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# Solidification mechanisms occurring in horizontal continuous casting. part 4: kinetics of dynamic skin solidification IN the 'hot' apparatus

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## ABSTRACT

A 'hot' apparatus was designed and exploited to simulate the solidification mechanisms of horizontal continuous casting or other similar processes without meniscus. Some of the tubes obtained presented particular longitudinal prominences on external surface. The understanding of their appearance led to imagine a particular mould with a series of more or less long linear cavities, for specifying the development kinetic of the dynamic skin. Solidifying tubes in such experimental mould allowed deducing the growth speed of the dynamic skin downwardly along the mould wall. Some data were also obtained for the inwardly transversal thickening of the tubes, by exploiting the microstructural size of ledeburite, in the case of the ones fabricated in white cast iron. © 2015 Trade Science Inc. - INDIA

## KEYWORDS

Continuous casting;
Model apparatus;
Cast iron;
Grooved mould;
Dynamic skin;
Solidification kinetics.

## INTRODUCTION

In horizontal continuous casting and for other similar processes of casting without free meniscus, the formation of the circumferential marks cannot be explained as in vertical continuous casting for which, effectively, the solidification of a meniscus[1-3] and its periodic deformation are at the origin of the marks[4-8]. Among the two simulation apparatus which were especially designed to be exploited for completing the first mechanisms descriptions[9-12], the first one[13] allowed observing the phenomena and their kinetic while the 'hot' one[14] appeared in a first time more devoted to post-mortem characterization of metallic products much closer to the real processes. In fact, thanks to the interpretation of some new particularities observed on the external surface of some tubes, a craftiness was discovered to access to the kinetic of the kinetic of development of the first skin, notably its dynamic part. In this fourth part, the external longitudinal prominences which appeared on these particular tubes will be first described, and their potential use for valuing the kinetic of dynamic skin development. In a second time, the experiences carried out with the 'hot' apparatus using a special mould designed to reproduce the prominences in conditions to be more suitable for such kinetic study, will be described and their results exploited to bring kinetic data about the dynamic skin solidification.

## EXPERIMENTAL

Since the use of the 'cold' transparent apparatus allowed directly observing the development of the first skin in to parts it was possible to take successive photographs at selected instants during a whole extraction cycle. On each of these photographs the lengths of the dynamic skin h(t) and of the static skin b(t) were measured (example in Figure 1, left).

This was of course not possible for the 'hot' apparatus and, initially, it appeared not possible to access to the real-time kinetic of development of the two parts of the skin, notably of the dynamic one which is the most interesting. First results were then obtained in terms of average speed, by measuring the average distance between the upper joint's mark and the junction's mark, h, and the one between this same junction's mark, b, and the bottom joint's mark (Figure 1, right). By dividing them by the extraction duration average speeds can be thus obtained.

However, concerning the 'hot' apparatus, it appeared possible to exploit kinetically the additional particularities which were sometimes observed on the external surface of some tubes. When a graphite mould was used instead a flake graphite cast iron one, the tubes fabricated after several extraction cycles began presenting longitudinal prominences of different types (Figure 2). These ones were of three possible categories, as schematized in Figure 3:

- continuous prominences
- discontinuous prominences starting above a joint's mark in the static skin, crossing the upper

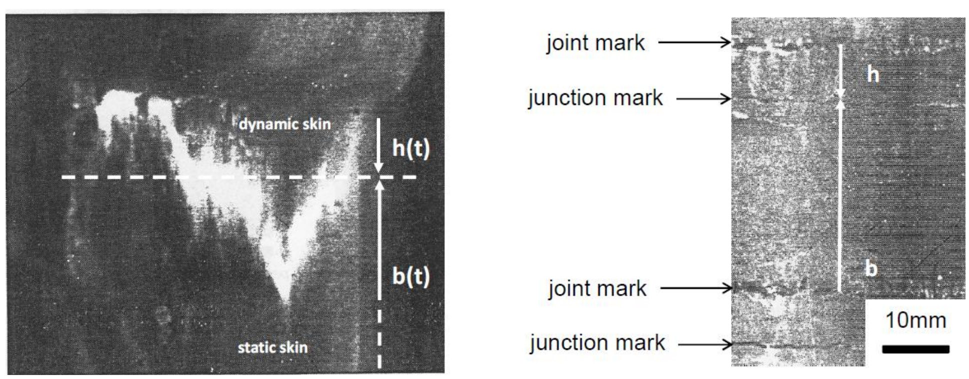


**Figure 1 : Real-time measurement of the skins' developments in the 'cold' apparatus (left) and post-experience determination of the only final development of the skins on tubes obtained with the 'hot' one**

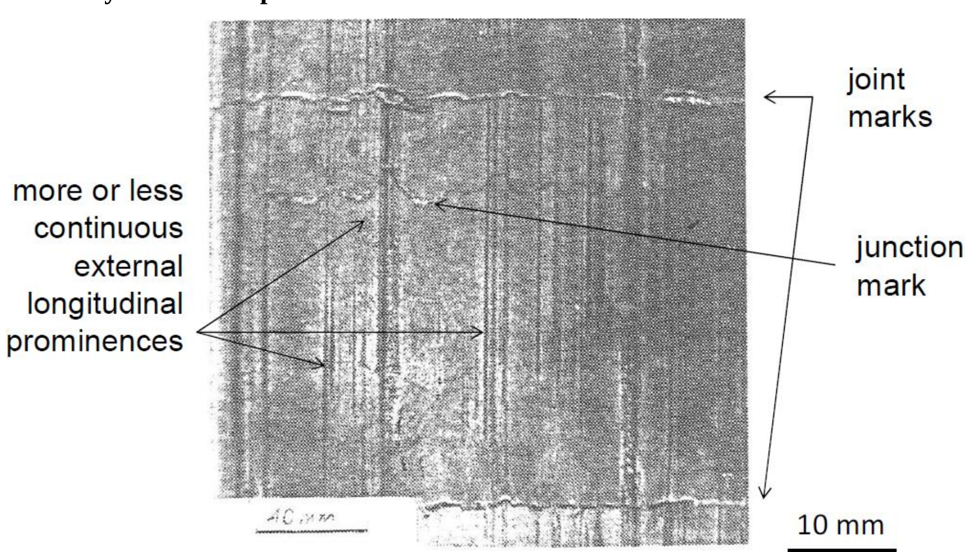


**Figure 2 : Real-time measurement of the skins' developments in the 'cold' apparatus (left) and post-experience determination of the only final development of the skins on tubes obtained with the 'hot' one**

junction's mark and going up to the upper joint's mark (1)

- discontinuous prominences starting higher in the static skin, crossing the upper junction's mark and finishing before the upper joint's mark (2).

By knowing now the double mode of development of the first solidified skin, static and dynamic, the appearance of these prominences was explained. Indeed, the solidification of the bottom part of the static skin may lead here and there to peaks solidified in some joint-mould interstices. During the following extraction cycle these peaks grooved the soft graphite mould (less hard than the metallic mould) either from the joint itself or from a higher location. Thereafter, during the following cycles, the two parts of the skin cast iron locally solidified in these location grooves, leading to the observed prominences, as described in Figure 4.

These prominences were of a good help to get information about the kinetic of longitudinal development of the dynamic skin. Indeed, the length of the dynamic skin had the value $h(t_0)$ when the tube extraction distance was $z = b + h(t_0)$ along the mould. This, by knowing the moving law z versus time, b +

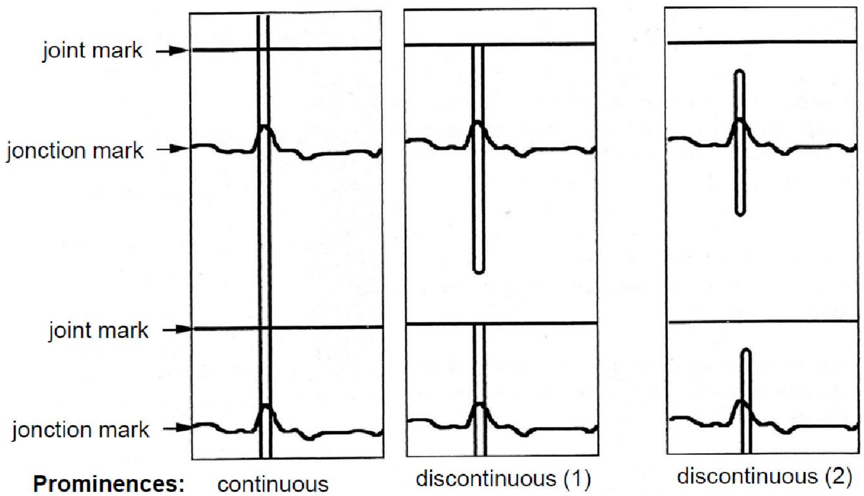


**Figure 3 : The three types of prominences visible on tubes fabricated by using a graphite mould**

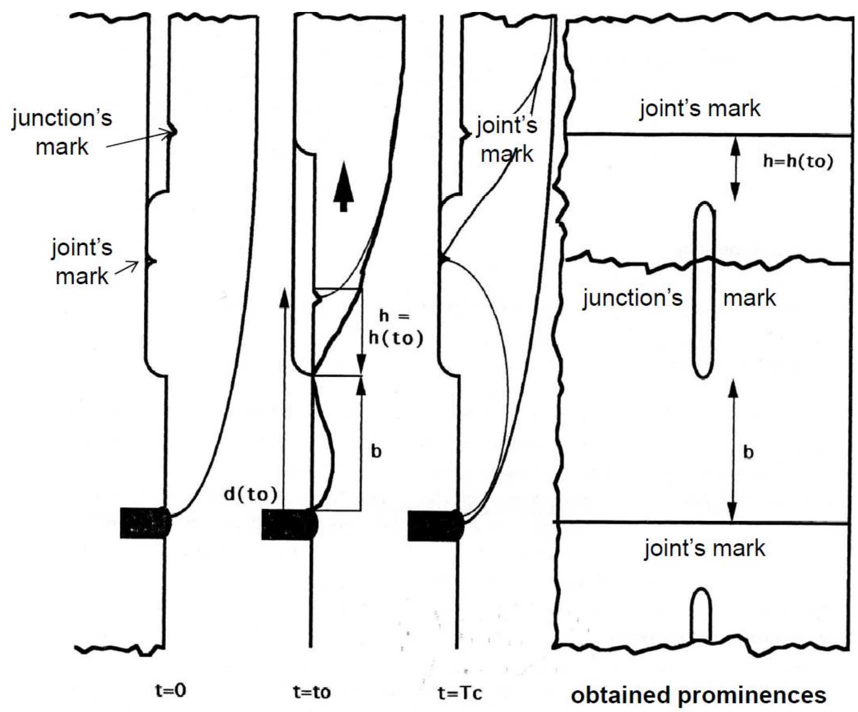


**Figure 4 : How a prominence of the (2) type was obtained**

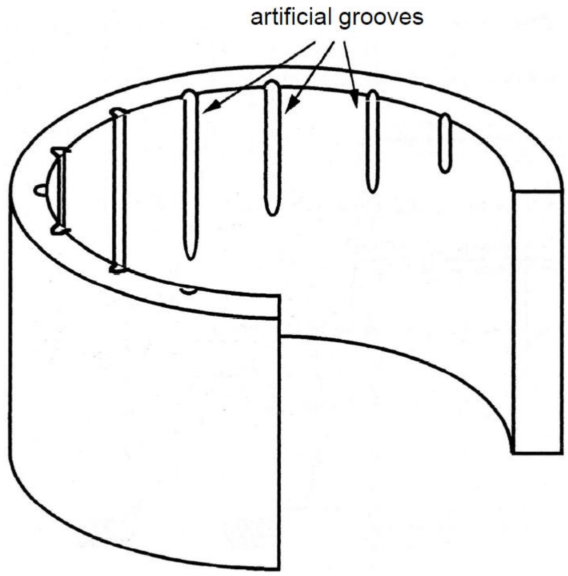


**Figure 5 : Scheme (partial view) of the especially grooved mould machined for kinetic study of the dynamic skin development**

$h(t_0) = z(t_0)$ allowed determining the value of the instant t0. Finally, associating h to the value of $t_0$ led to a point of the kinetic law of longitudinal development of the dynamic skin. Thus, exploiting all the discontinuous prominences allowed obtaining a series of h(t) values.

For a given tube the "natural" discontinuous prominences were both generally numerous enough and regularly scattered in term of length to allow a good reconstruction of the kinetic of development of the dynamic skin. This is the reason why a special mould was machined, with pre-existing grooves the lengths of which were regularly distributed (scheme in Figure 5). This mould was used in several sets of conditions.

## RESULTS AND DISCUSSION

### Average kinetics of development of the dynamic skin

The successive photographs taken during the experiences carried out with the 'cold' apparatus did not lead to successive lengths of dynamic skin in number high enough to allow real-time reconstruction of the development of the dynamic skin made of solidified organic compounds. In addition the length was not accurate enough (very irregular extremity of the dynamic skin). The obtained values were therefore considered only for average kinetic measurement. The results that they allowed led to the kinetic results illustrated by the examples given in Figure 6. In this graph one can see the different average speeds of downwardly longitudinal development of the dynamic skin along the cooled metallic wall, measured for different speed of vertical upwardly movements of the steel skate covered by the organic compound previously solidified on it. This clearly shows that the faster the skate movement, the faster the development of the dynamic skin. Furthermore it seems that the average development speed of the dynamic skin equal to half the skate speed, that is to say the dynamic skin and the static one develops with the same speed. However, this seems becoming not so true when the skate speed becomes faster: the development rate of the dynamic skin is then a little lower than half the skate speed.

The same type of determination was realized for the tubes fabricated with the 'hot' apparatus, by measuring the average distances separating the junction's

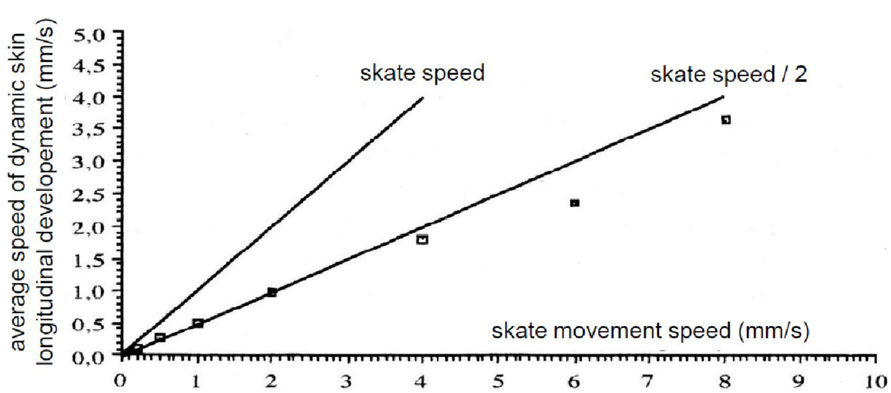


**Figure 6 : Kinetic of development of the dynamic skin of transparent organic compound as visually followed in the 'cold' apparatus**

marks and the joint's marks. Figure 7 presents some of the obtained average speeds of development of the dynamic skin for several extraction rates and for two types of mould. In all cases these average speeds of dynamic skin development are significantly lower than half the average extraction speed. However it is interesting to note first that it increases when the extraction speed increases, and second that the average speed of development of the dynamic skin is always higher when a graphite mould is used than when it is a flake graphite cast iron one.

### Real-time kinetic of development of the dynamic skin

In contrast with the 'cold' transparent apparatus, it was possible to kinetically specify the progress of the dynamic solidification along the mould by exploiting the obtained discontinuous prominences (example of obtained tube photographed in Figure 7). With the good distribution of groove lengths it was in all cases possible to know the instantaneous development speed of the dynamic speed all along the whole extraction cycle, with a part in the acceleration part, a part in the constant extraction speed part and a part in the deceleration part An example of kinetic reconstructed from the results issued from the exploitation of the obtained prominences is given in Figure 8. One can notably see that the development speed of the dynamic skin is maximal when the extraction speed is at its highest constant value: about: 25mm/s when the tube is extracted at 57 mm/s (as is to say almost the half). Thereafter it decelerates when the tube decelerates itself.

### Post-first skin solidification tube thickening

After the tube stopped for a given immobilisation time, solidification becomes transversal and the front progresses inwardly. This went on during the following successive extraction cycles, until the considered tube part emerged out of the molten cast iron bath (Figure 9). The successive layers of cast iron successively solidified cycle per cycle are visible with a naked eye on cross-section preliminarily etched with Nital, as schematized in Figure 10.

The average thickening is easy to value, by dividing the successive thicknesses by the cycle time. But, as for the development of the dynamic skin it is possible to get more detailed kinetic for the tube solidified without inoculation (thus solidified in white cast iron), by exploiting the metallographic results measured in the third part of this work[15]: the interlamellar spacing distribution measured in ledeburite from the external side to the internal side. Indeed this microstructural size is function of the local growth rate according to a law of the $\lambda = k.V^{-n}$ type ($\lambda$ = interlamellar spacing, V = solidification rate, k and n constants). Depending on the authors[16-21] and on the exact type of white cast iron, the k constant varies between 0.71 to 1.65, and n between 0.25 and 0.42. The exploitation showed that solidification was initially extremely fast, but thereafter decelerated to about 1mm/s.

### General commentaries

Thus, if it was possible to specify the average solidification kinetic of the tubes, longitudinally for the dynamic skin as well as transversally for the following thickening, some macroscopic particularities (natural or provoked) and microscopic ones al-

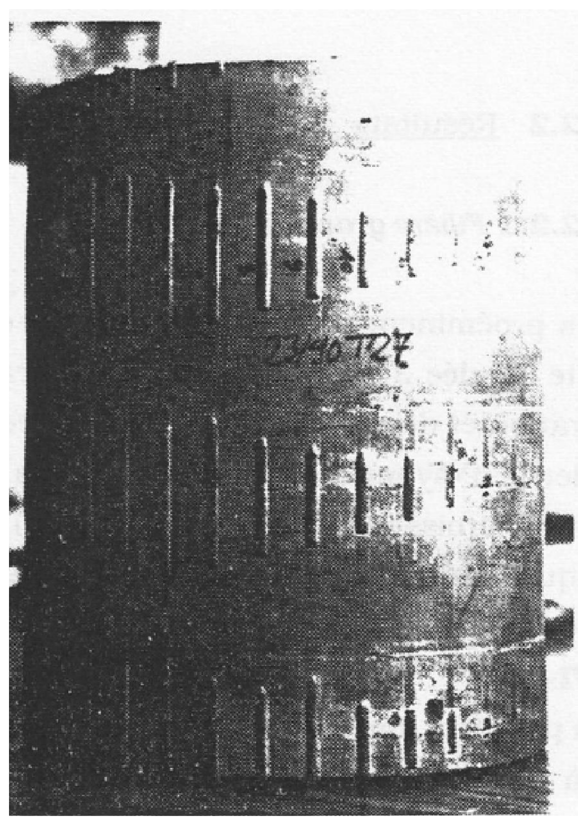

**Figure 7 : Photograph of one of the tubes obtained with the special artificially grooved mould (diameter of the tube: about 15 cm)**

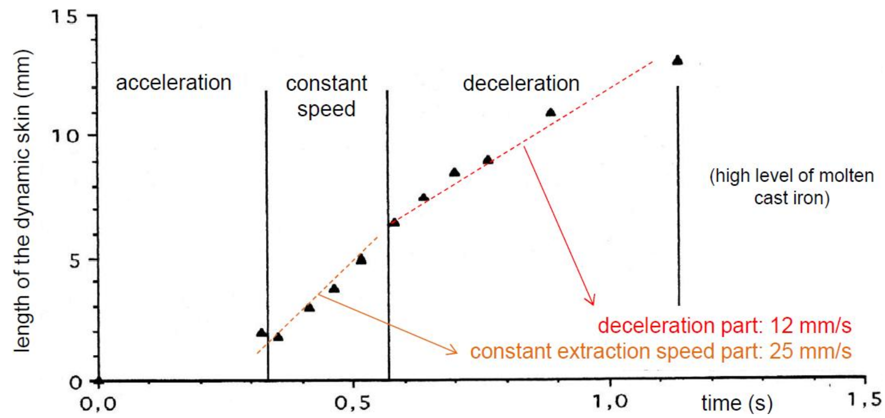


**Figure 8 : Law of the longitudinal development of the dynamic skin**

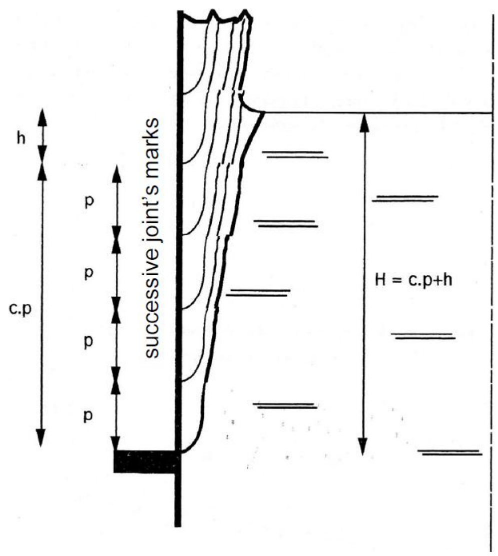


**Figure 9 : Scheme describing the thickening of the tube cycle per cycle**

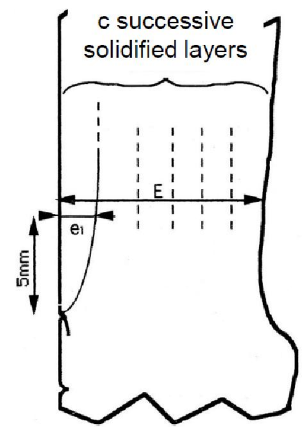


**Figure 10 : The layers successively solidified cycle per cycle, as visible after Nital etching**

lowed here to get much more detailed data in both fields. These obtained results will be of high importance for the complete description of what occurs in such solidification context.

## CONCLUSIONS

The use of the 'cold' and 'hot' apparatus, the observations which were directly possible as well as the descriptions of many of the numerous data collected on the organic compound or cast iron products obtained will be valorized together in the final part of this work[22], by the macroscopic and microscopic descriptions of the mechanisms through which the organic or metallic samples solidified in these two simulation apparatus. The knowledge obtained will be directly transposable to the different continuous castings processes for which no free meniscus is present, in first position horizontal continuous casting.

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