

Title	Why is hardness sometimes out of specification?
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Introduction

In the first three contributions of this series, the central role of inoculation in the metallurgical control of cast iron was analysed, from the critical issues of inoculation practice to the vulnerabilities of in-stream inoculation, up to the case study showing how over-inoculation and return remelting can significantly alter the solidification behaviour of the metal.

This fourth paper focuses on one of the most common and difficult-to-interpret consequences of non-stabilized metallurgy: hardness out of specification, with particular reference to cases where values are abnormally high. Hardness, often assessed as a simple numerical parameter, is in fact a direct indicator of the microstructure and of the solidification conditions that characterize the process.

The paper provides an overview of the main causes that can lead to undesirable hardness variations, including chemical, thermal, and microstructural aspects. Particular attention is given to the role of metastable structures such as cementite or undesired pearlitic areas, which are responsible for localized and unexpected hardness increases.

The paper is complemented by an industrial case study in which a foundry experienced recurring issues of high hardness despite a chemical composition within specification. Through base iron preconditioning, stabilization of nucleation potential, and the introduction of systematic thermal analysis control, it was possible to eliminate metastable structures and bring hardness values back within required limits.

In continuity with previous works, this contribution emphasizes that hardness is not an independent variable but the direct result of the metallurgical history of the metal. Only quantitative control of base iron quality and its solidification behaviour can ensure stable, repeatable, and specification-compliant hardness values.

What is hardness and what role does it play in cast irons?

Hardness is a conventional mechanical property that expresses a material's resistance to the penetration of a harder body and represents a synthetic indicator of the overall mechanical behaviour of the casting. In cast irons, hardness is an indicator of compressive strength and is strongly influenced by the overall microstructure, namely the combination of graphite shape, distribution and quantity, and the nature of the metallic matrix, whether ferritic, pearlitic, or mixed.

From an application standpoint, hardness plays a central role because it directly affects tensile strength, ductility, toughness, wear resistance, and machinability. It is therefore not uncommon for hardness to be used as an acceptance parameter. However, conflicting requirements between design, which often demands higher hardness for durability, and machining, which benefits from lower hardness, require the metallurgist to maintain hardness within a narrow and controlled range, an objective that is not always easy to achieve.

Why can hardness fall outside specifications?

Out-of-specification hardness values in cast iron components are generally the result of variations in the nature and distribution of microstructural phases rather than simple deviations in average chemical composition. The main causes can be traced to different levels of the melting process:

- variations in chemical composition, particularly elements affecting the matrix such as C, Si, Mn, Cu, and Sn, or phase stability;
- uncontrolled thermal conditions, including pouring temperature and rate, metal holding time, and local cooling conditions;
- charge materials, including high percentages of returns or contaminated scrap;
- spheroidization and inoculation management, particularly in the presence of fading or excessive additions;
- metal–mould and metal–refractory interactions, which may introduce undesirable elements or alter solidification behaviour;
- casting and gating system design, influencing thermal gradients and solidification rates.

A significant and often underestimated cause is boron absorption by cast iron, particularly in foundries producing pearlitic irons. In the presence of new or recently replaced refractories, molten metal can absorb boron from refractory materials, typically present as oxides or boron-based sintering additives. Even at concentrations of a few tens of ppm, boron can significantly alter the microstructure by reducing the pearlitic fraction in favour of ferrite, counteracting the effect of pearlite-promoting elements such as copper, resulting in lower-than-expected hardness values despite apparently compliant chemical composition.

Conversely, opposite situations can lead to localized and unexpected increases in hardness, especially when inoculation and preconditioning are not properly managed. In many cases, undesired metastable structures result from insufficient stabilization of the nucleation potential of the base iron, suboptimal inoculation practices, or, more generally, the lack of process control based on thermal analysis. For this reason, the following section presents a case study in which base iron preconditioning, stabilization of metallurgical quality, and systematic use of thermal analysis made it possible to eliminate metastable structures and bring hardness values within specification limits.

Base iron stabilization as a key factor: a case study

The case concerns a study conducted in a foundry producing grey iron castings for the automotive field, where defects of porosity and excessive hardness were observed, associated with the presence of cementite in some castings. These defects occurred sporadically, not systematically and not regularly over time, without an evident correlation with chemical composition or specific production stages, making the identification of a single root cause particularly complex.

The foundry operated five 25 t melting furnaces and applied inoculation exclusively through in-stream inoculation, using an inoculant system not supported by vision or monitoring technologies.

Process analysis through ITACAX™ thermal analysis software showed that the nucleation potential of the base iron was highly variable over time. In particular:

- during the first pours of the morning, the iron frequently exhibited very low nucleation potential;
- it progressively improved throughout the production day, also as a function of the increasing amount of remelted returns.

As a consequence, the base iron was not metallurgically stable, and this instability was inevitably reflected in the final iron. The constant and unmonitored in-stream inoculation was therefore unable to compensate for the wide fluctuations in nucleation potential of the incoming metal, promoting in certain conditions the formation of undesired metastable structures responsible for the observed defects.

Based on these findings, the following strategy was introduced:

- base iron preconditioning directly in the melting furnaces, with the aim of stabilizing nucleation potential before subsequent process stages;
- adoption of ITACA Inoc 1440, a FeSi-based inoculant with zirconium as the active element, particularly effective in improving and stabilizing the nucleation capacity of cast iron.

Preconditioning additions were managed dynamically, adjusting the dosage based on feedback from ITACAX™, with higher additions under low nucleation potential conditions and gradual reductions as metallurgical conditions improved. This approach drastically reduced base iron variability and, consequently, stabilized the behaviour of the final iron.

Thanks to this approach, not only was a significant reduction in scrap due to non-compliant hardness achieved, but unintended over-inoculation phenomena were also avoided, linked to the reintroduction of inoculants through return remelting, a phenomenon known as inoculant heredity, as discussed in the previous paper.

Conclusions

This study has shown that hardness in cast iron components should not be interpreted as a simple numerical property, but as the direct result of the metallurgical history of the metal and its solidification behaviour. Out-of-specification hardness values, particularly on the high side, are often symptomatic of microstructural instability,

such as the formation of undesired metastable structures, which can develop even in the presence of nominally compliant chemical composition.

The case study demonstrated how variability in the nucleation potential of base iron, if not controlled, can lead to irregular behaviour of the final iron, promoting localized formation of cementite and associated defects. In this context, constant and unmonitored in-stream inoculation is insufficient to compensate for metallurgical fluctuations in the incoming metal.

The adopted solution, based on dynamic base iron preconditioning, stabilization of nucleation potential, and systematic use of ITACAX™ as a process control tool, made it possible to eliminate metastable structures and restore hardness values within required specifications, while improving process repeatability and reducing scrap. In continuity with the previous three papers, this fourth contribution confirms that metallurgical quality must be controlled upstream of the process, before the metal enters the mould. Only a controlled management of base iron, supported by quantitative analysis and monitoring tools, allows the prevention of metallurgical drift that is difficult to interpret a posteriori and ensures stable, predictable, and specification-compliant mechanical properties.