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Solidification mechanisms occurring in horizontal continuous casting. Part 3: cross-sectional characterization of the metallic tubes obtaine dwith the 'hot' apparatus

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ABSTRACT

A 'hot' apparatus working with molten cast iron and especially designed for reproducing the solidification conditions of meniscus-free solidification to simulate the formation of the external circumferential marks surrounding the steel half-products produced by horizontal continuous casting led to tubes the various external surface aspects of which were macroscopically characterized. In the present work the tubes were cut and the obtained parts prepared as metallographic samples. The cross-sectional profiles of the two types of marks as well as of the wrinckles appearing at low extraction speed were analysed. The microstructures of the samples were additionally observed by regards with the conditions of fabrication. Furthermore the particular microstructures in the skin were examined by regards to its double growth modes.

KEYWORDS

Continuous casting;
Model apparatus;
Cast iron;
Metallographic characterization;
Skin microstructure.

INTRODUCTION

Continuous casting processes characterized by the absence of free meniscus at the beginning of the solidifying half-products may be notwithstanding affected by the presence of surrounding periodic more or less regular linear defects along them. If they more or less look like the natural marks and oscillation marks appeared during other processes as vertical continuous casting with solidification of a meniscus[1-3], the formation of which is explained since several decades[4-8], their own origin is only rather recently partially understand[9-12]. The present study, based on the exploitation of a 'cold' simulation apparatus[13] and a 'hot' one[14], aims to deepen the explanation of the involved macroscopic and microscopic mechanisms. The direct observations done with the first device and the post-experience global examination of the obtained tubes solidified in the second device, both gave first important indications about the macroscopic phenomena. In this part the obtained tubes were examined as cut and as metal-

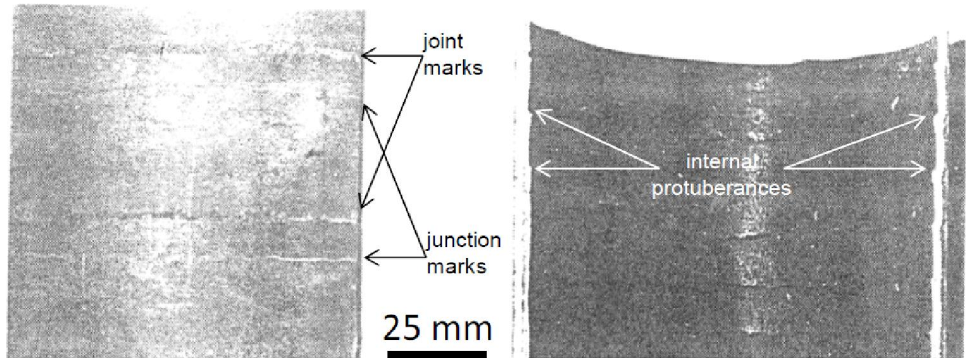

Figure 1: Photographs of the external surface and of the internal surface of one of the obtained tubes

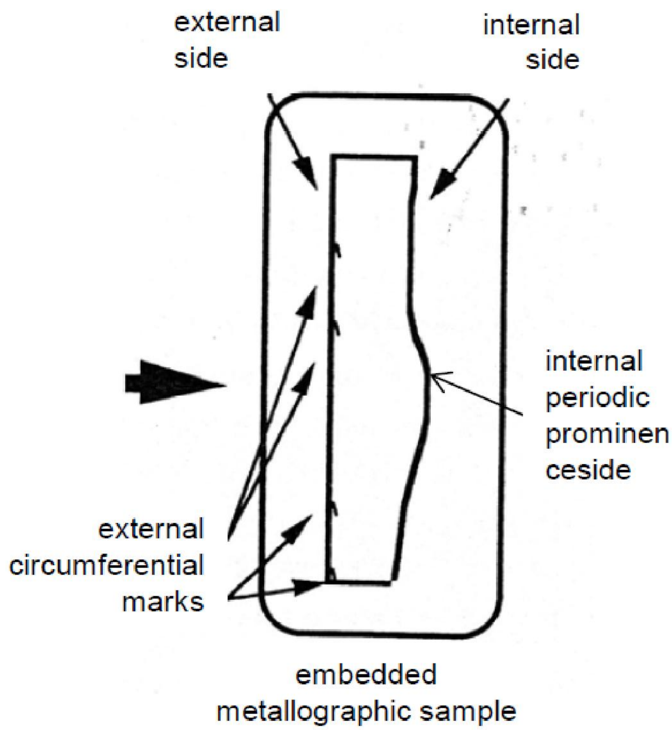

Figure 2 : Cross-sectional shape of a longitudinally cut sample

lographically prepared, in order to enrich the set of results for the final complete understanding of the microscopic phenomena.

EXPERIMENTAL

The tubes obtained for different conditions of fabrication (liquid cast iron inoculated or not, medium or low extraction speed…) were, by comparison with the previous observations of the external surface only, examined on the internal surface. Furthermore samples were longitudinally cut in the tubes for microstructure examinations. For that they underwent classical metallographic preparation, including precision cutting, embedding in cold resin, grinding with SiC papers (lubricant: water) with increasing grades (from 120 to 1200) and, after ultrasonic careful cleaning, final polishing (6µm hard particles, special lubricant) until obtaining a mirror-like state. For the mounted samples made of spheroidal graphite cast iron ("SG cast iron"), the final grinding with 1200-grit paper was realized without water and on preliminarily dried samples, in order to avoid any deterioration of the graphite nodules. In contrast, the white cast iron samples, issued from tubes solidified without inoculation, did not require such precaution.

To reveal the obtained microstructures, and before that possible macrostructure heterogeneity, the embedded then polished structures were etched with Nital. For that they were immersed during about ten seconds in a mixture composed of 96% of ethanol and 4% of nitric acid, slow with alternative movement, then rapidly rinsed under tap water. This Nital etching, well-known for not alloyed ferrous alloys such as pig iron and carbon steels, allows clearly seeing grain boundaries and distinguishing pro-eutectoid ferrite (remaining white), pearlite (grey) and cementite / ledeburite (white).

RESULTS AND DISCUSSION

External / internal outer surfaces of the obtained tubes

The external surfaces of the tubes were already described: always joint's marks and junction's marks, sometimes wrinckles on both sides of the junction's mark with local vortexes… The internal surfaces were themselves observed after cutting of tubes into two half parts Figure 1. This revealed the presence, on the internal surface too, of periodic defects, with the same average spacing as the one for the joint's marks on th external surface, but with a less regularly spacing. These are circumferential prominences existing on a several millimetres height.

Cross-sectional macroscopic aspect of the tubes' samples

After coarse plasma torch cutting, precision cutting, embedding and grinding the cross-sectional samples look like the scheme drawn in Figure 2. The most often, although small, the two types of marks are visible to the naked eye. The internal circumferential prominence is also very visible.

After Nital etching, the SG cast iron samples are general coloured in gray. This allows distinguishing an external part, looking like a knife, periodically present along the external side. This is discrete and not really visible for some tubes' samples. When they are clearly visible, one can see that these particular zones

May present different profiles Figure 4. It is generally possible to measure them. This was done in several cases and some results are given in Figure 5.

Shapes of the circumferential marks

The traces let by the external circumferential marks on the external side of the embedded and polished samples can be examined by optical microscopy. As illustrated by the micrographs presented in Figure 6 the joint's marks may show different morphologies. In fact two of them are the most often encountered: they are schematized in Figure 7.

Also as seen in cross-sectional conditions, the junction's marks may be of much more various types, as illustrated by some micrographs in Figure 8 and by a richer scheme in Figure 9 in which all the types of junction's mark geometry are shown with semi-quantitative data about their dimensions.

During rather slow extractions one saw earlier that a network of wrinckles developed on the external surfaces of the tube, on both sides by regards to the junction mark. When observed in cross sectional condition, these wrinckles result in surface waves or ripples which may be detected in optical microscopy at low magnification. Micrograph and scheme illustrate such ripples appearing on the external side of embedded sample, in Figure 10.

Longitudinal and transversal evolution of the microstructures: SG cast iron

The microstructures of the tubes may vary depending on the application or not of inoculation (SG cast iron or white cast iron, examples in Figure 11) and on the location of the observed zone in the cross-section, as for example the knife-like zones already mentioned.

When one observes the microstructure close to the external side of a SG cast iron sample, no evident

Longitudinal evolution appears. One can only detect that the graphite nodules surrounded by ferrite seem a little coarser (higher diameters) in the joint's mark neighbourhood than elsewhere along the external side.

In addition one can also mention that it seems

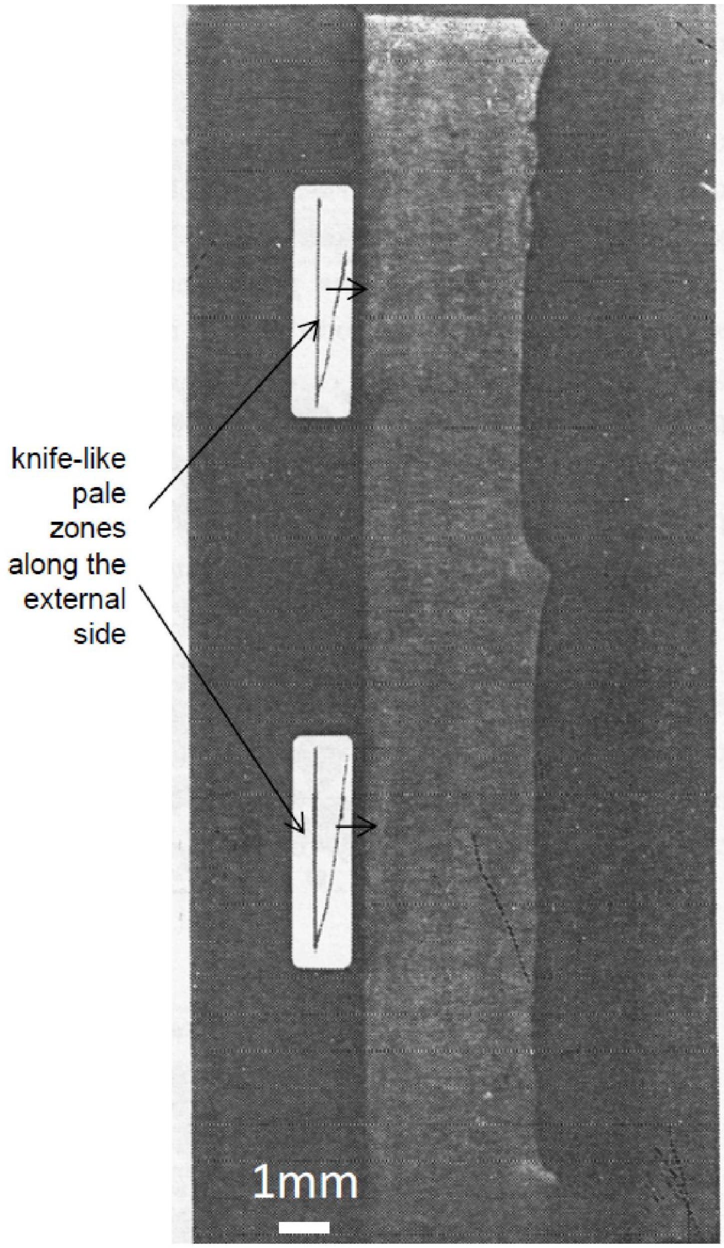

Figure 3 : Particular periodic pale microstructural zones along the external side of the SG cast iron tubes revealed after Nital etching

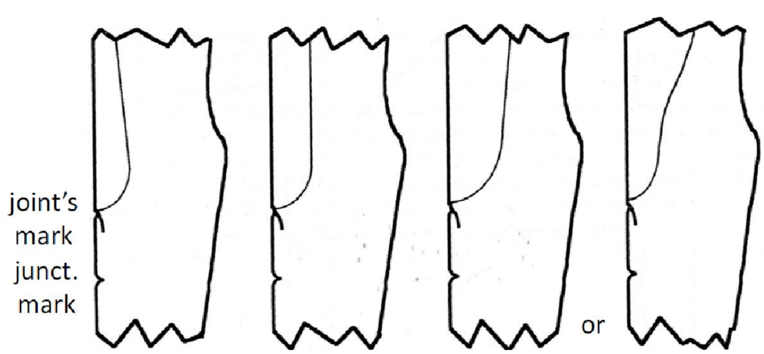

Figure 4 : Different types of external microstructurally different zones revealed by Nital etching of mounted polished cross-sections of SG cast iron tubes

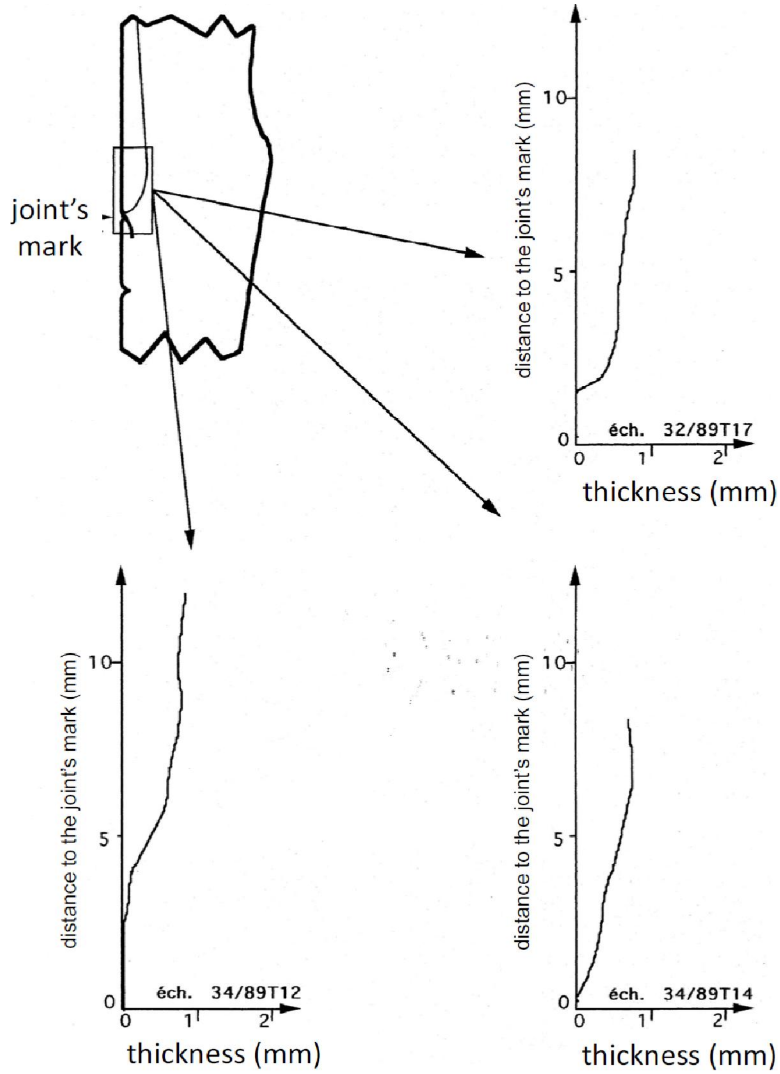

Figure 5 : Measurement of several pale zones existing periodically along the external side of etched SG cast iron tubes

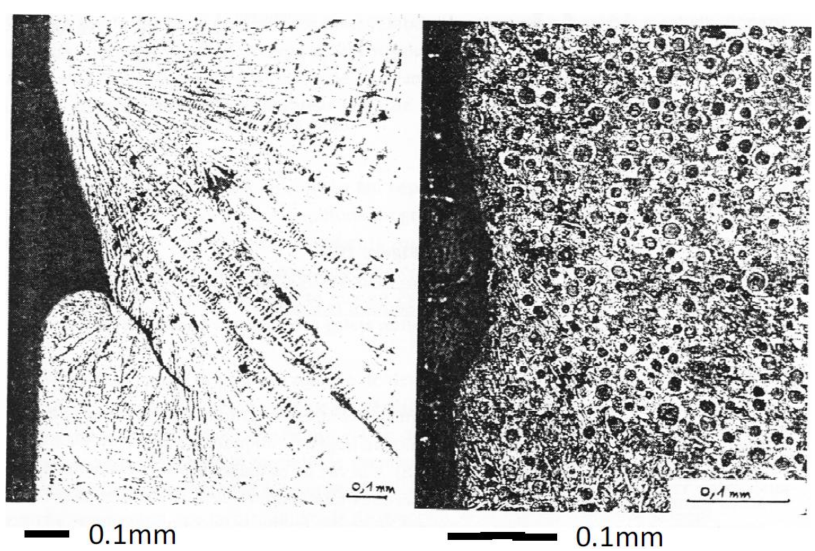

Figure 6 : Micrographs illustrating the two main types of joint's mark (left: a white cast iron tube obtained by suspending inoculation, right: a SG cast iron tube)

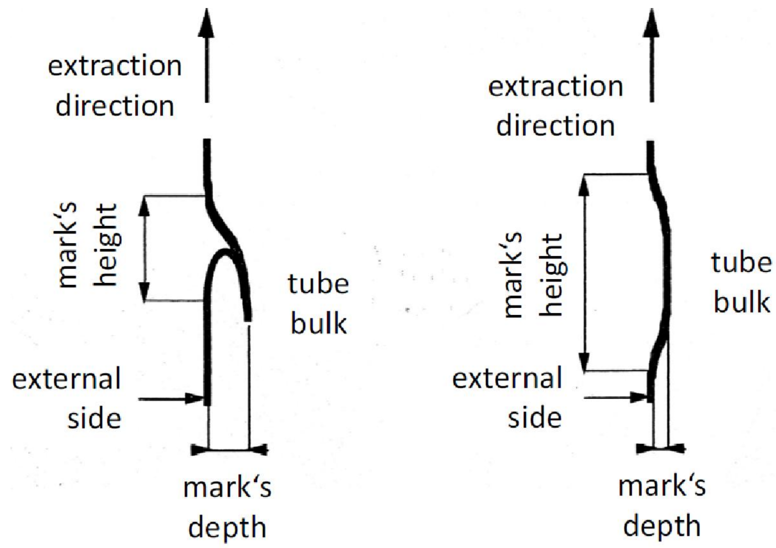

Figure 7 : Scheme describing joint's marks of the two main types

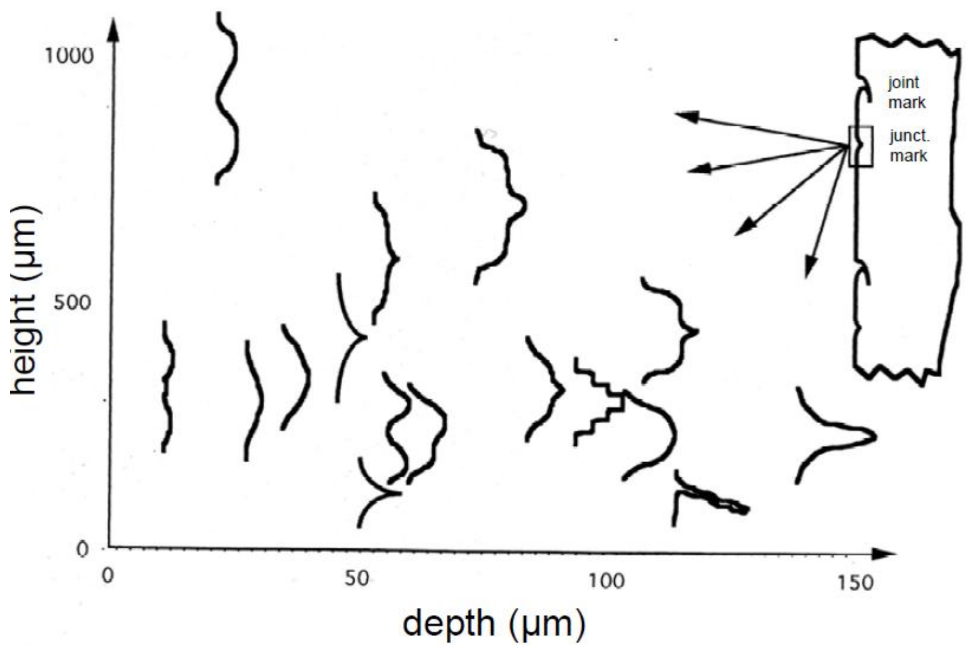

Figure 9 : Scheme / graph describing some of the observed junction's marks and giving their typical sizes

that an orientation of a carbides substructure (more precisely elongated parts of ledeburite), initially appeared because of too rapid solidification in direct contact with the metallic mould, and remaining a little after the annealing occurred during the subsequent thickening until emerging out of the molten cast iron bath, is still visible. This orientation is seemingly different whether if the observed zone is the one between the junction's mark and the upper joint's mark, or between the same junction's mark and the lower joint's mark.

Transversally Figure 13, the microstructure of a SG cast iron tube progressively loses all the possibly remaining ledeburite substructure while the graphite nodules become bigger and bigger.

When the observation point comes close to the internal side some cavities (porosities or shrinkage defects) appear Figure 14.

Longitudinal and transversal evolution of the microstructures: white cast iron

When inoculation is interrupted the graphite cannot nucleate sufficiently rapidly and, taking into account the high cooling power of the metallic mould, solidification develops according to the metastable

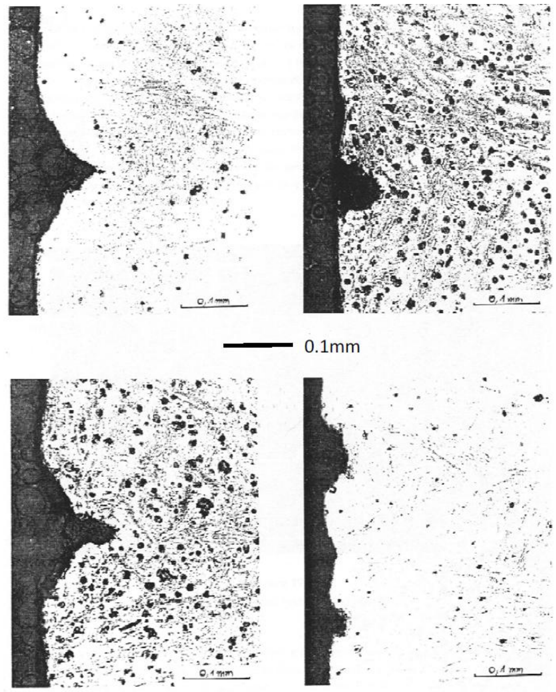

Figure 8 : Micrographs illustrating the geometry variability of the possible junction's marks

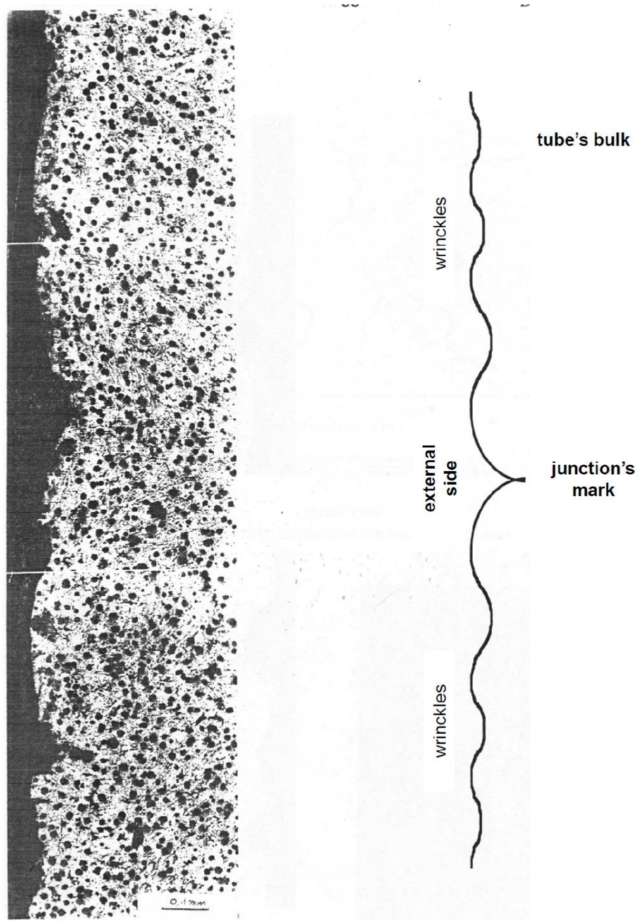

Figure 10 : Micrograph and scheme describing the ripples issued from the surface wrinckles which may appear on both sides of the junction's mark when the extraction speed is low (micrograph: SG cast iron tube after Nital etching)

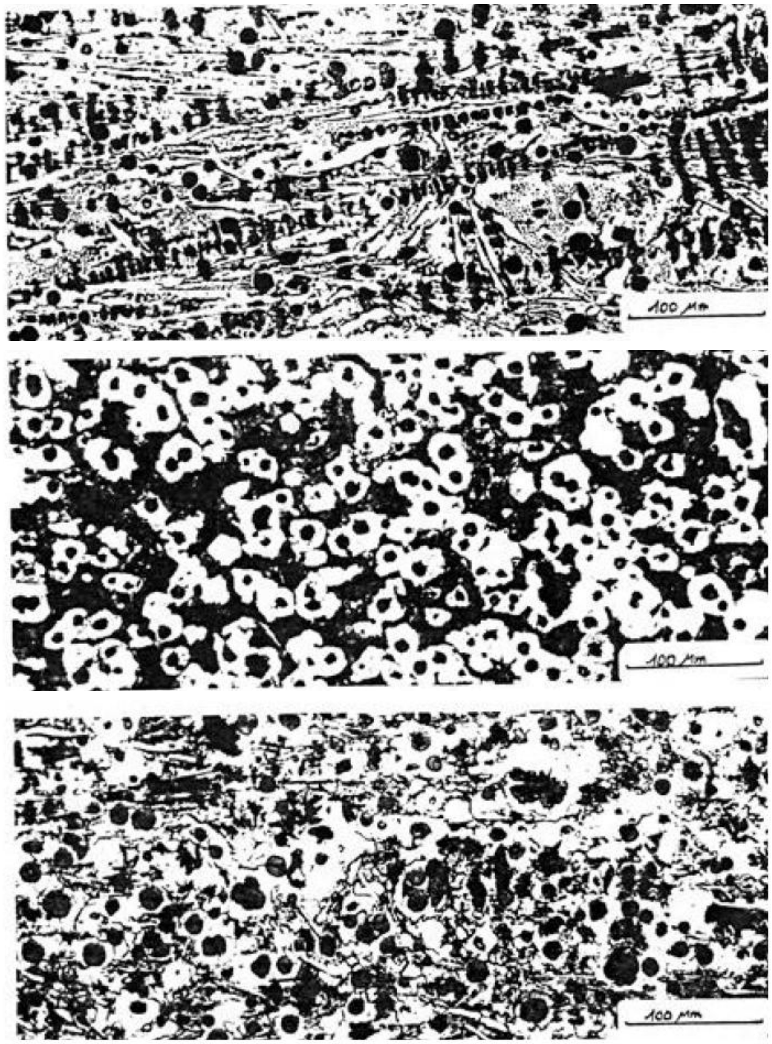

Figure 11 : Examples of the various types of microstructures in the tubes depending on the fabrication conditions; top: hypo-eutectic white cast iron composed of dendrites (initially austenite, now pearlite) and ledeburite, middle: ferrite-pearlite spheroidal graphite cast iron; bottom: microstructure intermediate of the two previous ones

austenite-cementite diagram. Thus, instead spheroidal graphite and its isotropy growth, this is pro-eutectic coarse acicular crystals of cementite (if hypereutectic composition) or austenite dendrites (if hypoeutectic composition, case of the white cast iron in Figure 15) followed by ledeburite (austenite & cementite white eutectic compound) which solidify. In these latter cases crystals are highly anisotropic and oriented along the the local thermal gradient existing during solidification. This is much more powerful for understanding the solidification mechanisms in terms of orientation and disorientation/reorientation-deviation. With much more visible ledeburite platelets and dendrites this allows confirming the first feelings issued from the skin ledeburite substructure of the SG cast iron samples: the structure tends to be upwardly oriented in the dynamic skin and downwardly in the dynamic skin (Figure 15, left). The microstructure thereafter developed transversally during the thickening, with partly a heritage of these orientations: always grey dendrites (austenite become pearlite during post-solidification cooling) and ledeburite (Figure 15, right).

By observing with the optical microscope at its highest magnification it was furthermore possible to measure the average spacing between alternated lamellar of austenite (become ferrite + cementite during post-solidification cooling) and cementite. This will be of importance later for valuing the kinetic of thickening. The results are graphically given

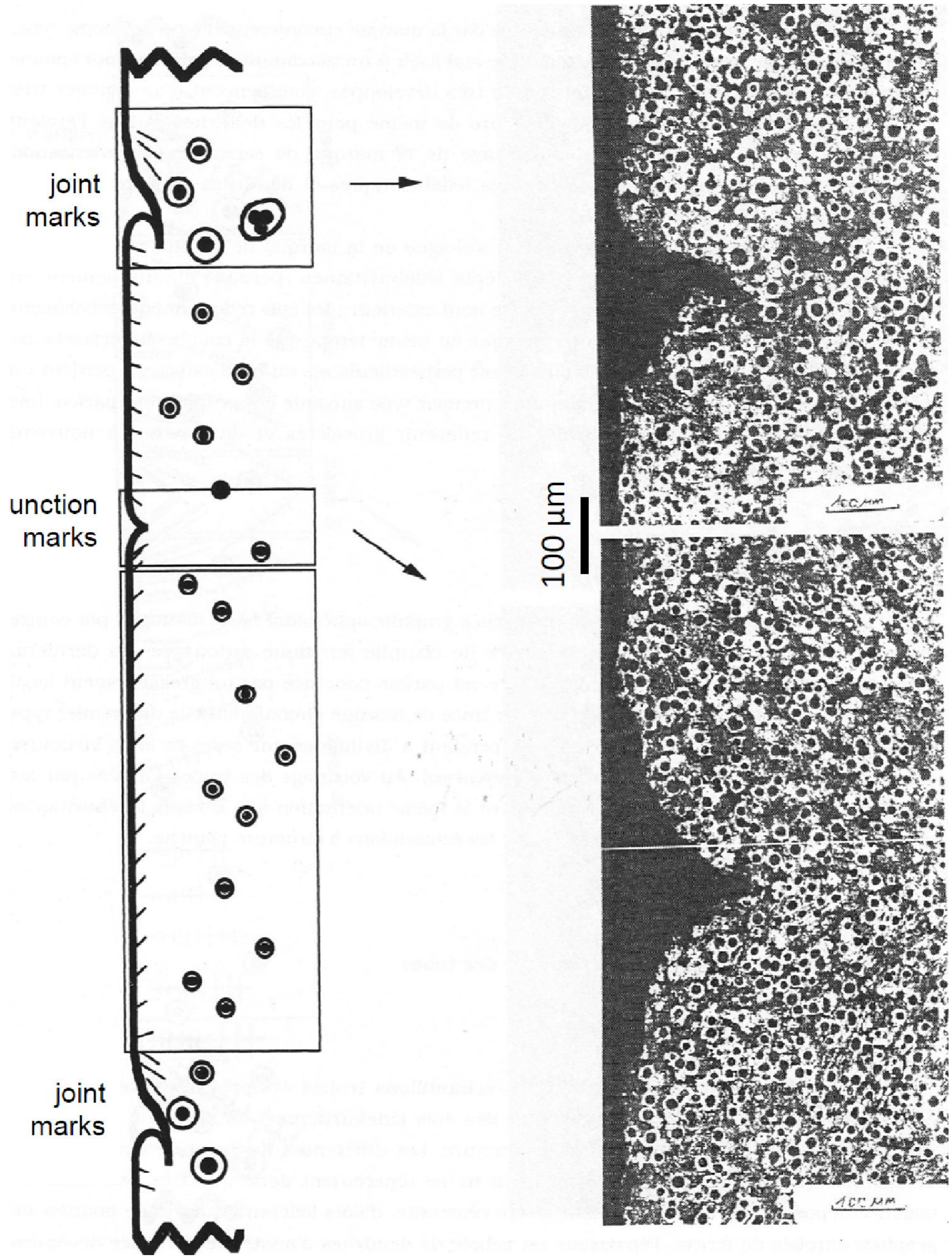

Figure 12 : Longitudinal microstructure evolution along the external side of a SG cast iron tube over a total inter-joint's marks space (left: scheme; right: optical micrograph after Nital etching)

in Figure 16 for to white cast iron samples.

General commentaries

Thus, after cutting the tubes one obtained additional information about the solidification of the tubes in the 'hot' apparatus. Except the circumferential prominences revealed on the internal surface – which is easily explainable Figure 17 – very interesting and useful microstructural data were collected. Notably, the curious but apparently typical profiles of the external circumferential marks of the two types (joint and junction) suggest that solidification of the two skins followed particular scenarios. In the same way the

Particular microstructure global orientations in the skins, which are not parallel to the thermal gradient existing during solidification and which seem deviated either upwardly or downwardly this depending whether this is the dynamic or the static skin, are interrogating observations but the explanation

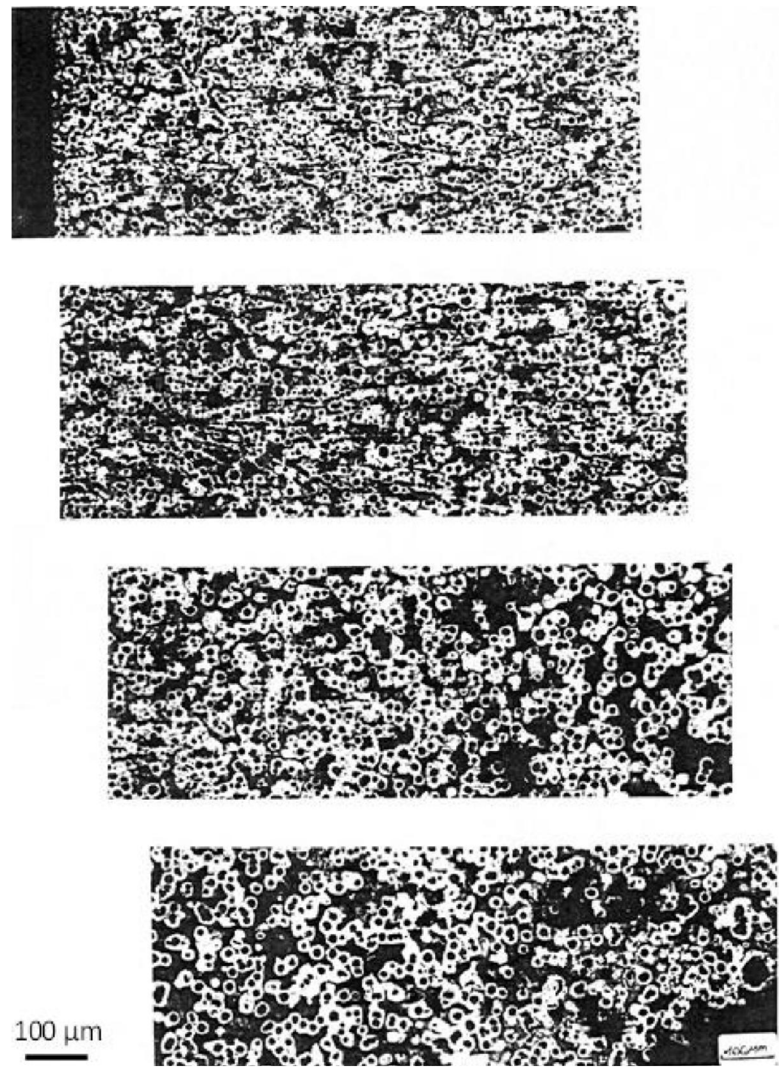

Figure 13 : Transversal microstructure evolution from the external side (top) to the internal side (bottom) of a SG cast iron sample

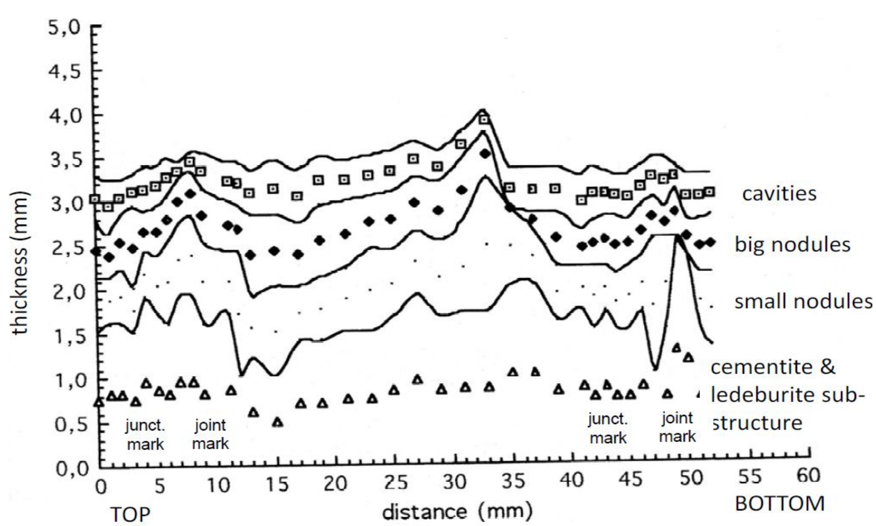

Figure 14 : Measurement of the successive microstructural zones from the external side to the internal side of a SG cast-iron sample

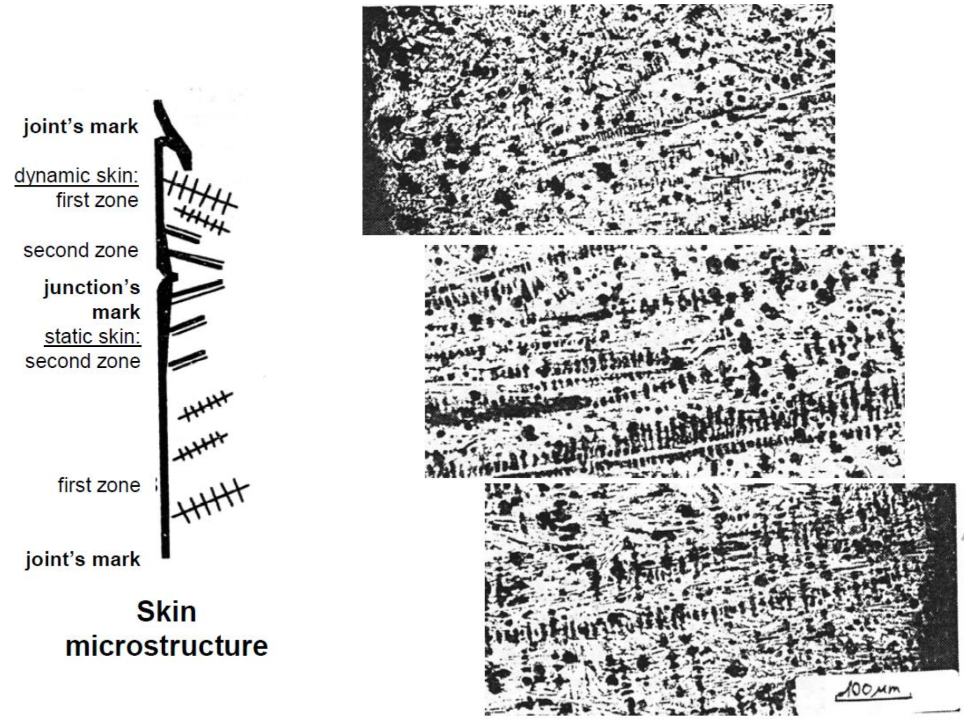

Figure 15 : Schematization of the longitudinal microstructure evolution along the external side of a white cast iron tube over a total inter-joint's marks space (left); transversal microstructure evolution (right: optical micrograph after Nital etching)

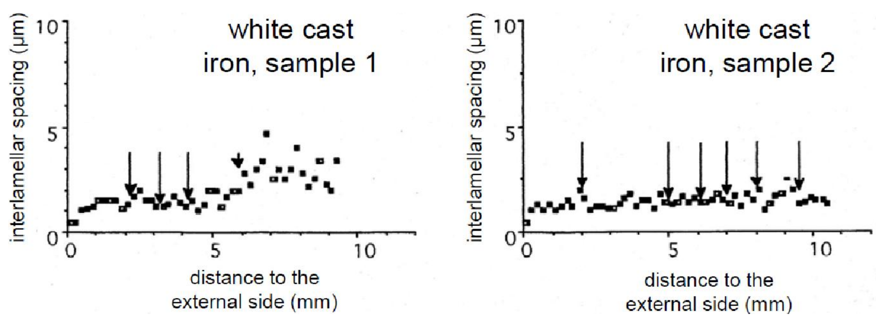

Figure 16: Evolution of the average inter-lamellar spacing in ledeburite from the external side to the internal side of a white cast iron sample (optical microscopy transversal measurements at a 5mm-height above a joint's mark); arrows show the thickness of the zones distinguished with the naked eye

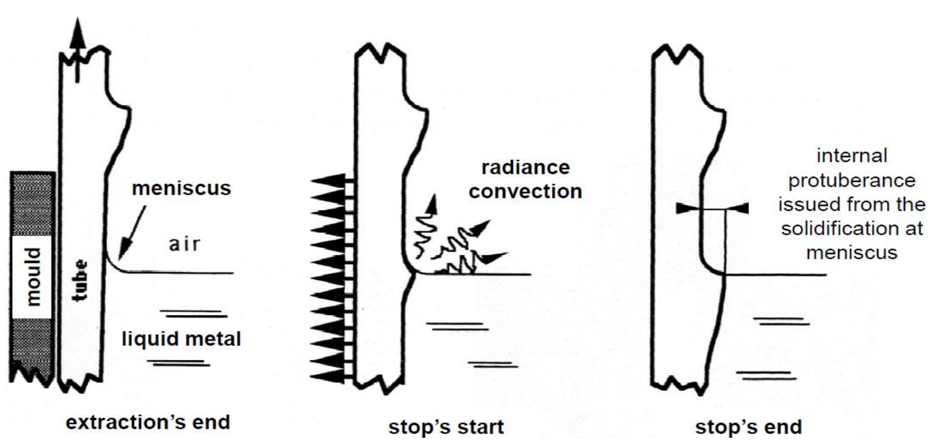

Figure 17 : How developed the circumferential internal prominences

of which may lead to the understanding of the microscopic mechanisms of development of the two skins.

CONCLUSIONS

The new data brought by the cross-sectional characterization of the tubes fabricated by the 'ho' simulation machine will be added to the previously obtained ones in order to clarify the mechanisms of solidification of the first skin in continuous casting without meniscus. In the two final parts of this consequent work, one will precise the kinetics of longitudinal growth of the dynamic skin and finally, using all the obtained data, propose microscopic mechanisms of solidification.

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