Journal of Energy Technology

JET Volume 15 (2022) p.p. 51-66
Issue 1, June 2022
Type of article: 1.01
www.fe.um.si/si/jet.html

REDUCING CARBON FOOTPRINT IN AN OEM SUPPLY CHAIN CAUSED BY INADEQUATE INTERPRETATION OF X-RAY RESULTS OF HIDDEN DEFECTS IN DUCTILE IRON CASTINGS

ZMANJŠANJE OGLJIČNEGA ODTISA V DOBAVNI VERIGI OEM-OV ZARADI NEUSTREZNE INTERPRETACIJE REZULTATOV RTG SKRITIH NAPAK V NODULARNI LITINI

Tadej Pavlin[1ℜ], Iztok Brinovar[1], Bojan Stergar[1], Zdravko Praunseis[1]

Keywords: carbon footprint, ductile iron, X-ray inspection, cutting inspection, hidden mistakes, defects, porosity, inclusion, green energy, reduction in energy production

Abstract

In the global market, the casting industry recorded a growth trend for ductile iron last year. Ductile iron is used due to its excellent mechanical properties, machinability and castability. The microstructure of nodular cast iron consists of a metal matrix and graphite extruded in the form of beads and nodules. In recent years, the production of ductile iron castings has increased significantly for parts for heavy transport vehicles and containers for permanent disposal of nuclear

ℜ Corresponding author: PhD student, Tadej Pavlin, Faculty of Energy Technology, University of Maribor, Tel: +386 (0)37 770 400, Mailing address: Koroška cesta 62a, Velenje, Slovenia, E-mail address: tadej.pavlin@livar.si

[1] University of Maribor, Faculty of Energy technology, Koroška cesta 62a, Velenje, Slovenia

waste, and it is expected that this trend of expansion will continue for at least the next twenty years. When poured in sand moulds, the quality of products can not be reached. There can be defects on the raw surface and/or on the machining surface, as well as hidden defects inside the material. For casting products, defects can be detected on raw and machining surfaces and inside material defects by carrying out a visual inspection. The results of the inspection depend on the inspection method used. In general, basic methods of cutting or milling inspection are used in the casting industry, which means that products are classified in terms of whether or not they meet the drawing specification(s). The authors of this paper focused on the hidden defects inside ductile iron material, which can be detected by carrying out a cutting or milling inspection or through an X-ray inspection. Huge amounts of energy and energy sources are used in the production of nodular cast iron, which creates a negative environmental footprint. Therefore, by being preventively rational and through appropriate control procedures it is possible to significantly reduce the carbon footprint.

Povzetek

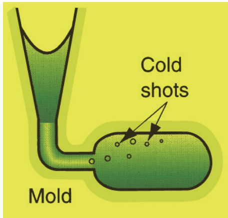
V livarski industriji se v zadnjih letih na svetovnem trgu soočajo s trendom rasti uporabe nodularne litine. Nodularna litina se uporablja zaradi zelo dobrih mehanskih lastnosti, dobre obdelovalnosti in dobre ulivne sposobnosti. Mikrostruktura nodularnega litine je sestavljena iz kovinske matrice in grafita, ekstrudiranega v obliki kroglic, nodul. V zadnjih letih se je močno povečala proizvodnja nodularnih litin za dele, kot so težka transportna vozila, zabojnike za trajno odlaganje jedrskih odpadkov in pričakujemo, da se bo ta trend širitve nadaljeval vsaj naslednjih dvajset let, ker gre za naj boljši približek jeklu. V litrski industriji je bilo splošno znano, da pri vlivanju v pesek nikoli ne doseženo 100% kakovosti izdelkov, lahko so prisotne napake na surovi površini, na obdelovalni površini ali minimalno vedno lahko prisotne skrite napake znotraj materiala. Pri izdelku za ulivanje lahko z vizualnim pregledom zaznamo napake na surovi in obdelovalni površini ter notranjo napako v materialu, odvisno je le, na kateri način pregleda dobimo rezultat pregleda. V splošnih primerih industrije litja lahko uporabimo osnovne metode pregleda rezanja ali struženja. To pomeni, da so izdelki v skladu s specifikacijo risbe ali ne. V članku je raziskava osredotočena na skrite napake v notranjosti nodularne litine, ki jih je mogoče odkriti z rezalnim ali rezkalnim pregledom ali z rentgenskim pregledom. Pri izdelavi nudularne litine se uporabi izredno veliko energije in energentov zato imamo prisoten tudi velik pečat odličnega odtisa na okolje v negativnem smislu. Zato smo lahko preventivno racionalni z ustreznimi kontrolnimi postopki in lahko bistveno znižamo ogljični odtis.

1 INTRODUCTION

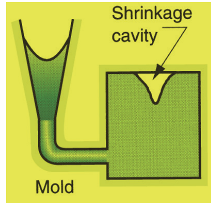
1.1 Basic or general defects of casting hidden mistakes for raw parts

There are numerous opportunities for things to go wrong in terms of the quality of casting in the production of casting in foundries, thus resulting in quality defects in the product. These defects can be classified into two groups: general defects common to all casting processes, and defects related to the sand casting process. See Table 1 for examples of a casting that has solidified before completely filling a mould cavity, a casting in which two portions of metal flow together but there is a lack of fusion due to premature freezing, and a casting in which metal splatters during pouring and solid globules form and become trapped in the casting.

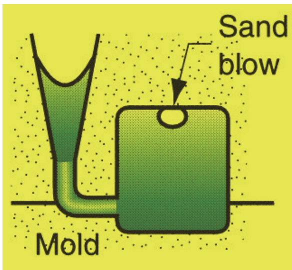
Table 1: *Basic casting defects [9]*



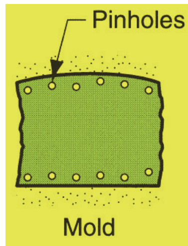
a) Metal splatters during pouring and solid globules form and become trapped in the casting.



a) A depression in a surface or internal void caused by solidification shrinkage that restricts the amount of molten metal available in the lowermost region from freezing.



a) A balloon-shaped gas cavity caused by the release of mould gases during pouring.



a) The formation of numerous small gas cavities at or slightly below the surface of the casting.

1.2 Control procedures for detection of hidden defects in the casting industry

The main purpose of non-destructive testing (NDT) is to examine the quality or conformity of inspected material with technical specification requirements and standards. Three inspection methods were used for the purposes of this paper: Visual testing (VT), Liquid penetrant testing (PT), Radiographic testing, i.e. x-ray – (RT).

Visual inspection method

In a visual examination, it is possible to determine geometric and dimensional surface defects with the help of visible light and the human eye (and sometimes also devices).

Liquid penetrant testing

The color penetrant, which fills the open defect to the surface due to its capillarity, enables extremely contrasting visibility of the defect when applied by the developer. Only surface defects can be detected.

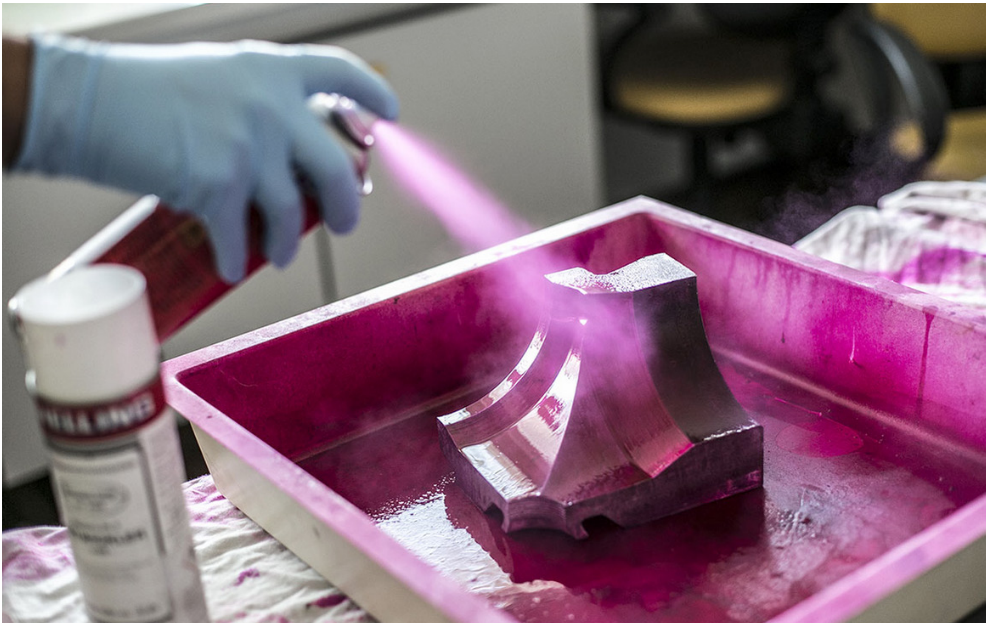


Figure 1: Liquid penetrant testing inspection method [10]

Interpretation of Radiographic x-ray testing

The most widely used non-destructive methods for detecting internal imperfections in cast products are radiographic and ultrasonic testing. The principles of how these methods work on different castings differ, and the basis for choosing one of the other depends on the type of casting, the type of casting material, the purpose of service, the undergoing load during service, the degree of safety and reliability, etc. The ultrasonic method (UT) is based on inducing the ultrasonic waves obtained in the transducer into material, whereby ultrasonic waves reflect from the eventual discontinuity (porosity, inclusions, shrinkage, cracks…) before returning. To obtain sound wave reflection, it is important that the shape of the imperfection with a major axis is approximately perpendicular to the sound beam axis. This means that the volumetric imperfections (porosity, inclusions) are well detected, regardless of the direction or the sound beam, however, planar flaws (cracks, some type of shrinkage, tears) can only be detected if the sound beam axis is approximately perpendicular to the major shallow flaw. These waves provide an indication on the ultrasonic instrument, so that the operator may conclude that there is an imperfection in the cast product. This allow the dimensional properties, and sometimes the origin, of particular imperfections in the casting volume to then be determined. Thereafter, an assessment can be made of whether or not the imperfections are acceptable based on pre-determined (as per specification) standardised acceptance criteria. The procedures for performing ultrasonic testing must follow standards, such as the EN 12680 series, various ASTMs and ASMEs. The standardised acceptance criteria are defined as various levels to permit more or less imperfections. The level of acceptance is usually selected based on the design requirements and service conditions. [10]

Radiographic testing (RT) is based on the attenuation of radiation energy while travelling through the material being tested. A radiation source (X-ray tube or gamma ray source) is required together with a detector to catch the differences in the radiation energy coming out of the material on the opposite side. The larger the eventual imperfection in the material, the higher the detected level of energy intensity. Therefore, imperfections can be identified based on different densities of the film. The procedures for performing RT are standardised approaches, usually according to EN ISO 5579 or ASTM E94. These standards prescribe all the measures, parameters, equipment and settings to get a film image of a proper quality level in order to be ready for evaluation of any eventual imperfections. This includes the selection of proper sources (appropriate radiation energy), films, lead screens, based on material type and thickness, selection of appropriate distances from the source to the test object to achieve correct image sharpness, requirements for image quality indicators to prove that the image on film has achieved the required quality level, film density requirements, film processing requirements, etc. There is a slight difference between the requirements of EN ISO 5579 and ASTM E94 in terms of how they determine radiation energy selection, image quality indicator type and selection and determination of the sharpness [10].

Other standards related to RT are those for assessing and evaluating the imperfection of radiographic films following exposure and processing; these are ASTM E446, E186, E280 and E689. The listed ASTM standards provide rules/guidelines for evaluation of imperfection indications in castings detected on films. They also contain the reference radiographs at a 1:1 scale for comparison during the evaluation of the films. Evaluation of imperfections in cast products is based on a comparison between the actual film and the reference radiograph from the ASTMs. E446 relates to steel castings of a wall thickness up to 2'' (51mm). There are three different volumes depending on the energy applied during exposure of the E446: Volume I: medium voltage (250kV x-ray), Volume II: 1MV x-ray or iridium-192 radiation, and Volume III: 2MV to 4MV rays and Cobalt-60 radiation. Reference radiographs of the correct volume must be selected while performing a particular evaluation based on the actual energy source used. Examples of a reference radiograph from ASTM E446 Volume I may be seen in the attached document (note: the document is not for official use). Similar radiographs are also included in ASTM E186, which covers castings with a wall thickness from 2'' up to 4.5'', and E280, which covers a wall thickness from 4.5'' to 12''. ASTM E689 is used for ductile iron castings (spheroidal graphite cast iron). This ASTM does not have specific reference radiographs but refers to the aforementioned reference radiographs for steel – ASTM E446, E186, E280. [10]

Whenever an evaluation is performed, e.g. according to E446, it is first necessary to recognise the type of defect; either it is porosity – Category A, or it is slag/sand inclusion – Category B, or it is shrinkage – Category C, etc. The second step is to determine the severity level for each particular category, if applicable. Level 1 is less severe whereas level 5 is the most severe – see Figure 2, Figure 3 and Figure 4, below.

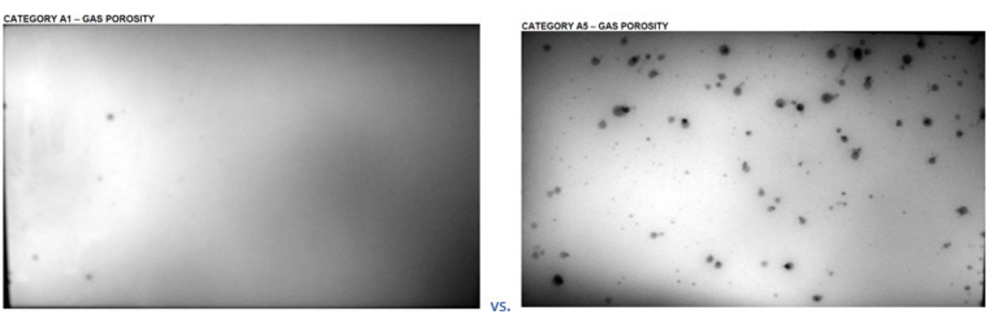


Figure 2: *Interpretation of the results using x-ray inspection [10]*

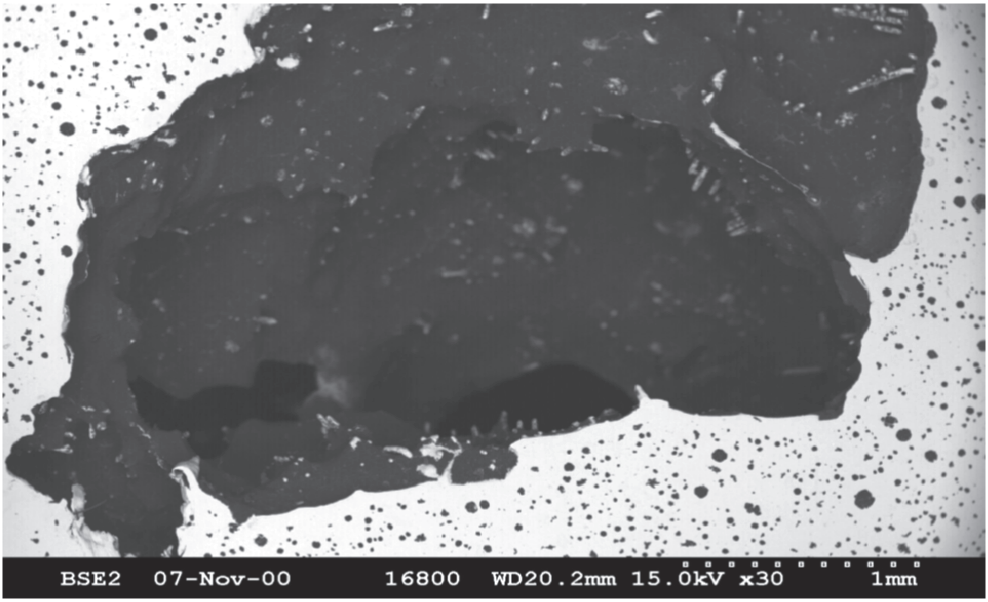


Figure 3: *Hydrogen gas porosity [9]*

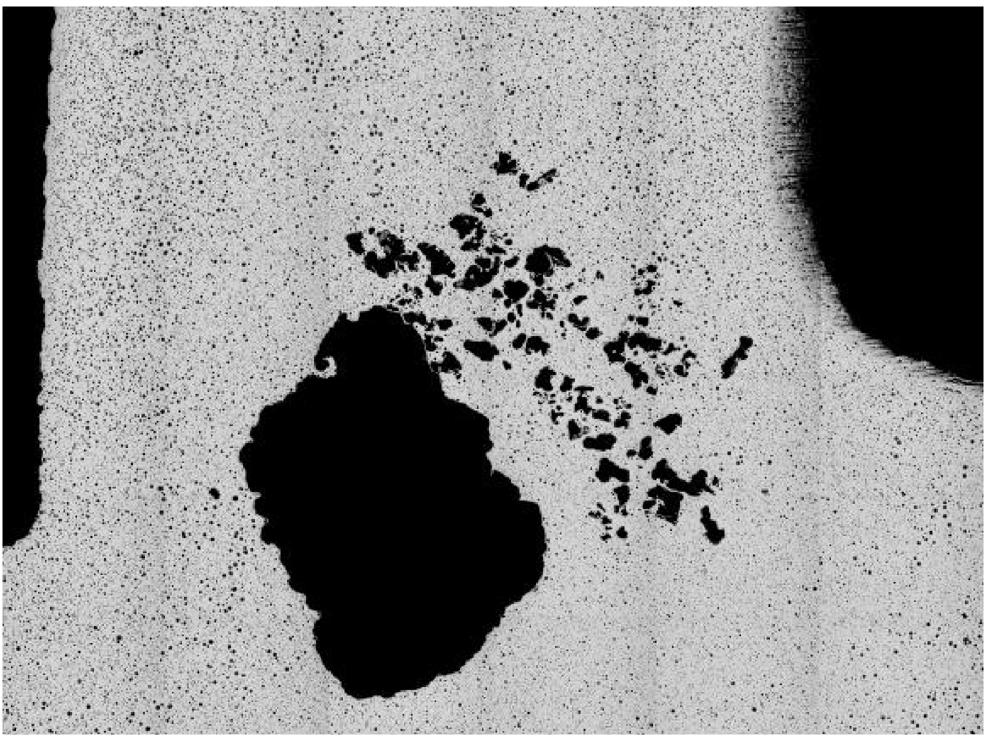


Figure 4: *Shrinkage porosity [9]*

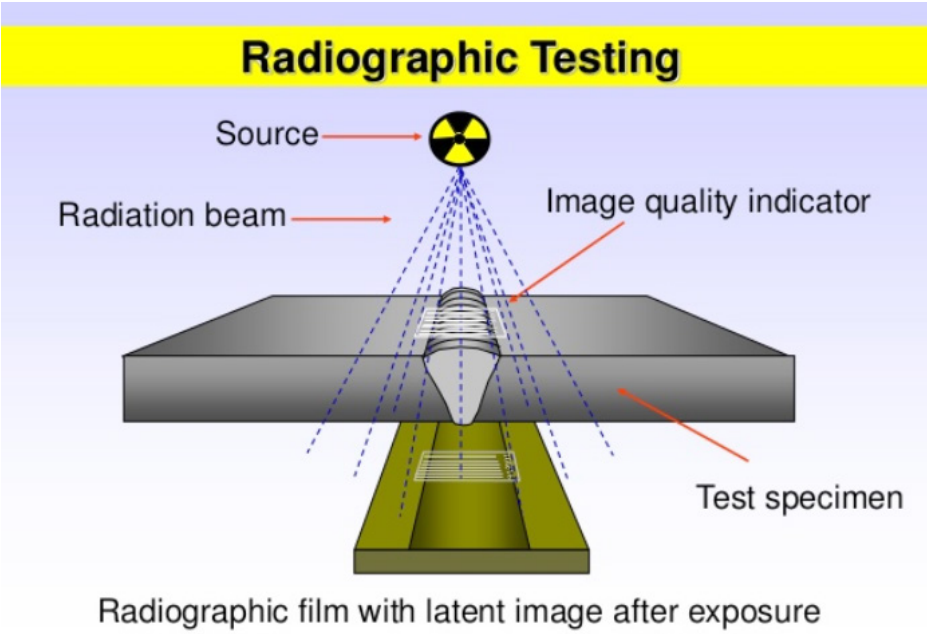


Figure 5: *Schematic illustration of x-ray inspection method [1]*

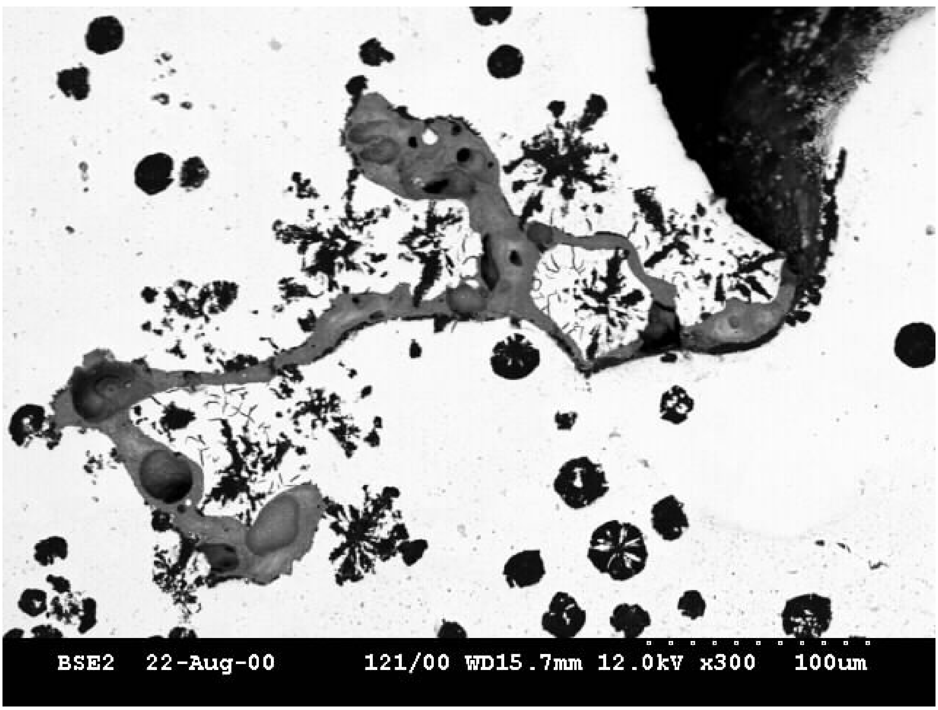


Figure 6: *Slag inclusion defects [9]*

Figure 7: *Visible porosity on machined surface [9]*

Slag inclusions resulted from incorrect discipline in the removal of slag from the ladle in foundry production, emptying of the ladle during procedures, improper improvements in the process of pouring and shaping of the casting system that reduce the use of filter or a slag trap, or a reduction in Mg content additives. Figure 6 shows an example of typical porosity or slag inclusions which are not allowed for critical components in the railway industry. There are high quality criteria for the safety component, which mean that this kind of component is present as scrap material.

2 EXPERIMENTAL PROCEDURE

The critical safety component of the brake holder was selected as the research subject for this paper. This is the most critical mechanical component in the railway industry, which was made at the casting production foundry in Ivančna Gorica for the final customer Knorr Bremse. The name of the product is KozolenBoltzen and it holds together the entire set of train brakes. The normal price of the product is around EUR 40 per raw part and EUR 25 for the machining price.

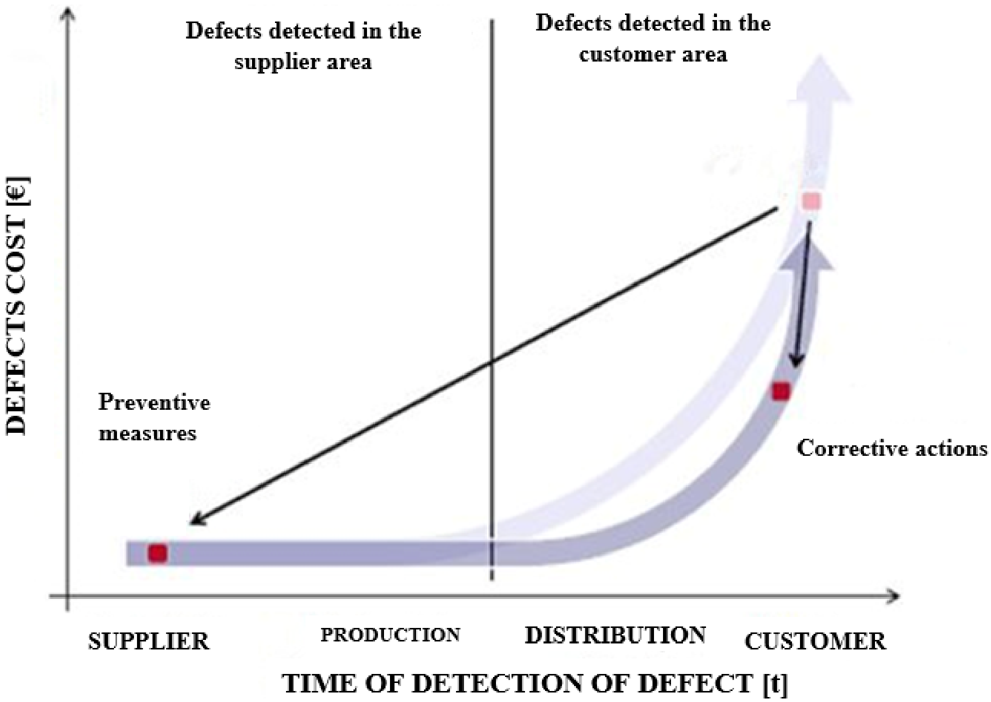


Figure 8: *Management cost of defect in OEM supply chain [9]*

For correct investigation of the basic example the sample must be captured in the correct way and at a precise interval. If the sample is too small, a realistic picture of the process cannot be obtained, and if the sample is too large it can lead to high costs. A large volume of samples provides information about irregularities in the process more quickly, however, this takes time. Data collection can take place for each product in the series and can be done once per shift or even once a day. However, it all depends on the importance of the characteristic. The sampling frequency of the sample data must also be specified. For the sampling frequency, it is necessary to determine whether the sampling will take place over a long time interval with more samples or over a short time interval with a smaller number of samples. As a rule, several small samples representing the whole population are taken in large batches.

There is a lot of low-hanging fruit ready to pick in most industrial sectors in terms of reducing energy consumption in manufacturing processes, such as newer and more efficient equipment, insulation on buildings, the use of LEDs, more effective logistics, etc. However, so much metal needs to be heated for the casting industry that this low-hanging fruit barely affects absolute energy consumption.

In addition, anyone can grab this low-hanging fruit, while addressing internal defects on casting is much harder than switching off a monitor left on standby, requiring years of engineering education in metallurgy, years of experience and a good brainstorming team.

The reduction of defective parts is the most effective measure to reduce energy consumption but also the most challenging to address. [5-8]

The Original Equipment Manufacturing (OEM) supply chain has changed dramatically since the 1970s, when automotive manufacturers and other large OEMs closed their own core processes and became massive outsourcing and offshoring labour-intensive casting and machining processes.

There were advantages to this new paradigm, as it allowed the optimisation of processes, the development of a new ecosystem of specialised supply chains and niche companies, a reduction in waste, faster R&D and lower costs.

There are, however, some downsides [5-7], particularly an increase in the carbon footprint of transporting parts and even worse, dealing with non-conformant products became a challenge. The machining site is no longer within minutes of the foundry, where casted parts with porosity could simply be recast and replaced by a new casting. There were no accounts of KPIs and PPMs in the middle of last century, only the memory of engineers who have since retired [4-5].

While since the 19th and 20th century foundries had been located in a building or were just minutes and metres away from the machining sites of shipyards, rail and later automotive facilities. Of late, however, offshoring means they have been moved further away – often days and hundreds or thousands of kilometres [3].

Dealing with rejects on casting has thus become a slow and time-consuming activity, ranging from being a nuisance to being problematic. One of the root causes of the increase in casting defects relates to the distance from design to casting, as 'Design for Manufacturing' needs good know-how and communication with the supplier, which is often not the case.

On the quality side, the ISO 9000 quality management standard was established in 1987 with guidelines intended to increase business efficiency and customer satisfaction. Due to the new requirement for quality assurance in the automotive sector, QS 9000 was established in 1992, led by Ford, General Motors and Chrysler in the US [8].

Other sectors followed the automotive trend of offshoring and requiring specific quality systems. The second wave was aerospace and in 1998, US aerospace contractors established AS 9000 based on ISO 9000. For the third wave, Europe created the International Rail Industry Standards (IRIS) in 2005 [1-3],[7].

These waves correlate with some major changes in the casting sector landscape. Increasing quality demands and a reduction in business volume hit the automotive sector. Many components were converted to other lighter materials and numerous foundries shut down due to higher volume and more efficient automation (horizontal) [2].

The reduction of time from concept to serial and increased product customisation presents another challenge for foundries by creating a 'high mix, low volume' of parts. Lower quantities of batches also challenge casting optimisation [2-3] as well as distant 'Design for Manufacturing', smaller batches and the technical challenges of detecting internal porosity. This becomes more necessary for critical safety components and difficult when even x-ray inspection is ineffective [1].

In recent years, many successful companies have been investing in reducing energy consumption and carbon footprint in all primary and secondary product manufacturing processes. Every step counts, since energy consumption can be drastically reduced by using proper planning process inspection methods in the casting industry [3-4].

Successful and leading corporations around the world are joining the EcoVadis tool programme, thanks to its unified and standardised networking and comparison and introduction of good practice across organisations. The EcoVadis methodology for assessing a company's sustainability management systems is based on international standards such as the Global Reporting Index (GRI), ISO 26000 and the guiding principles of the Global Compact [1],[6].

3 ANALYSIS OF RESULTS

3.1 Alignment of a decrease defects on raw surfaces in the casting industry

The first thing to be aware of is that this is a critical safety part for trains, which means that defects are not permitted. Each foundry aims to produce products of the highest quality, however, there are always some defects, therefore it is necessary to create procedures for handling them correctly prior to sending them for X-ray inspection to ensure proper selection is made and additional money and capacity are not wasted on the supplier side. The most important process control in production is to decrease the scrap rate on raw surfaces.

Figure 9: *3D model of a KozolenBoltzen bracket pin sample part [9]*

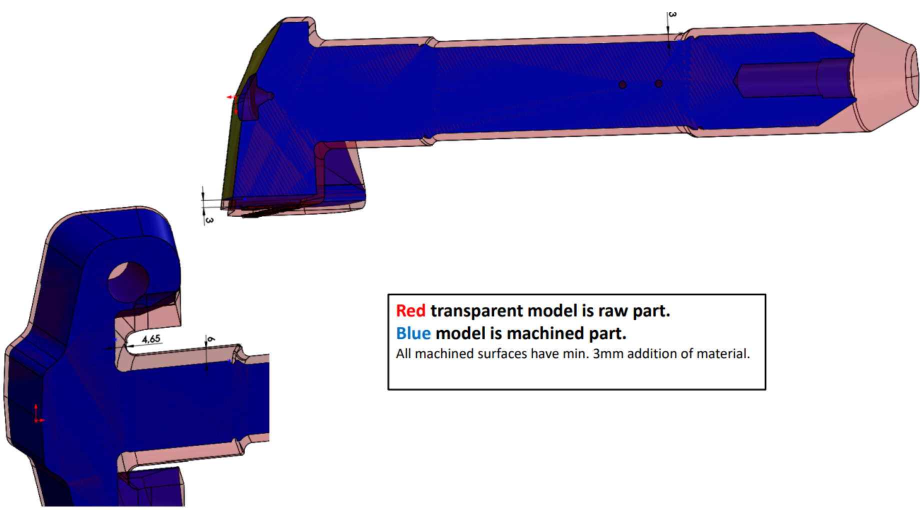


Figure 10: *A cross section of a 3D model of a raw and machined part [9]*

SCRATA surface comparators are used to classify the surface discontinuities for steel and iron castings. To date, the scrap discontinuities have been based on levels VC1 and VC2.

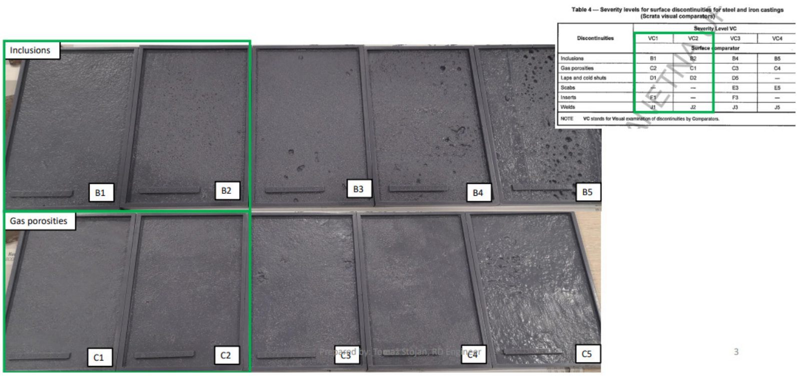


Figure 11: *SCRATA plates Standard SIST EN 1370 [9].*

Figure 12: *Defects on machining surface [9]*

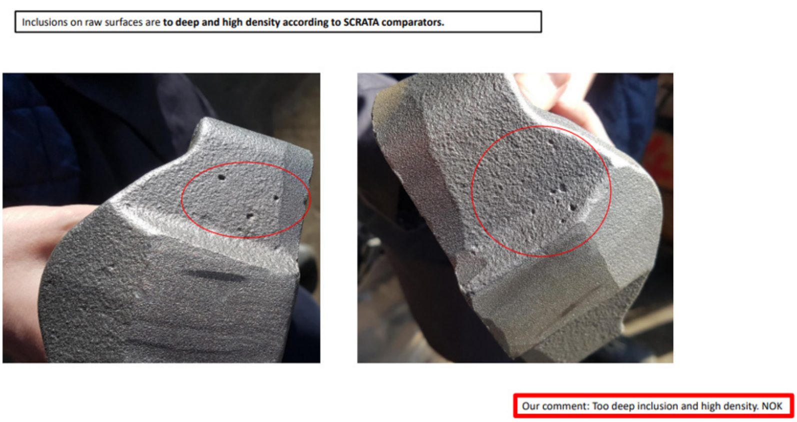


Figure 13: *Defects on the machining surface [9]*

3.2 X-ray inspection detection of the hidden defect

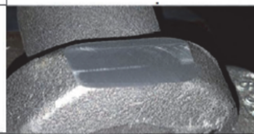
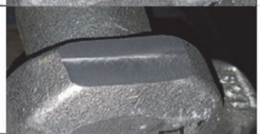
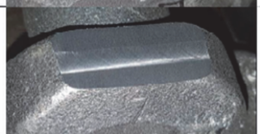
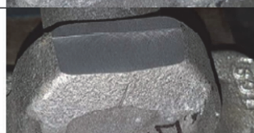
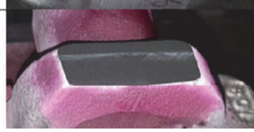
Depth [mm]	Machined surface	Penetrated surface	Surface condition
4			without indications
5			without indications
5,5			without indications
6			without indications
6,5			without indications
7			without indications

Figure 14: *Cutting inspection method using liquid penetrant P2 part with hidden defects [9]*

Pictures below show where casting was sectioned. All sections were without indications.

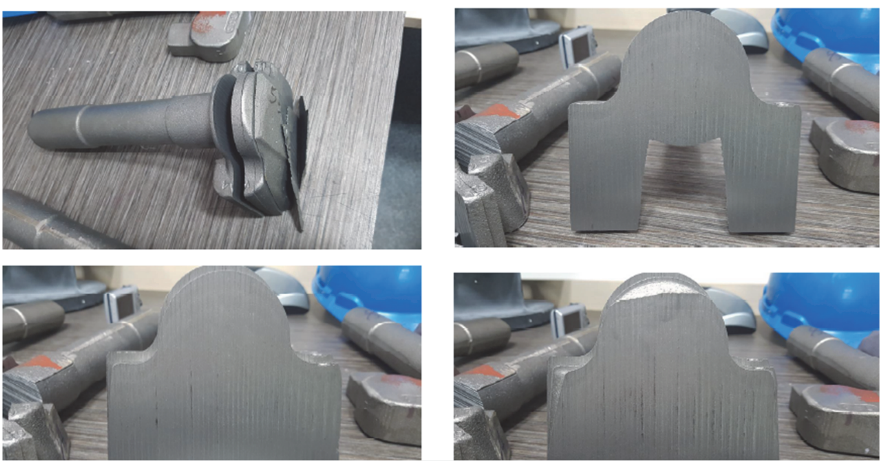


Figure 15: *Cutting P10 inspection method part [9]*

4 CONCLUSIONS

To avoid defects in grey cast iron with spherical graphite it is necessary to:

- Use secondary raw materials that are of good quality and have low contents of accompanying elements (Mn, S, V, Mo, Ti, Cr…) and/or actively control the state of the melt.
- Have a stable melting and processing process of nodulation and grafting, resulting in repeatable analysis and good temperature efficiency.
- Use a high quality nodulator of an appropriate composition and granulation. Use quality vaccines that are specific to the requirements of the cast iron.

References

[1] Engineering choice. Available: https://www.engineeringchoice.com/radiography-testing/ (31.03.2022)

[2] **L. Magnusson Aberg, C. Hartung, J. Lacaze:** *Trace elements and the control limits in ductile iron*, 10th International Symposium on the Science and Processing of Cast Iron – SPCI10, Argentina, Mar del Plata, 2014

[3] **J. Zhou**: *Colour Metallography of Cast Iron*, Spheroidal graphite Cast Iron–Part I, China Foundry, 2010

[4] **] R. Elliott:** *Cast Iron Technology,* Butterworths, London, 1988

[5] **V. Anjos:** *Use of Thermal Analysis to Control the Solidification Morphology of Nodular Cast Irons and Reduce Feeding Needs*, doktorska disertacija, Lisbon, Portugal, 2015

[6] Ecovadis. Available: https://support.ecovadis.com/hc/en-us/articles/115002653188-What-is-the-EcoVadis-assessment-process (01.04.2022)

[7] **S. F. Fischer, A. Bührig-Polaczek, J. Brachmann, P. Weiβ:** *Influence of nickel and cobalt on microstructure of silicon solution strengthened ductile iron*, Materials Science and Technology,31 Nemčija, 2015

[8] **C. H. Hsu, M. L. Chen and C. J. Hu:** Microstructure and mechanical properties of 4% cobalt and nickel alloyed ductile irons, Materials Science and Engineering A 444

[9] **T. Pavlin**: Internal investigation R&D dept. in melt area Livar d.d,. 2021

[10] American national standard EE446-98 reference radiographs for steel castings, USA, 2018

Nomenclature

(Symbols)	(Symbol meaning)
t	Time
X-ray	Radiographic testing inspection
GRI	Global Reporting Index
OEM	Original equipment manufacturer
VT	Visual testing
PT	Liquid penetrant testing
RT	Radiographic testing
NDT	Non-destructive testing
UT	Ultrasonic method