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Solidification mechanisms occurring in horizontal continuous casting, part 1: preliminar experiences with a 'transparent' apparatus

Patrice Berthod[1,2]*, G.Lesoult[2]

[1]University of Lorraine, Faculty of Sciences and Technologies

Institut Jean Lamour (UMR 7198), Team 206 "Surface and Interface, Chemical Reactivity of Materials"

B.P. 70239, 54506 Vandoeuvre-lès-Nancy – (France)

[2]LSG2M, Ecole des Mines de Nancy, Parc de Saurupt, 54000 Nancy – (FRANCE)

E-mail: patrice.berthod@univ-lorraine.fr

ABSTRACT

Many steel products are obtained by continuous casting. Several techniques are usually exploited, notably vertical continuous casting and horizontal continuous casting. The obtained ingots are generally affected by the appearance of periodic linear defects all around them which may induce problems for final products after lamination. The origin of these defects is known for the vertical continuous casting but this is not totally the case in horizontal casting. The purpose of this work is to look for explanations of the appearance of such external defects, by driving different types of experiences, either with "cold" apparatus or by "hot" ones. In this first part this an automated apparatus working with {low fusion point}-transparent organic alloys which will be used. The experiences made with this device will clearly show that the first skin develops in two parts, a static one by direct solidification on the denuded mould wall and a dynamic one by growing along the denuded mold from the drawn already solidified part.

KEYWORDS

Continuous casting;
Solidification mechanisms;
Model apparatus;
Transparent organic compounds.

INTRODUCTION

Besides conventional casting which consists in pouring liquid metal or alloy in a finite mould Figure 1, there exists other industrial means for obtaining products by foundry practice. In addition to directional or single-crystalline solidification which concerns superalloys for example, there are also the different plants in which continuous casting allows obtaining half-products. Continuous casting of steel may be done mainly vertically or horizontally but, in both cases, the obtained half-products present special aspects. Indeed, the surface states of the steel products obtained through continuous casting pro-

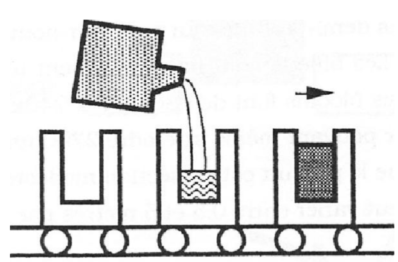

Figure 1 : Conventional (discontinuous) casting

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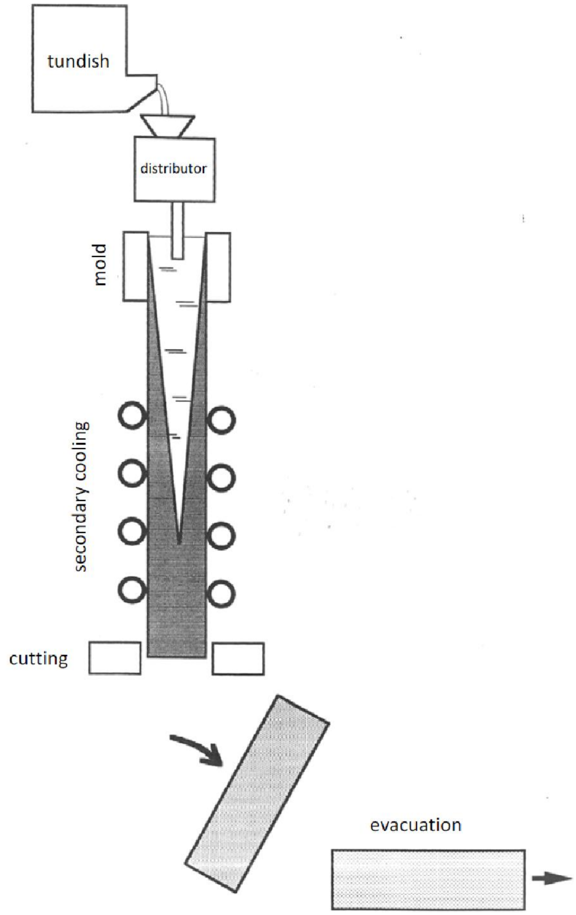

Figure 2 : Principle of the vertical continuous casting

sometimes more spaced, depending on the cooling rate and the frequency of the mould oscillation) while the second ones, which may be encountered even in conventional casting[2] Figure 1, are present every several millimeters only. The first propositions for explaining the formation of these marks in vertical continuous casting were given around 1960[3]. Along the following decades the descriptions of the involved phenomena were enriched[4-8]. The formation of the "natural wrinckles" and of the "oscillation marks" can be described as in Figure 4 (natural wrinckles) and in Figure 5 (oscillation marks).

As illustrated by Figures 4-5 the free meniscus existing in vertical continuous casting plays an important role. However such description cannot be used in horizontal continuous casting, the principle of which is given in Figure 6, since no such meniscus exists, even if similar wrinckles and marks Figure 7 may exist along the half-products issued from this second type of continuous casting process. Only macroscopic models were proposed in the latter case[9] or for the vertical continuous casting under charge[10,11] for which there is also no meniscus able to promote the formation of wrinckles or marks.

The purpose of this work, presented in several

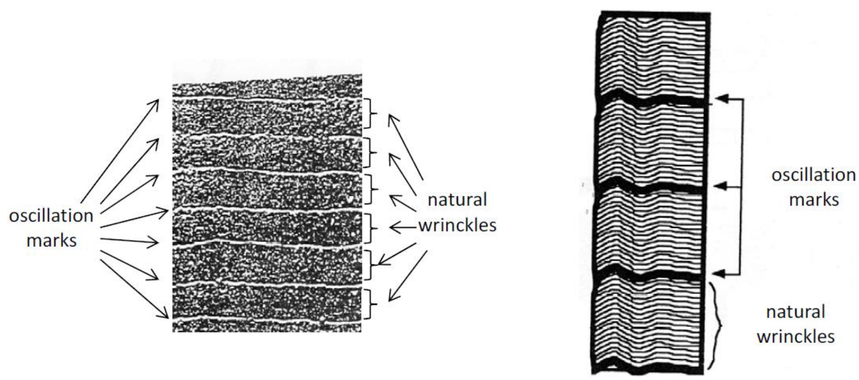

Figure 3 : The two types of marks appearing along the half-products obtained by vertical continuous casting

cesses are often characterized by the presence of hollow marks regularly spaced along the ingot. Such marks are defects which make compulsory a post-solidification surface rectification. In the case of the vertical continuous casting process Figure 2, the obtained half-products may present "natural" marks for several steels only[1]. There are the "oscillation marks", the formation of which is well-known, and the "natural wrinckles". The first ones are present typically every one centimetre (but in some cases

successive parts, is to better know the solidification and mechanical mechanisms involved in the formation of marks when no free meniscus exists, as in the case of horizontal continuous casting for example, to enrich first results earlier obtained[12]. For that, two main experimental apparatus were created for physically simulating the process, one using {low temperature melting}-substances allowing direct observation of the phenomena, and one working with molten metallic alloys at high temperature. In this first

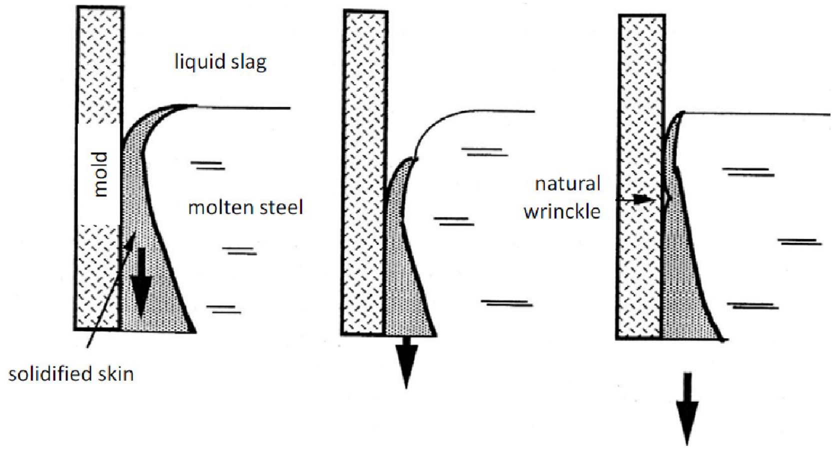

Figure 4 : Description of the phenomena leading to the "natural wrickles"

part this is the first apparatus which will be described as well as the macroscopic results to which it allowed obtaining.

EXPERIMENTAL

The solidification of metallic alloys can be easily simulated by some organic compounds, able for some of them to crystallize at moderate temperature with a macroscopic dendritic structure. This is notably the case of 99%-pure succinonitrile (melting temperature: 58°C). This first organic compound was effectively considered to simulate steel at a much more accessible temperature. A second organic substance was also used: stearic acid (melting temperature: 54°C). Both were particularly interesting here since they are opaque in the solid state but transparent in the liquid state. This allowed to clearly observe their solidification in a "transparent" apparatus.

Such a "transparent" apparatus Figure 9 and Figure 10 was designed to allow transversal observations of the solidification of organic compounds transversally in a geometrical and thermal context reproducing continuous casting process without free meniscus. This apparatus was composed of U-type square-section metallic (aluminium alloy) part divided into two parts: a J-type one continuously crossed by a constant flow water maintained at 60°C by a heating machine (thermo-cryostat Lauda RCS, temperature range [-30°C, 150°C]) and a I-type one continuously crossed by a liquid (glycol) maintained at -25°C by a cooling machine (thermo-cryostat Lauda RUK50 (temperature range [-50°C, 100°C]). Ahead and behind two transparent windows crossed by 60°C-heated water closed the apparatus in which the transparent organic liquid was poured. This one froze on the mobile steel flat piece initially covering the cooled aluminium wall. After about one minute or more, the mobile flat piece was moved upwards along the cooled surface with a speed chosen between 0.1 and 8 mm/s. During the upward translation the bottom part of the cooled surface was progressively uncovered and the liquid organic compound solidified on it. The macroscopic mechanisms of its solidification was continuously observed and photographed, not hindered by any parasite solidification on the transparent plaques thanks to the warm water internal circulation.

RESULTS AND DISCUSSION

Visualization of the phenomena

In the two cases, succinonitrile or stearic acid, it appeared that the liquid organic compounds froze not only on the progressively denuded cooled metallic wall (leading to what can be called a "static skin"), but also on the extremity of thee sliding solid along the denuded wall. This can be illustrated by the photograph presented in Figure 11, taken through the lateral windows warmed by the internal circulation of heated water. One can clearly see that the cooled fix metallic wall is progressively covered by opaque solidified organic compound which thereafter grows perpendicularly to the cold wall to be-

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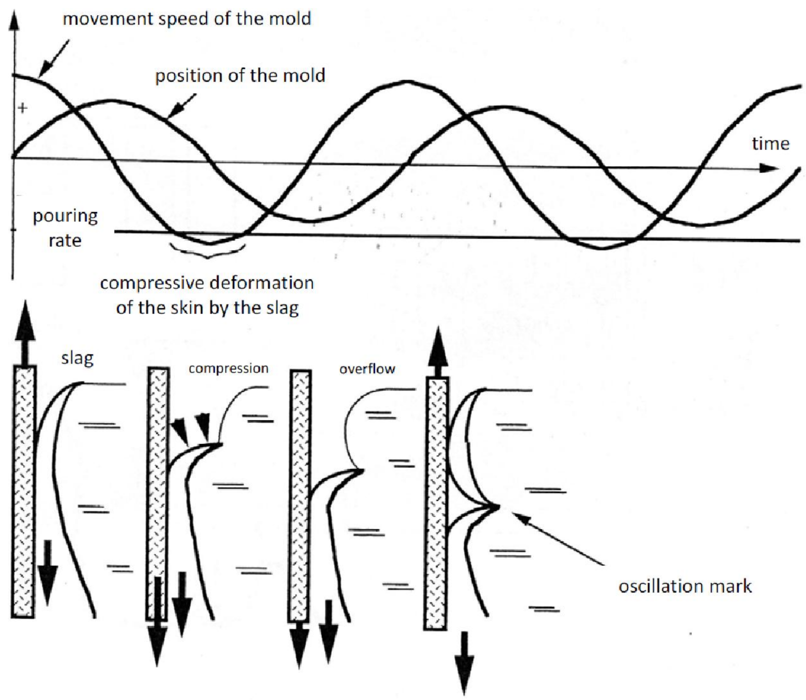

Figure 5 : Description of the phenomena leading to the "oscillation marks"

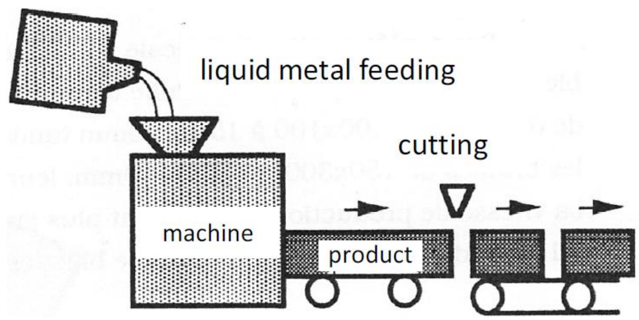

Figure 6 : Principle of the horizontal continuous casting

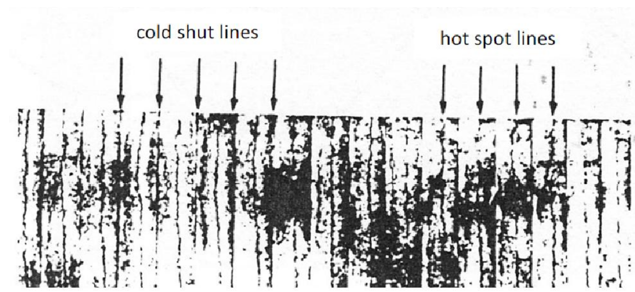

Figure 7 : The marks also present on the half-products obtained by horizontal continuous casting

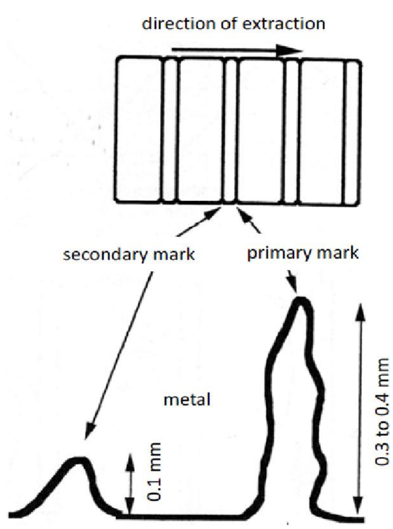

Figure 8 : Schemes describing macroscopically (top) and microscopically (bottom) the two types of marks appearing on the half-products issued from horizontal continuous casting

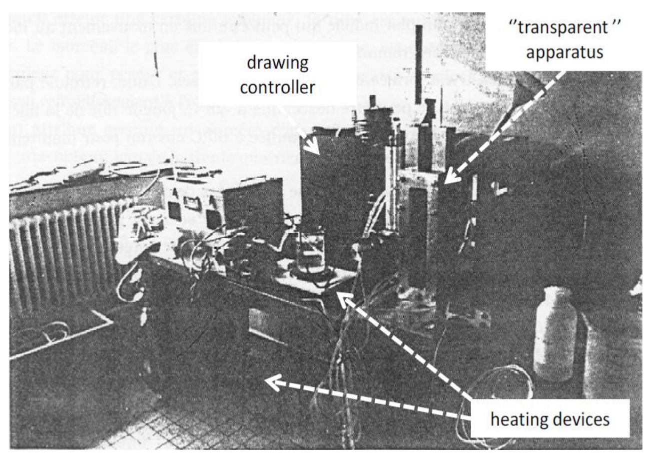

Figure 9 : General view of the environment of the "transparent" apparatus allowing the observation of the solidification of transparent organic compounds simulating the solidification of steels in a meniscus-free context

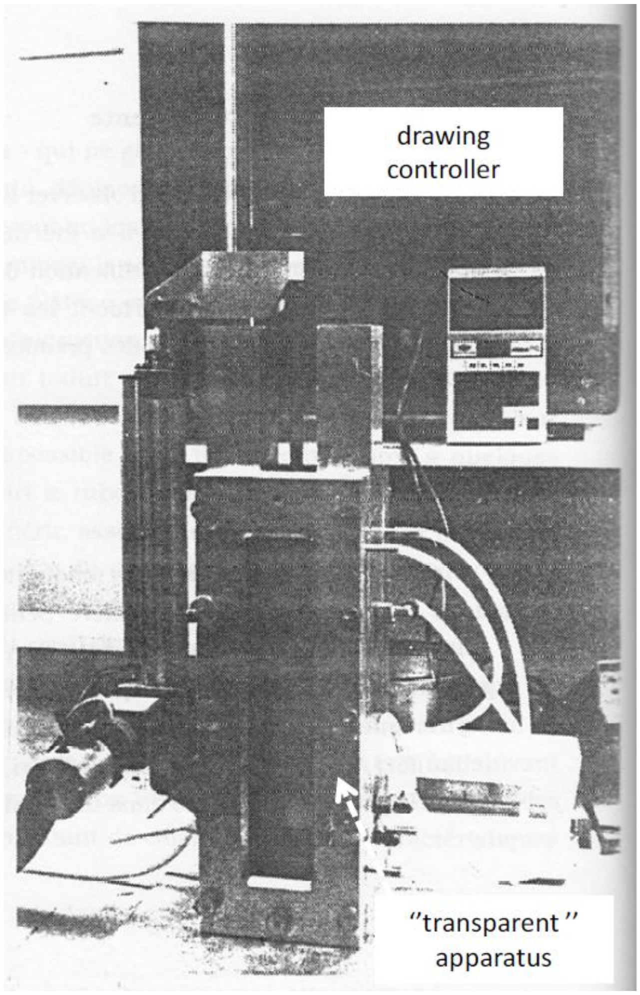

Figure 10 : Closer view of the "transparent" apparatus

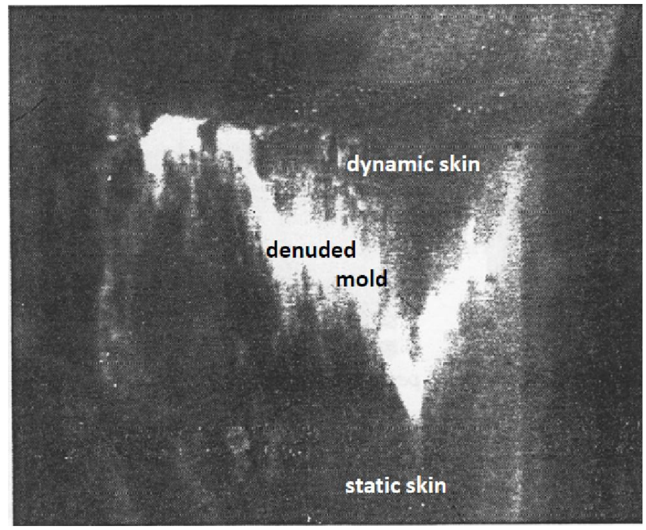

Figure 11 : Photograph of the new first skin developing in two parts after the mobile steel piece had discovered the cooled metallic wall; taken through the transparent plaques

along the same cooled metallic wall but remaining in translation movement by regards to this later one. This "dynamic skin" get more and more extended along the cooled metallic wall, being seemingly in competition with the "static skin". When the translation movement stops, the two skins become welded together and the total new skin get thicker and thicker until stabilization by fitting to the thermal equilibrium solid/liquid interface.

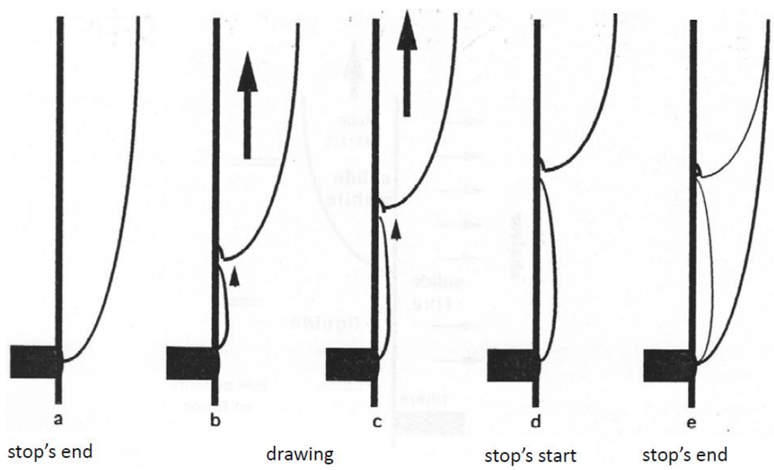

Figure 12 : First limit scenario exclusively consisting in a direct germination and growth of a static solid skin

comes thicker and thicker until a stationary state is reached, with a correspondence between the solid/liquid interface and the equilibrium isothermal T=Tsolidus surface. Simultaneously a second skin develops from the rising solid organic compound,

Post-experiment examinations

It is generally possible to start again the extraction and to continue it until totally exiting the whole new solid from the liquid organic compound. The other side of the formed solid can be then examined

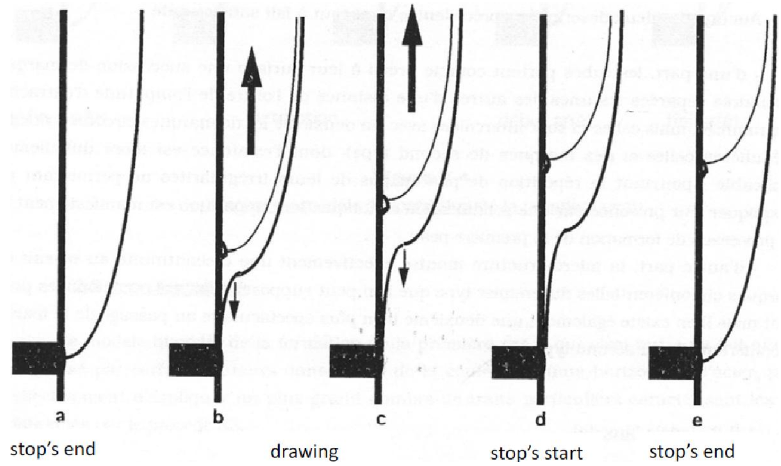

Figure 13 : Second limit scenario exclusively consisting in a extension along the denuded mould of a dynamic skin from the previous extremity of the casting

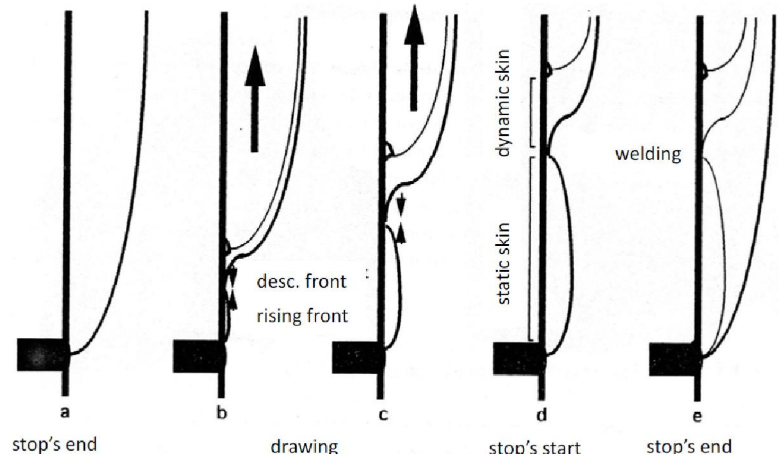

Figure 14 : The real scenario: the two previous ones acting simultaneously

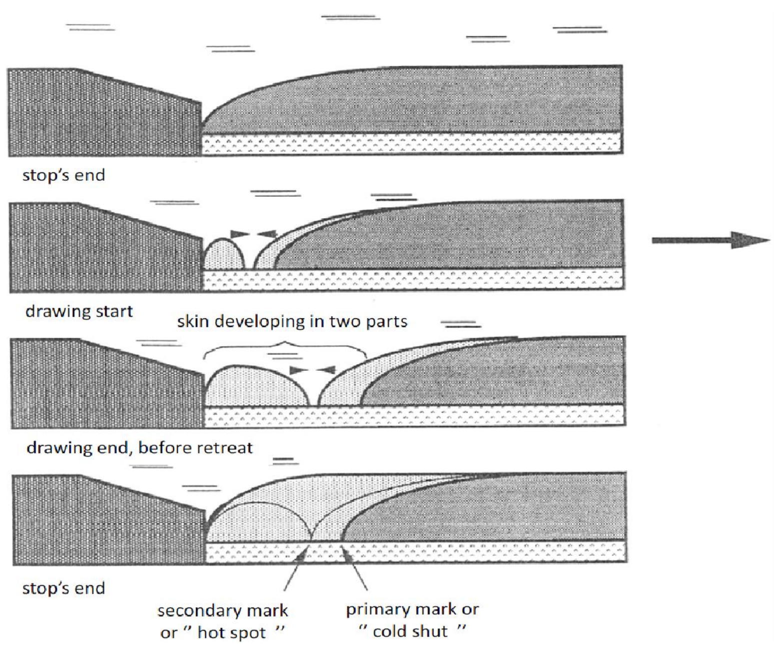

Figure 15 : The doubled mechanism of new skin formation usually evocated

and for not too fast extraction more or less straight successive linear marks can be observed, on both sides by regards the junction of the two skins. These marks look like the natural wrinckles existing on the half-products issued from continuous casting.

General commentaries

In continuous casting with solidification without meniscus two limit cases may be envisaged. Either the new skin appears directly on the progressively denuded mould Figure 12 and is welded to the previous one when the cycle arrives at the stop step, or a skin develops downwards from the mobile solid along the mould wall to almost continuously separate it from the liquid alloy Figure 13.

In fact, this is the two phenomena which occurred together, simultaneously. This double skin growth, illustrated in Figure 14, is in good accordance with the macroscopic mechanism earlier described by other authors Figure 15.

CONCLUSIONS

Thus, the design and fabrication of a "transparent" apparatus allowed, by performing experiences on model organic compounds the solidification of which was possible, to directly observe and confirm some hypotheses earlier advanced. The study of the formation of the skin and the resulting periodic marks will be kept on by using another experimental apparatus, allowing this time the solidification of real metallic alloys. Direct observations will be not possible but the examination of the obtained products will be of importance to enrich the knowledge which will allow further more precisely describe the solidification mechanisms.

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