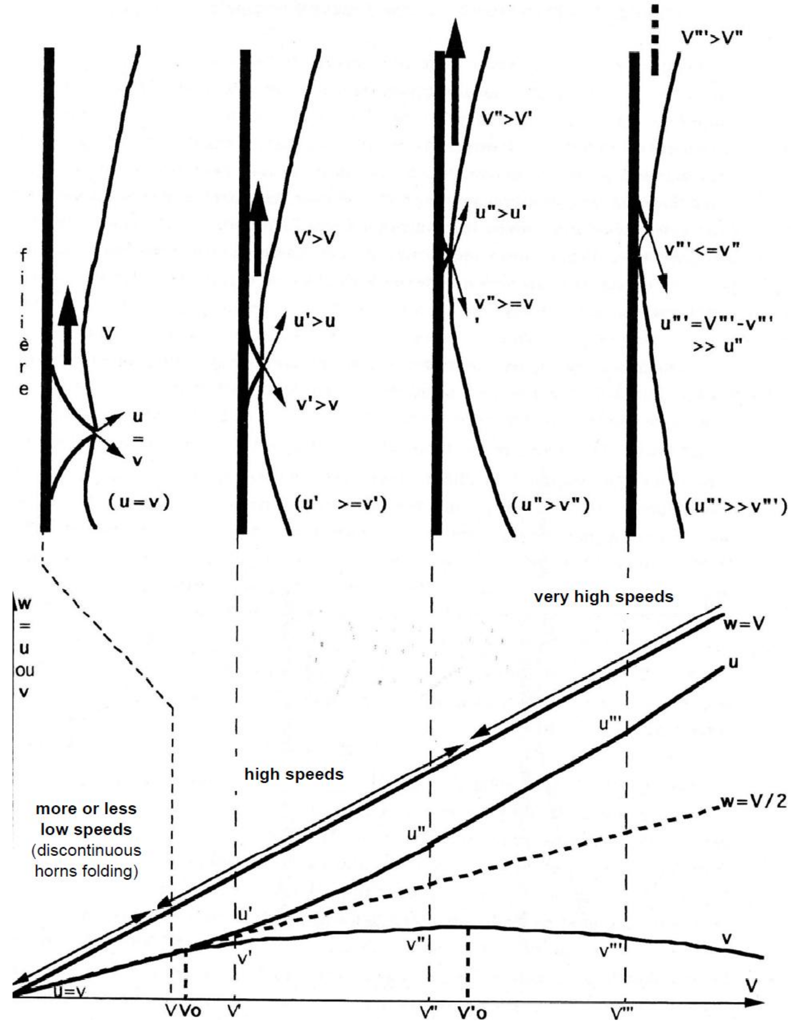

Figure 11 : Why the dynamic solidification cannot compete with the static one at high extraction speeds

ing when the tube movement was still slow (Figure 8).

The second one results from the initial infiltration of liquid behind the extremity of the tube which started moving after the stop part of the cycle (Figure 9): case of the flake-cast iron mould which progressively deforms inwards because of microstructural evolution of the base of the mould[14].

When ledeburite or dendrites are still visible later on Nital-etched cross-sections[15], their downward orientation in the dynamic skin and their upward orientation in the static orientation result from the microstructure disorientation accompanying the bending of the superior horn and the bending of the inferior horn (Figure 10). In the latter case, when the extraction was particularly fast, the inferior horn did not existed and the microstructure was then perpendicular to the external side.

The absence of inferior horn at high extraction speed revealed by the perpendicular microstructure orientation in the static skin demonstrates that the static solidification is not dependent on the presence of a inferior horn. Therefore the rate of development of the static skin is not kinetically limited: molten cast iron arriving directly on the mould wall as soon as the corresponding mould part is discovered by the extremity of the extracted tube freezes immediately and joint the already solidified part of the skin. This is not the case of the dynamic skin the development of which depends on the existence on the superior horn. Thus, at high speed, its development rate is governed by the bending rate of the superior horn as well as by the solidification rate at the extremity of this one. Furthermore this is slower at high speed because of the faster relative movement of the tube extremity by regards to the mould, which induces a decrease in thermal transfer coefficient and then of heat evacuation. In such conditions, if the thermal and mechanical conditions of the bending of the superior and the inferior horns are similar this leading to equal development rates for the dynamic and static skins (half the extraction rate), higher extraction speeds penalize the dynamic solidification only, with consequently a higher development rate for the static skin (Figure 11), as seen in the latter part[16].

CONCLUSIONS

Thus, mechanisms were here proposed for the formation of the different parks appeared on organic and metallic solidified pieces issued from the two apparatus used in this work, as well as for the formation of the ones formed on the half-products industrially fabricated by horizontal continuous casting. Thanks to this understanding it appear possible to suppress the marks along the horizontally continuously cast half-products by suppressing the dynamic horn. Unfortunately the first solution which can be deduced from the present results, casting them at much higher speed, is not applicable since minimum time is necessary to allow the half-products solidifying from their surface to their centre. By considering their section sizes, the centre zones are very far from the mould, this considerably limiting the solidification rate.

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