www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES of FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2022
Issue 1/2022

13 – 17

10.24425/afe.2022.140211

2/1

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Flaw Detection of Cast-Steel Safety Parts in Automotive Application

K.C. Dizdar [a], H. Sahin [a], M. Ardicli [b], D. Dispinar [c, *]
[a] Istanbul Technical University, Turkey
[b] Bosch Powertrain Solutions, Bursa, Turkey
[c] Foseco Non-Ferrous Metal Treatment, Netherlands
* Corresponding author. E-mail address: derya.dispinar@gmail.com

Received 16.08.2021; accepted in revised form 25.10.2021; available online 20.01.2022

Abstract

Casting is the most economical way of producing parts for many industries ranging from automotive, aerospace to construction towards small appliances in many shares. One of the challenges is the achievement of defect-free cast parts. There are many ways to do this which starts with calculation and design of proper runner system with correct size and number of feeders. The first rule suggests starting with clean melt. Yet, rejected parts can still be found. Although depending on the requirement from the parts, some defects can be tolerated, but in critical applications, it is crucial that no defect should exist that would deteriorate the performance of the part. Several methods exist on the foundry floor to detect these defects. Functional safety criteria, for example, are a must for today's automotive industry. These are not compromised under any circumstances. In this study, based on the D-FMEA (Design Failure Mode and Effect Analysis) study of a functional safety criterion against fuel leakage, one 1.4308 cast steel function block, which brazed-on fuel rail port in fuel injection unit, was investigated. Porosity, buckling, inclusion and detection for leak were carried out by non-destructive test (NDT) methods. It was found that the best practice was the CT-Scan (Computed Tomography) for such applications.

Keywords: NDT, Cast steel, CT, Porosity, Leakage

1. Introduction

Casting is one of the economic ways of producing a mass number of parts. The process involves pouring the liquid alloy into a mould cavity and letting it solidify. During solidification, due to the density difference between the liquid and the solid, the alloy shows a volumetric change which may lead to a defect known as shrinkage porosity [1]. This can be eliminated by using feeders. Yet, the alloy solidification rate may vary depending on the part geometry. Hence, the feedability becomes the key parameter. If not properly designed, the casting starts to suffer from porosity. In this case, the part is rejected and thus, a significant economic impact occurs [2]. Typically, porosity is considered as the major factor for rejection of parts; and it is classified as shrinkage or gas porosity. While shrinkage occurs due to inefficient feeding, gas porosity occurs as a result of dissolved gas in the liquid state. On the other hand, during the casting operations, a certain amount of charge is melted in a crucible and the number of moulds is prepared in accordance with the weight of the material that can be cast. Thus, the casting is a sequential operation where number of parts are produced within minutes. Nevertheless, the porosity type, size and location typically appear randomly. It may show a variance from cast to cast. This is mainly due to the design of runners and the quality of the initial melt cleanliness. The defects known as bifilms are reported to be the main cause of porosity formation [3].

As stated above, the nature of casting tends to create several types of defects. However, casted steel is widely used in automotive applications due to its high toughness and ductility, as well as its low carbon content. Ducker states this fact and reported the rate of cast steel usage per vehicle in the automotive sector between 2015 and 2025, and it was predicted that the usage rate, which was 8% in 2015, will remain the same in 2025 [4]. Therefore, reaching low degrees of ppm (part per million) during the casting process plays a key role in automotive applications.

In today's technology, cast steels are inspected as destructive or non-destructive methods. As destructive methods are out of our scope, only two types of non-destructive tests that serve different purposes can be applied to such casted materials:

1. Flaw detection of cracks, porosity and shrinkage type defects arising from the nature of the casting [5-7]
2. Microstructural examination for graphite distribution of the material, strength, hardness and elasticity, etc. to measure the characteristics [8-10]

Some of the typical applications of non-destructive tests include UT (Ultrasonic Testing), CT (Computed Tomography), MT (Magnetic Particle Testing), PT (Penetrant Testing) and Eddy current methods. PT is the application of color or fluorescent penetrant to the cleaned surface followed by the developer application. The smallest cracks and imperfections are revealed by this test. MT is applied to the sample with a liquid or powder. Defects are revealed by the alignment of particles in different directions. UT uses a probe that emits sound waves and the reflection is detected. If a defect is present, sound waves return faster than the thickness (another surface). CT is the X-ray application to the part where defects are detected by their location according to their size and type (pore or inclusion).

This paper focuses only on 1st point given in the list to understand the quality of casting and its behavior on safety applications in the automotive industry. To achieve this, the function block (FB) part is subjected to several NDT methods. (Eddy-current, Ultrasonic wave, Magnetic field imaging, Radiography) These will be introduced, and it will be shown whether this part is suitable for analysis with NDT methods. As a result, the most appropriate inspection method will be chosen to be used as non-destructive test in the mass production line.

2. Experimental work

In ICE (internal combustion engine) application highly pressured fuel by pump passes through the product called the fuel port (Figure 1), and it transfers it to the injectors that spray the fuel through the part called the function block (FB).

The dimension of FB part is 20x65x40 mm and produced by casting from 1.4308 stainless steel (Figure 2). Thus, it is suitable for mass production and has an inner structure of ductile behavior to withstand high pressures. This non-magnetic material contains 18-20% chromium and around 10% Nickel in its content. The investment casting method was used to produce the parts. The chemical composition is given in Table 1.

Table 1.
Chemical composition of the alloy sued to produce FB (%wt.)

Cr	Fe	Ni	Mn	Si
17-18	73-74	7-8	< 1	< 1

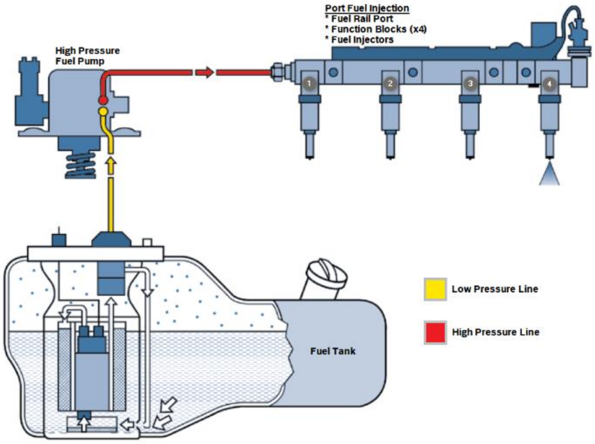


Fig. 1. Fuel pump system

Casting was applied according to DIN EN 1559 standard and thus, FB provides sufficient strength for usage under high pressures.

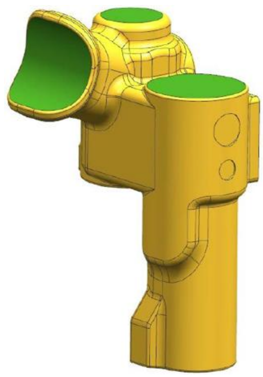


Fig. 2. The geometry of the tested part (20x65x40 mm)

3. Results

Due to the geometrical restrictions, Eddy current and ultrasonic tests were unable to be conducted for this sample and this will be issued later in the Discussion section. As a promising solution X-ray and CT (Computed Tomography) analysis were carried out using YXLON MU-2000 & GE Phoenix v|tome|x s. Due to the part geometry and its wall-thickness, the pore detection job required fine-tuning of some parameters (i.e. power in kV, current in µA, projection time, pixel size and filters), especially for CT machine. For that purpose, high power outputs combined with low current rates in CT and part were examined for 3 hours long to fine detection of the pore. In this way, the deep penetration of beams inside the part was ensured and accordingly tin (Sn) filter was employed during rendering for getting better accurate images from the machine.

As seen in Figure 3, porosity was detected at the joint location where a close-up image is given in Figure 4. A general overview of the sample and location of defects are given in Figures 5-6.

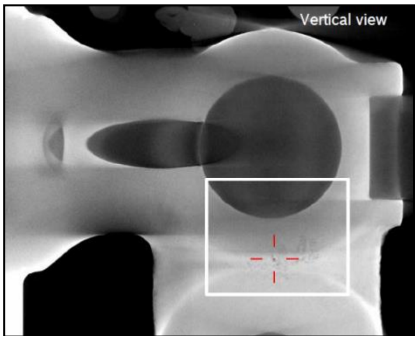


Fig. 3. X-ray images of porosity that is detected in the cast sample

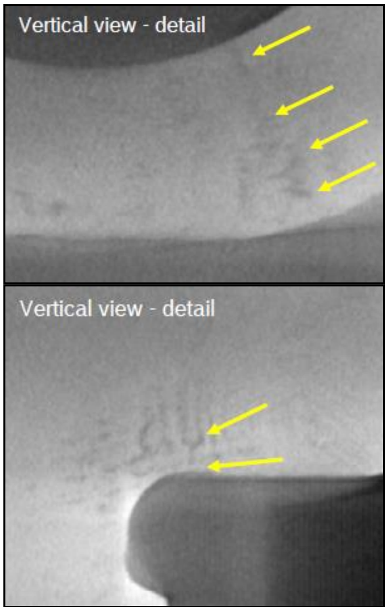


Fig. 4. Close-up X-Ray images of porosity region in Fig 3.

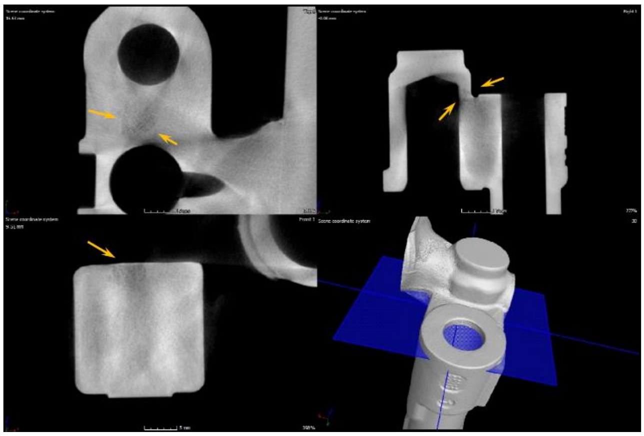


Fig. 5. Observation of porosity on top of the part in the thickest section

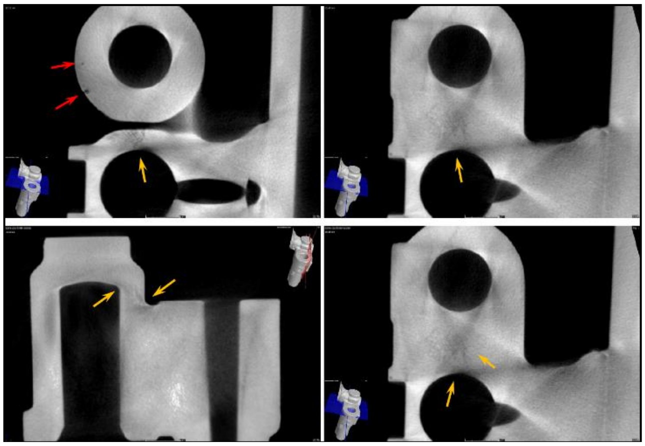
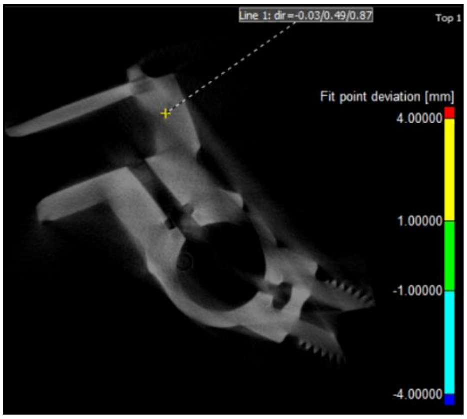
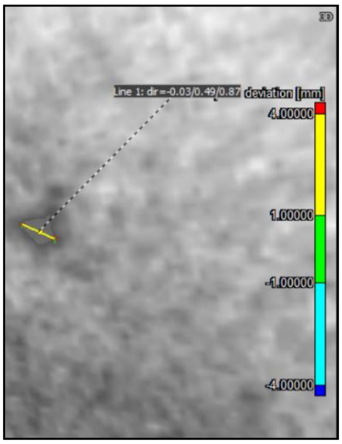


Fig. 6. Detection of two spherical porosity on the edges with sponge type porosity on the second section

As can be seen in Figure 7, slicing and moving across the axis can reveal the shape and size of porosity easily. The ability of the CT to detect internal defects in cast parts provides sufficient information.



a)



b)

Fig. 7. Cross-examination of the porosity

4. Discussion

The problems that may occur in the casting of this part will cause the high-pressure gasoline to leak out of the engine block during the operation of the engine and subsequently cause the vehicle to catch fire. For this reason, this part needs to be examined with high precision. In this context, the applicability of the methods given below to the part and then its integration into mass production will be analyzed.

For the FB part that is subjected to analysis, a first trial was made with the Eddyliner device available in the laboratory with the help of special probes. However, a healthy measurement could not be taken due to the large wall thickness of the piece and the fact that it cannot rotate around its own axis due to its geometry. For the second trial, ultrasonic testing methods were used. Krautkrämer [11] described the best possible test frequency bands for such kinds of cast steel austenitic materials and indicates the relationship between frequency band, damping level of probes and its penetration into the material. Therefore, as advised only around 1 MHz frequency with highly damped probes were applied into FB. However, this combination brings disadvantages like reduced pulse length and reduced wave cycles as well. So, only a low penetration level was achieved in ultrasonic testing and this wasn't sufficient to detect pores of the function block. As a third trial magnetic particle imaging methods were applied to the material. As long as FB is made of non-magnetic material, magnetic particles didn't cling to the surface. Thus, Radiography analysis were carried out for the next evaluation.

X-ray imaging of the volumetric parts is an easy application to assess whether there is porosity or not. However, the location of the pore can tell a different story. In many applications, the presence of porosity may be considered as pass or fail. Actually, the important point is the size and location of porosity. There are parts that consist of critical locations where a certain dimension of porosity can be accepted. Based on the analysis, there could be some areas where no porosity is accepted, on the other hand, there could be some regions where porosity can be accepted to a certain level. In such cases, when 2D X-ray analysis is carried out, the porosity can be observed but its location may vary which may not be known.

Ziolkowski [12] had used X-ray CT method to quantify the amount of porosity in SLM (Selective Laser Melting) produced 316L stainless steel. It was reported that not just the size, but the location of the pores was also determined together with the shape factor of pores which had provided more insights about the characterization of the material. Du Plessis [13] used two different techniques to compare 4 different materials one of which was a stainless-steel blade. It was reported that quick assessment could be made faster using CT Scan.

Kurz [14] used the probability of detection (POD) curves for the detection of specific welding flaws in austenitic and ferritic samples with an NDT method. It was discussed that the use of X-ray computer tomography (CT) would be necessary to detect the flaws in detail because there was a risk of high false flaws that decreases the POD values.

Sika [15] had come up with Open Atlas Defect tool to identify the possible casting defects using acquisition and data mining tools.

5. Conclusions

The size, geometry and complexity of cast parts can result in some of the analysis techniques difficulty in applications. The volumetric analysis using CT Scan reveals the volumetric porosity in detail which allows the shape and distribution of pores. This non-destructive method using porosity analysis provides solid information about the internal defects that can be observed in cast materials. This method provides useful data that can be obtained in a short duration of analysis making this test a good option for detecting defects in short times. This paper presented the adaptation of CT Scan for the detection of porosity in cast steel parts as a quick assessment tool.

References

[1] Stefanescu, D.M. (2005). Computer simulation of shrinkage related defects in metal castings–a review. *International Journal of Cast Metals Research.* 18(3), 129-143.

[2] Kweon, E.S., Roh, D.H., Kim, S.B. & Stefanescu, D.M. (2020). Computational modeling of shrinkage porosity formation in spheroidal graphite iron: a proof of concept and experimental validation. *International Journal of Metalcasting.* 14, 601-609.

[3] Campbell, J. (2015). *Complete casting handbook: metal casting processes, metallurgy, techniques and design*. Butterworth-Heinemann.

[4] Duckers, (2015). AISI Materials Content Analysis: Final Report.

[5] Meola, C., Squillace, A., Minutolo, F.M.C. & Morace, R.E. (2004). Analysis of stainless steel welded joints: a comparison between destructive and non-destructive techniques. *Journal of Materials Processing Technology.* 155, 1893-1899.

[6] Menzies I. & Koshy, P. (2009). In-process detection of surface porosity in machined castings. *International Journal of Machine Tools and Manufacture.* 49(6), 530-535.

[7] Ushakov, V.M., Davydov, D.M. & Domozhirov, L.I. (2011). Detection and measurement of surface cracks by the ultrasonic method for evaluating fatigue failure of metals. *Russian Journal of Nondestructive Testing.* 47(9), 631-641.

[8] Vazdirvanidis, A., Pantazopoulos, G. & Louvaris, A. (2009). Failure analysis of a hardened and tempered structural steel (42CrMo4) bar for automotive applications. *Engineering Failure Analysis.* 16(4), 1033-1038.

[9] Gupta, R.K., Ramkumar, P. & Ghosh, B.R. (2006). Investigation of internal cracks in aluminium alloy AA7075 forging. *Engineering Failure Analysis.* 13(1), 1-8.

[10] Smokvina Hanza S. & Dabo, D. (2017). Characterization of cast iron using ultrasonic testing, *HDKBR INFO Mag.* 7(1), 3-7.

[11] Krautkrämer, J. & Krautkrämer, H. (1990). Ultrasonic Testing of Materials" Springer-Verlag.

[12] Ziółkowski, G., Chlebus, E., Szymczyk, P. & Kurzac, J. (2014). Application of X-ray CT method for discontinuity and porosity detection in 316L stainless steel parts produced with SLM technology. *Archives of Civil and Mechanical Engineering.* 14(4), 608-614.

[13] A. du Plessis, A., le Roux, S.G. & Guelpa, A. (2016). Comparison of medical and industrial X-ray computed tomography for non-destructive testing. *Case Studies in Nondestructive Testing and Evaluation.* 6(A), 17-25.

[14] Kurz, J.H., Jüngert, A., Dugan, S., Dobmann, G. & Boller, C. (2013). Reliability considerations of NDT by probability of detection (POD) determination using ultrasound phased array. *Engineering Failure Analysis.* 35, 609-617.

[15] Sika, R., Rogalewicz, M., Kroma, A. & Ignaszak, Z. (2020). Open atlas of defects as a supporting knowledge base for cast iron defects analysis. *Archives of Foundry Engineering.* 20(1), 55-60.