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# Solidification mechanisms occurring in horizontal continuous casting. part 2: experiences with a 'HOt' apparatus; external aspect of the metallic products obtained

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## ABSTRACT

The metallic products obtained by continuous casting with meniscus-free first skin solidification, notably in horizontal continuous casting, are usually covered by periodically linear defects. To study and explain their formation a "hot" apparatus simulating such process was realized and exploited for the solidification of cast iron, a {low melting point}-iron alloy allowing solidification at temperatures much lower than with steels. The obtained cast iron products, empty tubes and not full ingots as in steel continuous casting, present many types of linear defects: joint marks, junction marks, and for low extraction speeds: wrinckles and vortex. In case of lack of liquid metal feeding, the tube may be emerging with the dynamic skin and the static skin not joined to one another all around the circumference. Furthermore, when the mould was made of graphite, another type of surface defects has appeared on the external tube surface: a couple of two longitudinal linear protuberances present in some case on the same generating line, starting and stopping in both the dynamic skin and on the static skin. These two new observations demonstrated a second time, after the visualization allowed by the 'transparent' apparatus in the first part of this work, the twin growth of the first skin.
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## KEYWORDS

Continuous casting;
Solidification mechanisms;
Model apparatus;
Cast iron.

## INTRODUCTION

In some cases continuous casting of metallic alloys, for obtaining half-products of steel for example, may be processed without free meniscus. The obtained ingots generally present external defects periodically present all along the pieces, and these linear defect surrounding the pieces must be removed by surface treatments to do not induce problems for the following operations. Contrarily to the "natural marks" and "oscillation marks" appearing on the external surface of the half-products issued from vertical continuous casting[1-3], the formation of which was explained since several decades[4-8], the formation of the periodic linear marks obtained even without meniscus is not totally explained[9-12]. To progress in the understanding of the origin of these surface defects, a new study was undertaken, involving the fabrication and the exploitation, one the one hand of a first experimental apparatus working with transparent organic compounds solidifying at low temperature, and on the other hand of a second experimental apparatus working at high temperature with metallic liquids. In the first part of, this work the 'cold' apparatus allowed observing directly the macroscopic phenomena[13] while, in this second part, the 'hot' apparatus will permit to be much closer to the real metallurgical mechanisms. Here there are the macroscopic characteristics of the intact half-products which will be presented while, in a next article, the microscopic observations in cross-sections will be detailed.

## EXPERIMENTAL

The material simulating steel with a better phenomena-reproducibility than organic compounds at the microstructural scale was chosen as a cast iron. This choice was governed by the wish to remain close to the steel material (iron-based) and by the necessity to work at a not too high temperature. With a melting temperature range both not too large and centred on about 1200°C, the eutectic Fe(bal.)-4C-1.8Si (weight percent) cast iron was adequate for that. Furthermore it was wished to solidify in the stable austenite-graphite diagram to avoid any brittleness due to possible high fractions of ledeburite (cementite-austenite eutectic compound). For similar purpose of sufficient mechanical properties it was wished to obtain spheroidal graphite instead lamellar graphite. Thus, with solidified pieces composed of sufficiently ductile and tensile resistant cast iron, it was possible to mechanical stresses high enough for extracting step-by-step the piece after its solidification.

The apparatus which was built and used for this study is schematized in Figure 1. Pig iron directly coming from a blast furnace, with consequently a chemical composition exclusively made of essentially iron, carbon and silicon (with extremely low contents in sulphur and other elements poisoning for the spheroidal growth of graphite), was melted in a 500kg induction furnace. The liquid cast iron was then treated by immersion of ferro-silico-magnesium powder (spheroidisation treatment or magnesium treatment) to lower the residual sulphur and oxygen contents down to extremely low values compatible with the future crystallization of graphite as spheroids. The treated liquid cast iron was conveyed to a rotating furnace in which it was poured. Thereafter, the liquid cast iron was continuously poured in the entry of a siphon, being simultaneously treated. Indeed, an inoculant, also based on iron, silicon and magnesium mixed powders and containing microscopic nuclei efficient to help graphite to nucleate, was injected continuously in the cast iron flow. At the other side of the siphon the cast-iron solidified as a tube part on the internal wall of a graphite or metallic mould cooled on its external side by water circulation.

Every about one second an extracting device pull the solidified over a distance, preliminarily chosen between 25mm and 45mm, before stopping a little moment before pulling again. The average {pulling, stop} cycle varies between 1 and 2 seconds, this depending on the step distance. The average production rate is about 1.5 meter per minute. Farer, the step-by-step continuously formed tube is periodically cut.

The obtained parts of tube were, in a first time, simply observed. Their surface states are going to be described and their possible variation commented by regards with different process parameters.

## RESULTS AND DISCUSSION

### Profile of the obtained tubes; circumferential marks

Several tubes were elaborated, with two types of mould (flake graphite cast iron covered by a thin layer of chromium, or graphite), different values of the step distance and various extraction speeds. Tubes cast using a FG cast iron mould present periodical diameter variations Figure 2, left. Such diameter variation along the tubes seem being absent in the case of the tubes cast using a graphite mould. For the two types of mould and for medium extraction speeds, there are also linear marks surrounding

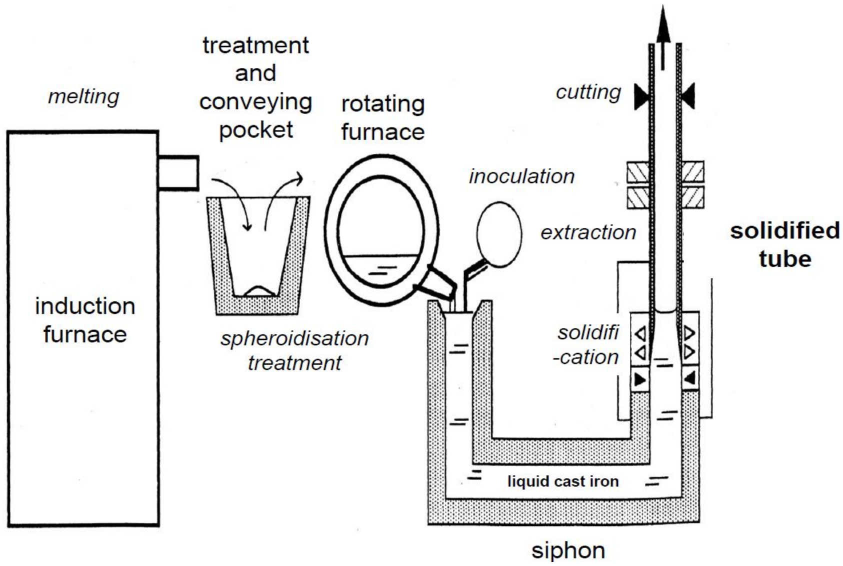


**Figure 1 : Scheme of the 'hot' apparatus and running from the melting of the cast iron to its cutting as solidified tubes**

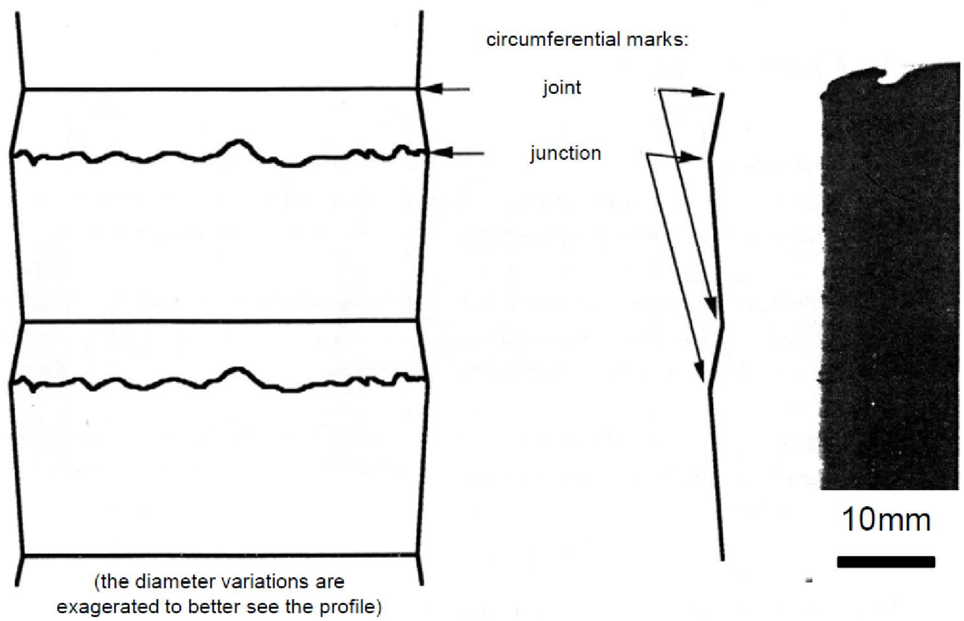


**Figure 2 : Diameter evolution along a tube cast using a FG cast iron mould; correspondence with the joint and junction marks**

the tube. These ones are obviously of two types Figure 3, a first one particularly deep and irregular, but globally circular, and a second one finer but much more irregular. The two marks are reproduced along the external surface of the tubes with the same spacing. In the case of a FG cast iron mould, this periodicity is the same as for the diameter variations. More precisely there is a correspondence between the diameter profile and the periodical marks Figure 2, middle and right side): from the bottom joint mark up to the following junction mark the tube's diameter continuously increases. Thereafter, from the junction mark to the upper joint mark, it decreases progressively.

## Circumferential marks; wrinckles at low extraction speed

The circular periodic marks and the irregular ones look like, respectively, the joint mark and the junction mark seen at the external side of the succinonitrile or stearic acid solidified in the 'transparent" apparatus[13], the formation of which were

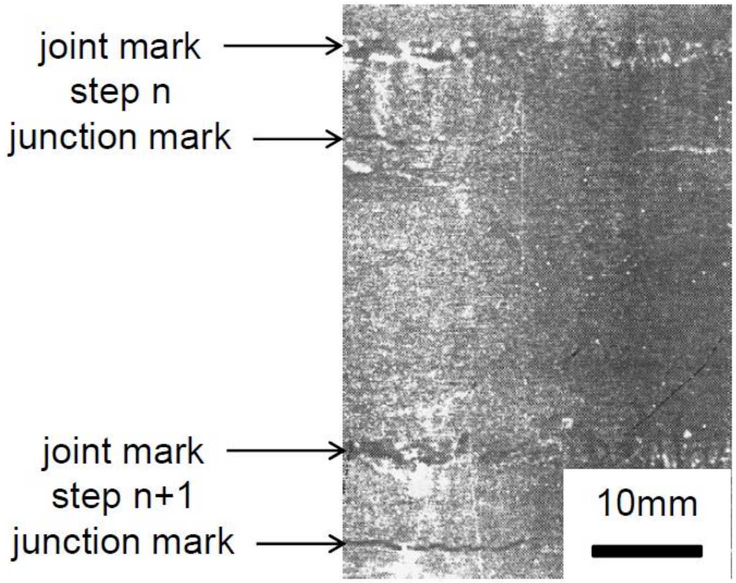


**Figure 3 : External surface of an obtained tube, on which two {joint; junction}-couples of marks are visible**

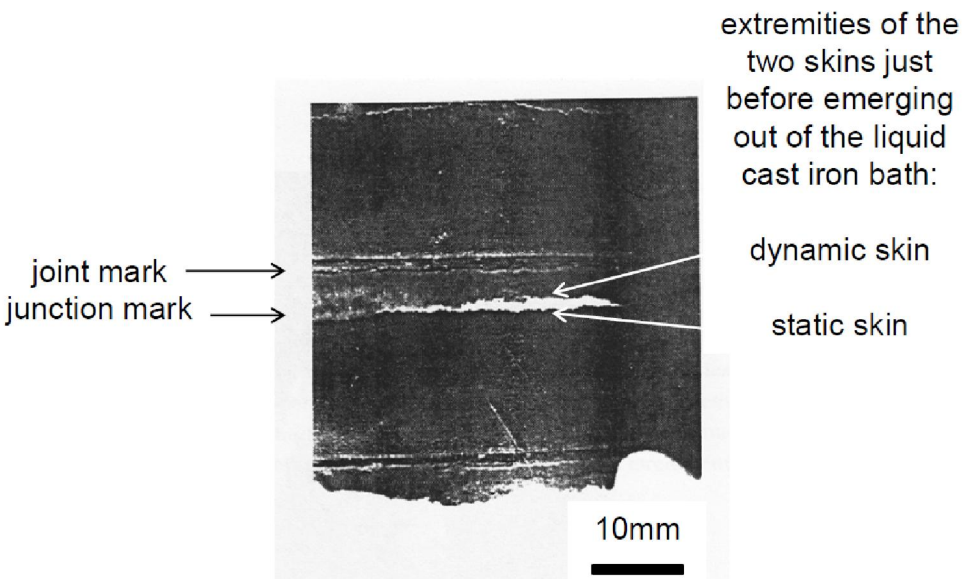


**Figure 4 : Photograph of a end of tube extracted out of the molten cast iron bath not longer supplied in liquid metal at the other side of the siphon; semi-circular elongated void evidencing the on-going growth of a static skin and a dynamic skin**

clearly visualized[13]. Furthermore, in some cases, the extraction of the tubes out of the 'hot' apparatus when the feeding was stopped, led to tubes' ends clearly showing the same double-growth of the first skin Figure 4 as for the 'cold' apparatus[13], with a first skin developing in two parts: a "dynamic skin" and a "static skin".

For the experiments driven by applying much lower extraction speeds, new circumferential appear Figure 5. These ones are on both sides of the junction mark and are finer than the later one. At the same time, in some locations around these tubes (but without systematic reproducibility step after step) and either in a single part superposed on the junction mark, or in two parts (one in the dynamic skin and one in the static skin), there are special features that one can call "vortex", the geometry of which evocates a rotating deformation Figure 6.

## General commentaries

Thus, the 'hot' apparatus realized for this study was successfully used for reproducing the periodic

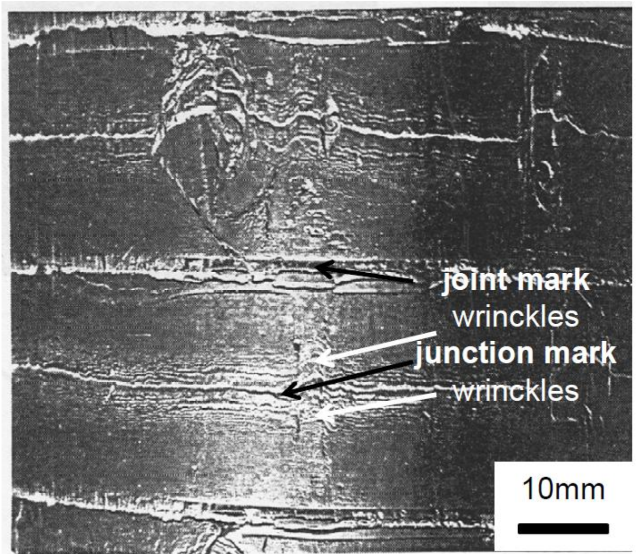


Figure 5 : Tubes cast with low extraction speeds: appearance of new networks of circumferential marks (wrinckles)

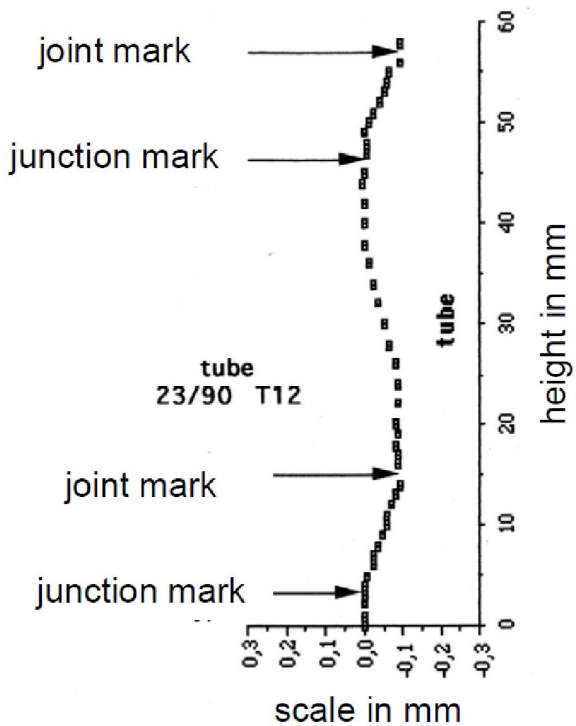


Figure 7 : Amplitude of the diameter variations along the external surface of a tube cast using a FG cast iron mould

marks on the surface of half-products issued from continuous casting without free meniscus, horizontal continuous casting for example despite the difference of casting and extraction direction. Thanks to the use of eutectic spheroidal graphite cast iron, first the operating temperature were not as high as

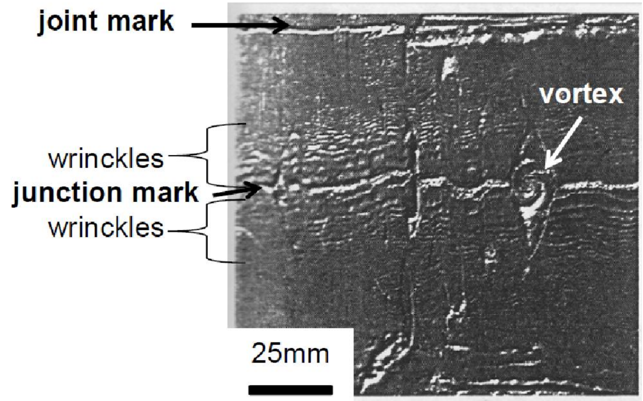


Figure 6 : Tubes cast with low extraction speeds: wrinckles and local rotating figures (called "vortex")

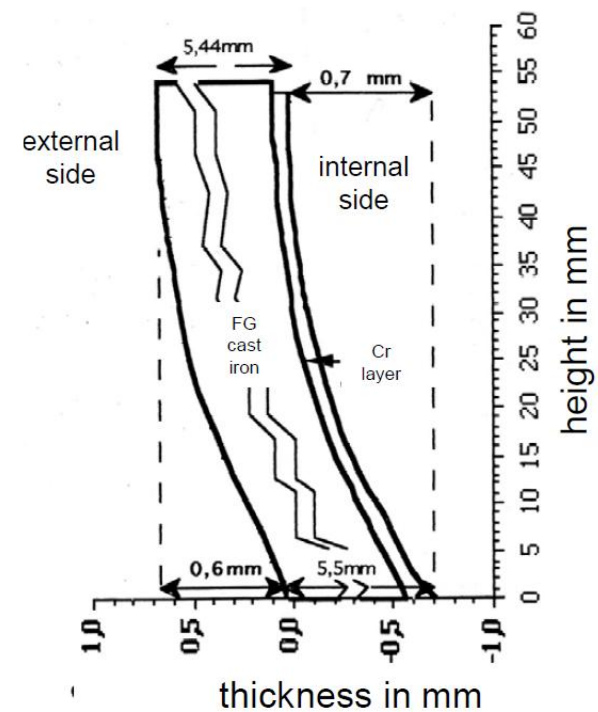


Figure 8 : Residual deformation of a FG cast iron mould after long use life (bottom part)

for steel casting, and second the mechanical behaviour of the solidified tubes allowed conducting the experiments without problems. The fact that this was not blocky half-product but tubes which were solidified was not a problem for the study of the solidification of the first skin only.

The first particularity noted upper concerning the tubes obtained with the 'hot' apparatus was the periodic variation in diameter when this was a mould made of a flake graphite cast iron which was used. The amplitudes of these diameter variations, which are only of several tenths of millimetres Figure 7, Full Paper

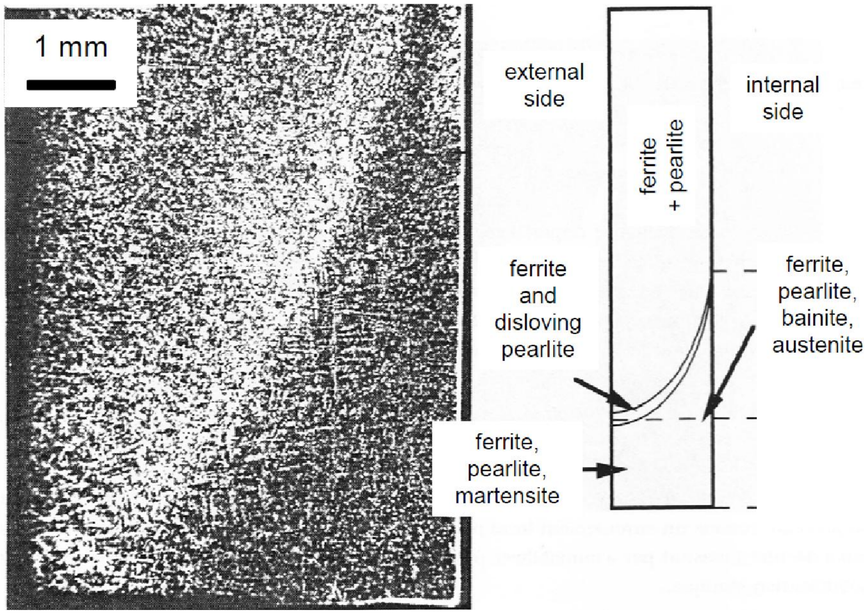


**Figure 9 : Microstructural evolution of the bottom part of a FG cast iron mould after long life at high temperature in thermal cyling**

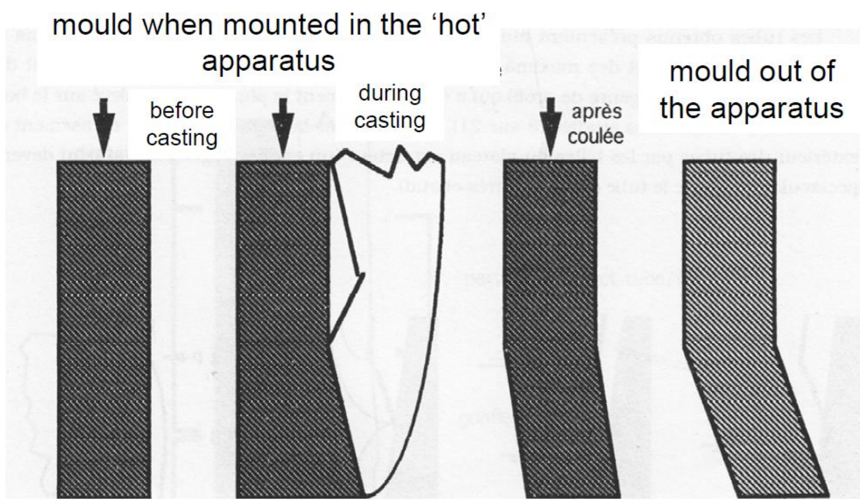


**Figure 10 : Bottom deformation of the FG cast iron mould induced by the local microstructural transformations**

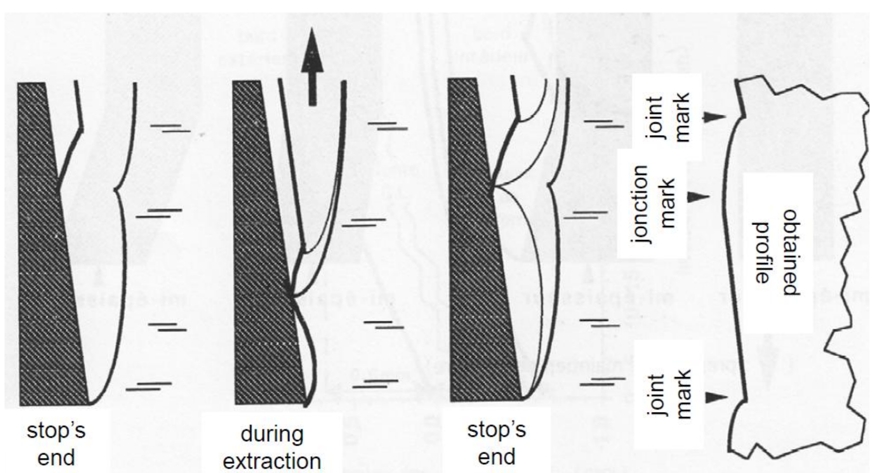


**Figure 11 : How the diameter periodical variations appeared along the tubes cast using a FG cast iron mould**

did not affect the representativeness of the apparatus concerning the studied phenomena. But it is interesting to explain what occurred. After disassembly of the mould it appeared that the bottom parts of the FG cast iron moulds were geometrically deformed Figure 8. FG cast iron, which was used for some of the moulds because its high thermal diffusivity due to the high thermal conductivity of graphite which is enhanced when it has this flake morphology, underwent metallurgical evolution during its local exposure to cyclic high temperatures (Figure 9). The initial microstructure, which was composed of a ferrite-pearlite matrix mixed with flake graphite. During the cycling at high temperature this structure locally transformed into a partially quenched/aged structure containing bainite and martensite. This induced a contraction of the bottom of the mould Figure 10, which influences the solidification of the dynamic skin and of the static skin and was responsible of this final periodically diameter heterogeneity for the final tubes.

Second, the obtained marks were identified either as being joint marks or junction marks, thanks to their geometry (circular or more irregular, respectively). The feeding stops allowed post-mortem visualizing the interrupted development of the first skin in two distinct parts, a dynamic one and a static one, confirming the previously done direct observations allowed by the 'transparent cold' apparatus[13]. The experiments driven with low extraction speeds allowed the formation of wrinckles, reminding the natural wrinckles appearing in steel continuous casting, and which will be later of great importance of the understanding of the fine microscopic mechanisms which will be exposed in a nextpart of this work. The vortex, which were also seen on the external side of the organic pieces solidified in the 'cold' apparatus, are obviously due to local contacts and mechanical interactions between the extremities of the growing dynamic skin and static skin.

## CONCLUSIONS

After the use of a 'transparent cold' apparatus this was here the use of a 'hot' one which completed the simulation of the solidification mechanisms governing the development of the first skin. Confirmations of the main preliminary observations obtained with low fusion temperature organic compounds were found here in the case of metallic simulating alloys closer to the real alloys (steels). Next work[14] will deal with cross-sectional characterization of the obtained SG cast iron tubes in order to enrich the experimental data before exposing the understand mechanisms.

## ACKNOWLEDGMENTS

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