Chapter

Root Cause Failure Analysis of Castings: A Case Study of a Brake Rotor

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Abstract

A premature failure of a vehicle brake rotor was investigated and reported. The brake rotor was manufactured from a grey cast iron material and had covered about 10 670 miles before it failed. The failure-generated tremendous concern for the autoparts manufacturer due to the warranty claims from the Original Equipment Manufacturer (OEM). This chapter, however, intends to describe the methodical approach used to identify the failure's main cause using a root cause failure analysis technique and offer suggestions to prevent a similar failure from re-occurring. The results of this investigation showed that the disc's early failure was caused by oxide inclusions that were accidentally entrapped into the disc's neck region. The eventual disc failure was initiated by micro-cracks developed within the inclusion particles and propagated through the weakest interface between flaky graphite and the pearlitic matrix. To ensure that nonmetallic inclusions are kept out of cast components, several solutions for improving casting quality were proposed.

Keywords: failure analysis, gray cast iron, brake rotor, root cause analysis, fractography, nonmetallic inclusions

1. Introduction

A failure occurs when an engineering system, a mechanical component, an engineering material, or a process cannot correctly perform its intended or design function. When a system or component fails, it causes unimaginable disruption of operations and services; sometimes, it attracts or incurs a legal tussle and a stringent warranty claim. On several levels, failure can be described as (i) a loss of function, implying that the component or system works but cannot accomplish the designed function; (ii) a loss of operational life, that is, when the component or system performs its function but is unsafe or unreliable to operate; and (iii) an inoperable, meaning that the system or engineering component is completely unusable [1]. The above definitions categorize the failure of an engineering system, component, material, machine, assembly, or process. However, an engineering system or components can experience a mechanical failure in service due to design insufficiencies, maintenance deficiencies, manufacturing and material imperfections, service abuse and overload, and a hostile service atmosphere [2–4].

Structural and engineering components are generally used to produce automobiles, aircraft, buildings, power generation plants, jet engines, military equipment, manufacturing plants and marine equipment. These components are made from different materials, such as gray cast iron (GCI), steel, aluminum alloys, titanium alloys, etc. Engineering components are typically exposed to various externally applied shear and perpendicular stresses [5]. These engineering components habitually function under changeable amplitude recurrent loadings in service, although they are designed considering the level of static stress or constant amplitude fatigue strength [6]. In many cases, failure of components may lead to fatalities, property loss, degrading of the company image or loss of credibility, and many legal issues; therefore, it is of great concern to the industry [4]. Failure of some engineering components and accessories used in various engineering applications, such as railway wheels, automotive brake discs, engine cylinder heads, crankshafts, foundation bolts, chains and hooks, cranes, conveyors, and excavators, have been studied to establish the root cause of failure [6–14].

An automotive brake rotor is a critical component of a brake system designed to reduce the acceleration of or stop vehicles in motion. The fundamental comprehensive responsibilities of vehicle braking systems are to decrease the car's speed, bring the vehicle to a standstill, prevent spontaneous acceleration during downhill driving, and keep the car stationary when stopped [15, 16]. Automotive brake rotors have been generally produced from GCI material for several decades because of their inherent properties. Besides the automotive, many other industrial sectors, such as wind power, agriculture, machines, and tools, use cast iron parts extensively. Several engineering components of complex geometries and thin sections that require a combination of mechanical and thermal properties to achieve the desired function are commonly produced from cast iron materials. The existence of flaky graphite in their microstructure offers good thermal conductivity, while the pearlitic matrix is usually accountable for its mechanical properties. GCI material has the essential attributes required for the functioning of an automotive disc brake. It is a material of choice for brake rotors due to its excellent friction properties, good thermal conductivity and castability, retain strength at elevated temperatures, relative ease of manufacture and thermal stability with excellent damping capacity [11, 17–19]. However, the significant disadvantages of using GCI brake rotors include high density, susceptibility to corrosion and the propensity to noise and vibration issues. Despite these drawbacks, GCI brake rotors remain the most sought in the automotive industry to manufacture brake discs rotors due to their relatively cheap cost, inherent properties, and well-known production process.

The automotive brake discs are usually produced through a metal casting process technique. A sand mold casting is used to manufacture brake rotors, where four to six brake discs are simultaneously cast in a mold. Cast components may look perfect visually, but occasionally they may contain concealed inadequacies which might not be noticed until the part fails in service. Different factors could influence the failure of an engineering component; these factors may include (i) hidden manufacturing defects/imperfections, (ii) poor design, (iii) the type and size of load the component is exposed to, (iv) inappropriate raw materials, (v) improper repair or maintenance, and (vi) the environmental conditions under which the component served. However, cast components' functionality strongly depends on the soundness of the castings. Cast components are consequently required to be virtually free of imperfections that can impair their quality and lead to early failure of castings, failed machine tools, or poor mechanical properties of cast components. According to the International Committee of Foundry Technical Association, casting defects are classified into seven categories - metallic projections, cavities, discontinuities, defective surfaces, incomplete casting, incorrect dimension, and inclusions or structural anomalies [20]. The operation of the foundry process is a complex multi-step process with varying technical levels. Therefore, the final quality of the cast products can be influenced by the operator's skills, defective pattern design, improper metal melting, adopted quality management system and equipment, defective molding material, incorrect quality of raw materials used, improper mold venting, casting processing problems, and improper service condition and maintenance of the available equipment. If the defects in cast products are not effectively inspected, it will impair the quality of the manufactured products and hence lead to unsatisfied customers due to a faulty product. Generally, the most severe defects that can serve as stress raisers or crack promoters in cast components include pre-existing cracks, internal voids, and nonmetallic inclusions.

Casting inclusions defects can be defined as nonmetallic and occasionally intermetallic phases embedded in a metallic matrix. They are frequently simple oxides, sulfides, nitrides, or their complex compounds in ferrous alloys and can include intermetallic phases in nonferrous alloys. In almost all instances of metal casting, they are considered detrimental to the cast component's performance [11, 21]. Casting inclusions are subsurface defects, which may sometimes be detected during the machining operations or even, in many cases, remains undetected until the component fails in service. Nonmetallic inclusions can adversely influence the mechanical properties of castings because they act as a stress raiser. Some mechanical properties are more sensitive to inclusions than others; for instance, elongation or reduction in area is very sensitive to the presence of inclusions and generally adjusted more significantly than ultimate tensile strength. Therefore, cast products use ductility specifications as standard quality-control indices. Inclusions defects have different chemical roots and negatively influence the cast products' mechanical properties, such as machinability, corrosion resistance, fracture toughness, and formability. Inclusions are classified into indigenous or exogenous, depending on their source [11, 21]. The inclusions derived from external sources, such as slag, dross, ladle lining, eroded and entrapped mold and refractories materials, are classified as exogenous; at the same time, those that are native, innate, or inherent in the molten metal treatment process are known as indigenous inclusions. Exogenous inclusions are also derived from ferroalloys, flux materials, and other starting materials that do not float to the surface of the liquid metal or dissolve in it [22]. Sometimes, exogenous inclusions are visible to the naked eye at the casting surface. They may be seen beneath the peripheral casting surface when the casting is sectioned if they have had insufficient time to float out or settle due to density differences concerning the molten metal. Indigenous inclusions, however, are of micro size and can easily be identified under the microscope, and they are frequently distributed uniformly within the casting's microstructure. These inclusions are the products of the liquid melt reactions with deoxidizers such as silicon, manganese, and aluminum particles or during desulphurization, leaving some residual oxide inclusions in the casting. The distribution of indigenous inclusions in a grain boundary in the microstructure of the cast components can severely impair their mechanical properties [21] and reduce the components' service life.

To unravel how a cast product failed correctly, the failure analysis techniques adopted for the castings must include a systematic understanding of how the component was made and processed. However, the scope of the failure examination depends on the problem's definition. Still, in all failure analyses, the understanding of the reasons (how and why) for a casting failure can only be determined if the pertinent background information is collected, thorough examinations are conducted, representative castings are inspected, the proper material assessments are accomplished, and the service conditions to which the cast components are subjected to are undoubtedly understood [23]. The brake rotor under investigation was newly manufactured and installed in a brand-new car. The rotor had been in service for about one year and three months and covered 10,670 miles before its failure. However, under normal circumstances, a quality set of automotive brake rotors should have an average life expectancy ranging from 30,000 to 70,000 miles traveled, which depends primarily on the size of the vehicle, the way it is driven, and the quality of the brakes (including pads and discs) [11]. The above information suggests the rotor had failed prematurely in service. There are several reasons for undertaking a comprehensive understanding of why and how a cast product failed prematurely. The reasons may include – i) evaluating the effectiveness of an in-process quality-control system, ii) assessing the efficiency of the installation or assembly plant where the part was assembled, iii) improving product design and manufacturing processes; iv) preventing similar problems with identical components, v) absolving a company of liability, and vi) determining and understanding the cause(s) of a failure to resolve financial warranty claims where applicable [23–25].

A failure analysis investigation generally involves collecting and analyzing failure information, identifying the root causes, improving product design, ensuring product compliance and assessing the liability of product failure. Besides, the data collected from the failure analysis can improve component design, regulate maintenance plans, improve maintenance processes where necessary, and improve asset reliability. However, this chapter describes the practical application of root cause analysis in automotive brake rotor failure, details the step-by-step approach to unraveling failure root cause, documents the inspection and characterization of the failed brake rotor, and provides recommendations to avert the recurrence of such a failure in the future.

2. Practical application of root cause failure analysis in brake rotor failure

Nowadays, automakers and automotive part manufacturers are under intense pressure to avoid warranty claims/costs and litigation by elevating the quality of their products to ensure safe operation. The component that fails earlier than expected usually attracts financial liability and challenges the manufacturers to scrutinize the root cause(s) of failure to evade future recurrences. However, in some cases, if the cause of the damage cannot be recognized and resolved, it increases the service and warranty costs until the appropriate solution is accomplished.

A failure is when a component or machine cannot satisfactorily perform its intended functions correctly. A metallurgical failure analysis technique is usually adopted for determining the next step to resolving the problem. Failure analysis is a systematic, methodical process to determine the physical causes of failures. Sometimes, the failure analysis process can be complex, draws upon many different technical disciplines, and employs various observation, inspection, and laboratory techniques [25]. Performing a failure analysis is tedious and complex, and it does not necessarily conclude when the physical causes of the failure are recognized.

Consequently, a well-organized, comprehensive, and straightforward way of resolving failure analysis problems is required to achieve enhanced product quality and failure prevention. A reasonable failure analysis approach first requires a clear understanding of the problem definition and the distinction between an indicator, a cause, a failure mechanism, and a consequence [25]. However, a complete understanding of the conditions associated with the failure would enhance the knowledge of its causes and significantly improve the ability to specify appropriate corrective measures.

The root cause failure analysis (RCFA) procedure is commonly used to discover more profound contributors to failures, such as human and hidden root causes. RCFA is a process for identifying the actual root cause of a particular failure and applying the information to set a pathway for corrective and/or preventive measures. RCFA, in combination with physical analysis, are essential steps in the general problem-solving process and are vital constituents for amending and preventing failures, achieving higher levels of quality and reliability, and ultimately enhancing customer satisfaction [25].

In solving failure or quality-related problems, it is better to visually structure the information relating to the problem because it can sometimes be challenging to see how different aspects of the issue interact. The fishbone diagram is an applicable technique for visualizing causal factors and their effect on the quality or failure of a product. This diagram is also known as the cause-and-effect diagram (**Figure 1**). The chart is a visual method for root cause analysis that organizes cause-and-effect relationships into categories [26]. The idea behind this diagram is that several factors may be responsible for the poor quality or failure of a product/component, which is hidden but can be categorized and viewed clearly from the chart. This diagram has been employed by aerospace, information technology, and medical industries for process and product quality improvement. Cause-and-effect graphs allow the visualization and organization of potential causes of a problem into an applicable framework for solving it. The charts are also helpful for incorporating cross-functional influences.

The damaged rotor in this investigation was produced by sand casting, machined to the specified dimensions, and installed in a new vehicle. The rotor had operated for approximately fifteen (15) months and covered 10,670 miles before it failed. However, the potential causal factors that possibly led to the failure of the rotor are classified and identified, as illustrated in **Figure 1**. The "fish" head represents the

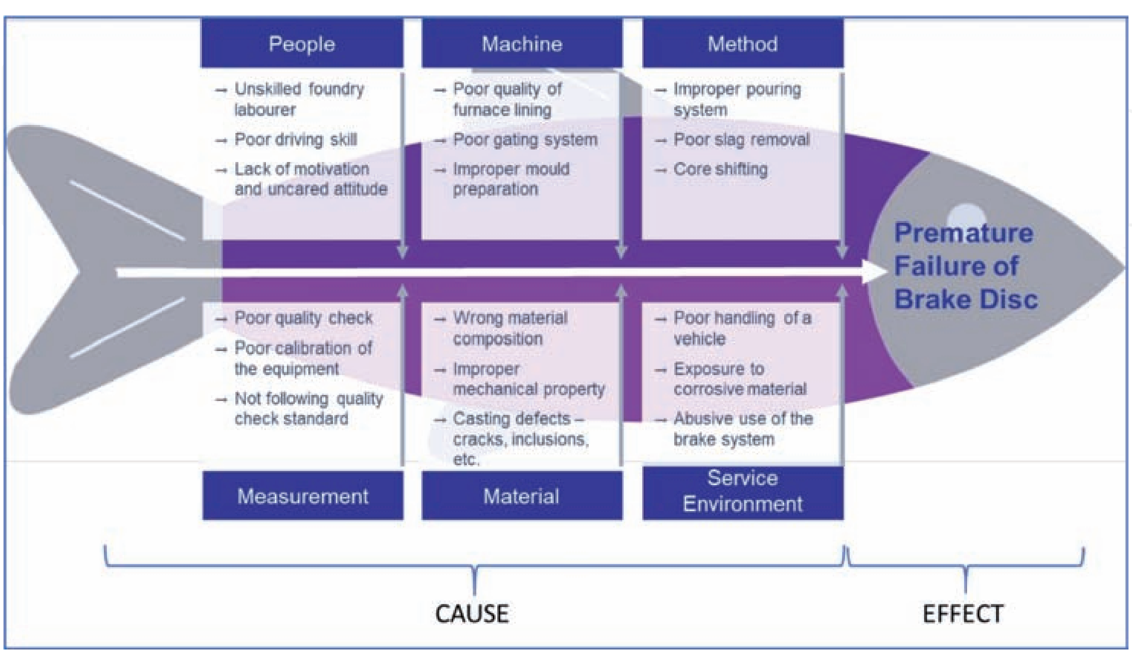

Figure 1.
Fishbone diagram illustrating the potential causes of brake rotor failure.

problem to be studied, and each critical branch denotes a specific functional area. Based on the information presented in **Figure 1**, the failure root cause analysis was begun by critically evaluating each operational unit of the diagram. The background information provided at the beginning of the investigation assisted in eliminating the need to investigate the other branches further. The root cause investigation was focused on the manufacturing process and the application of the brake rotor.

However, in this investigation, a systematic approach of root-cause failure analysis was undertaken to understand the factors contributing to the brake rotor's failure. In addition, this chapter presents some recommendations that will improve the quality of automotive brake rotors during manufacturing and inspection and prevent future failure reoccurrence.

3. Methodology

Firstly, the "as-received" failed GCI brake rotor (**Figure 2a** and **b**) was critically inspected to observe any abnormalities or predominant features on the disc before samples were extracted from it. The rotor was cautiously handled to avoid further

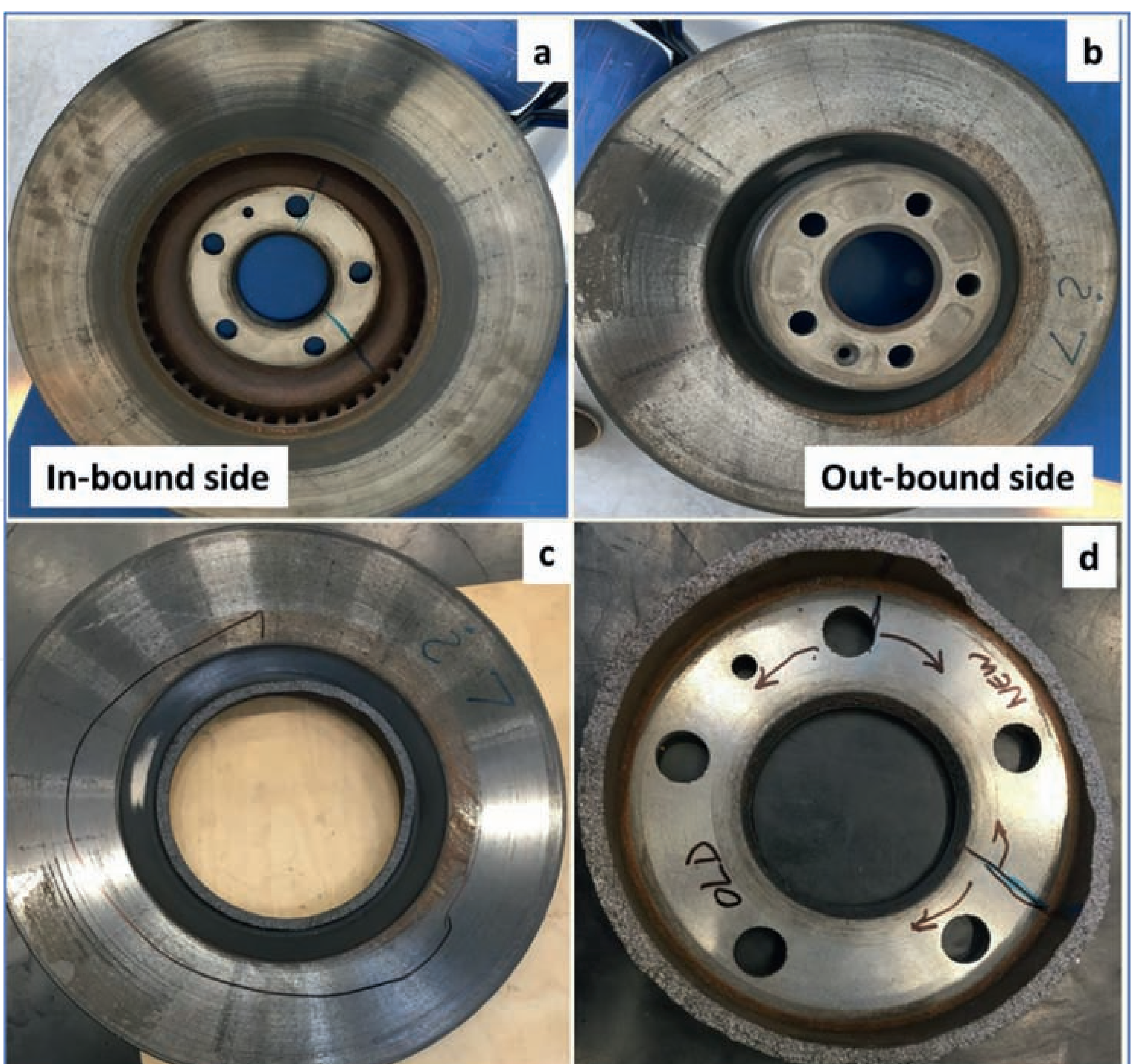

Figure 2.
The as-received brake rotor (a) in-board (b) out-board sides of the disc, and (c) and (d) represent the split rotor.

damage to the cracked surface throughout the investigation. To inspect the fracture surface, the as-received rotor was cautiously divided into two (**Figure 2c** and **d**) along the fracture line. The broken surface was critically examined to identify abnormalities and the origin of the fracture. Visual inspection was done using a stereo microscope (SZ-CTV Olympus, Japan). Samples for chemical composition and microstructure analyses were obtained from the swan-neck region of the as-received rotor using a spark optical emission spectrometer (OES) and scanning electron microscope, respectively. The rotor swan neck thickness was determined using a TI-007X Precision Ultrasonic Wall Thickness Gauge.

The metallographic samples were extracted from the damaged section of the rotor and prepared to identify any microstructural irregularities. The samples were etched with a 2% Nital solution to reveal the pearlitic structure of the GCI rotor. For microstructural investigation, the samples were observed under a light optical microscope (LOM) and a scanning electron microscope coupled with energy dispersive X-ray microscopy (SEM-EDS). A scanning electron microscope (JEOL JSM-IT200) and

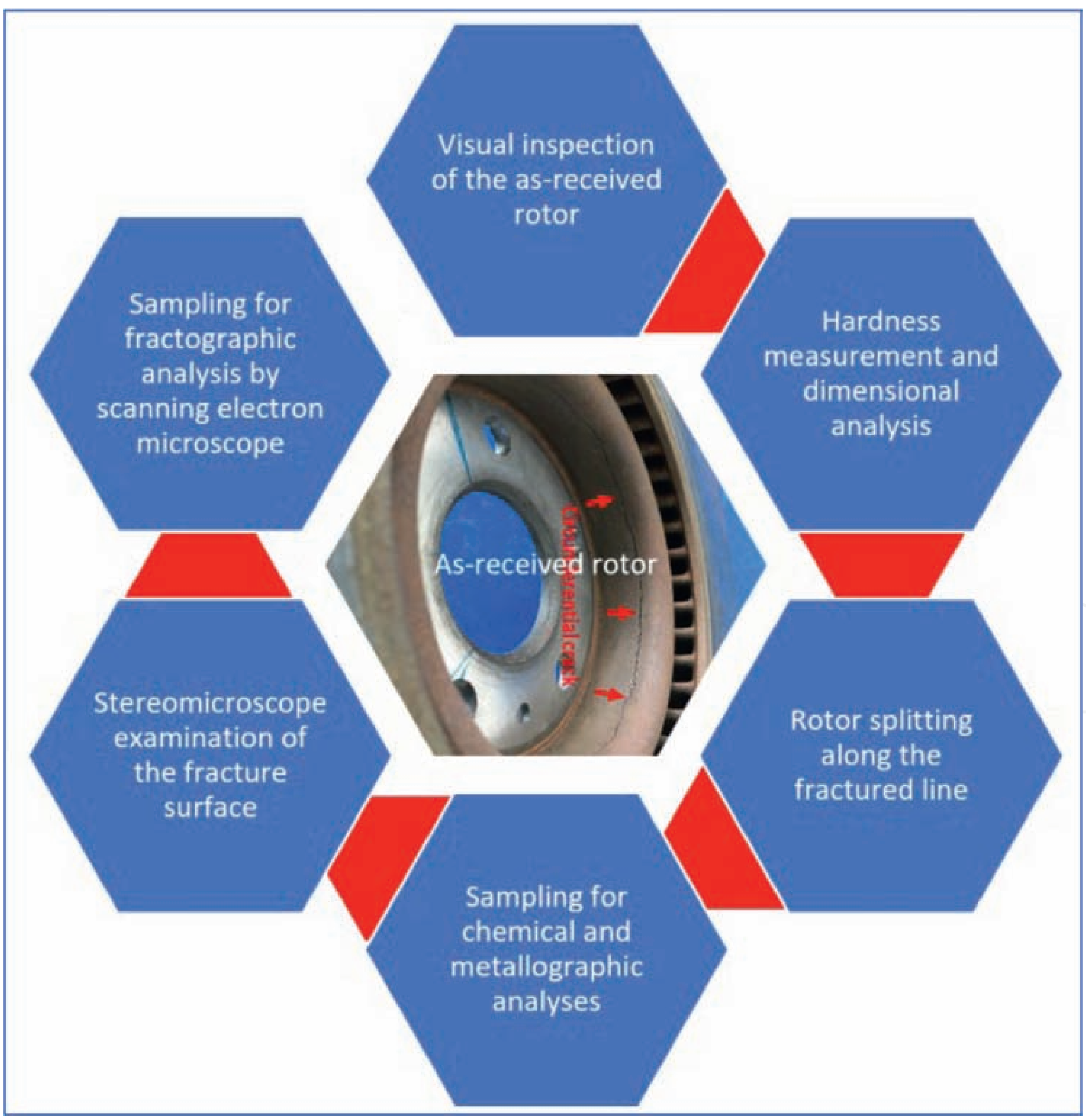

Figure 3.
Chart illustrating the step-by-step approach to finding the cause of the rotor failure.

Olympus optical microscope (Leica, DM2500M, Germany) were used for the microstructure analysis. A Brinell hardness tester was employed to measure the rotor's hardness on the friction surface and the disc hat. The average value of the hardness was reported. The fractographic investigation was accomplished using SEM-EDS to determine the constituent phases found on the cracked surface. **Figure 3** illustrates the systematic method adopted to understand the root cause of the rotor failure.

4. Results and discussion

4.1 Visual inspection

The failed "as-received" brake rotor was carefully examined before cutting samples out of it to observe any signs of aggressive use or inappropriate installation of the rotor with other brake system components, such as pads and calipers. As shown in **Figure 4**, a circumferential crack was noted at the swan neck region of the rotor, indicated by the arrows. The damage covered over 75% of the disc neck perimeter. It is also observed that the in-board area and the rotor's vents have been rusted, while the out-board region is still coated with graphite black paint that protects it against corrosion. A thorough examination of the brake surfaces (in-board and out-board) does not suggest any symptoms of abusive use of the rotor (**Figure 2a** and **b**). The friction planes do not show a blue discolouration marking. Blue discolouration of the friction surface emanates from excessive heat generated from braking due to the misalignment of brake calipers or inadequate heat dissipation by typical brake components [27]. This discolouration could occur due to extreme pressure mounted on the brake pads even when the brake system is not used. However, the brake surface blue marks

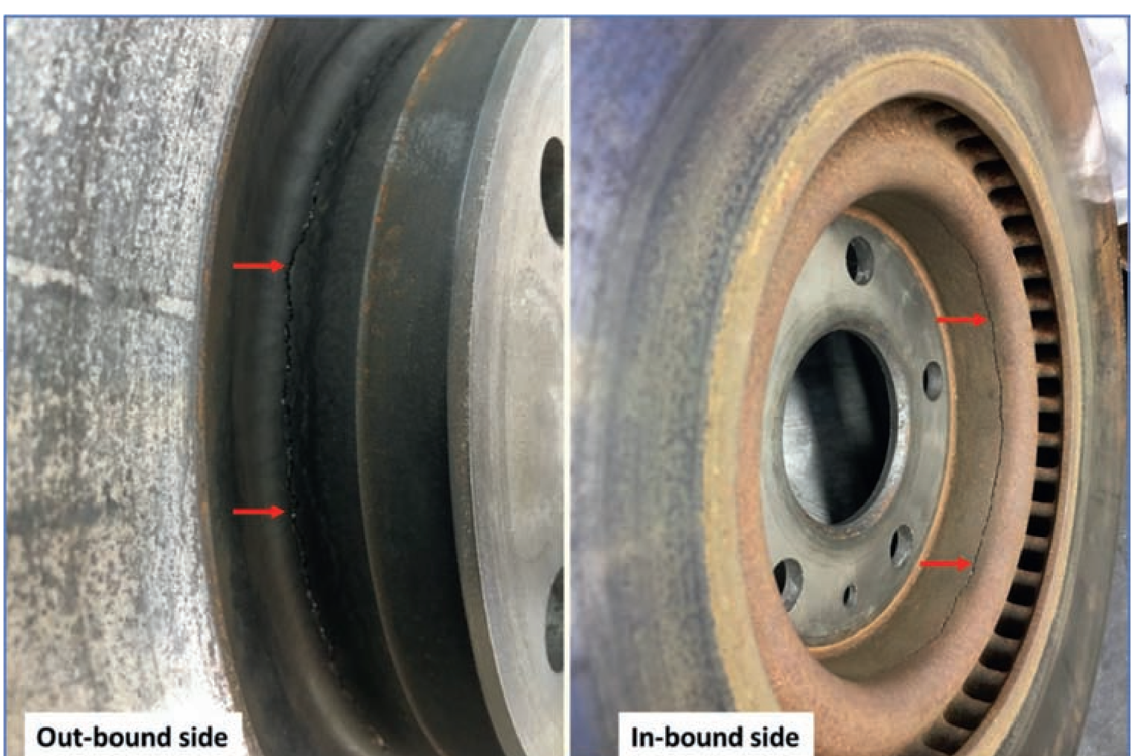

Figure 4.
A circumferential crack around the swan neck of the rotor.

can suggest faulty calipers and brake pads, disc cracks, and non-uniform brake pad wear. This analysis does not indicate any of the abovementioned issues as the cause of the failure, implying that the rotor was installed correctly and operated normally.

4.2 Analysis of brake disc material

4.2.1 Dimensional analysis

During the casting operation, a core shifting may occur, which could alter the dimensional correctness of the disc swan neck thickness. Therefore, inspecting the correctness of this thickness is sometimes crucial to avoid a reduction in load-bearing capacity. A core is a pre-determined shape of the mold, which provides internal cavities, recesses, or projections in the casting. The tendency for core instability during the casting operations is high due to pressure build-up or operational error during the mold filling. A core shift is a defect due to the buoyancy of liquid metal that causes the core of the cast to move from its correct position. If a core shift occurs, it causes a dimensional inconsistency in the casting. **Figure 5** shows a schematic illustration of the brake rotor suggesting the design requirement of the rotor swan neck thickness. As indicated in the figure, the specified thickness is 6.5 ± 0.25 mm. The failed disc swan neck thickness was determined as 6.62 ± 0.02 mm, which is still within the design specifications. This analysis suggests that the failure was not caused by core shifting.

4.2.2 Hardness measurement

Hardness is an easy method to assess the mechanical property of castings, and it is the measure of material resistance to deformation. Brinell hardness test is one of the standard techniques used for hardness measurement. The hardness was determined on the friction surface, and the hub of the failed rotor, and the measured value ranges from 163 to 180 HB. However, the design hardness specification is 160–220 HB. It can be said that the hardness of the disc is within the specification when the measured value is compared to the required hardness.

4.2.3 Chemical composition

It is essential to check the chemical composition of any failed cast component to approve that it was manufactured from the standard material. A sample was extracted from the neck region of the rotor and investigated for its elemental composition. The measured value was verified against the standard material composition. The results are presented in **Table 1**. The chemical analysis of the failed rotor confirmed that the disc was produced from the appropriate GCI material and that there were no deficiencies or abnormalities in the composition.

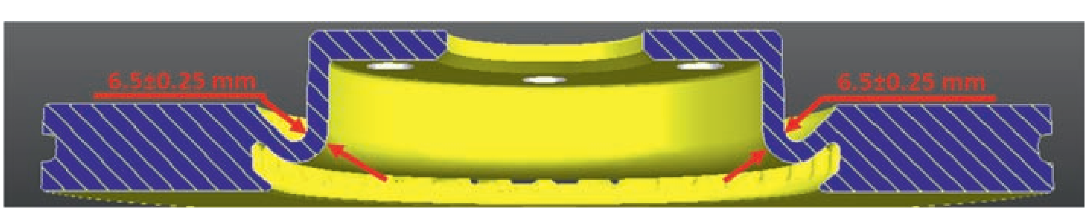

Figure 5.
A schematic representation of the rotor showing the specified swan neck thickness.

Element	Failed rotor	Material standard
C	3.79	3.60–3.90
Si	1.84	1.80–2.20
Mn	0.57	0.50–0.80
P	0.05	0.00–0.10
S	0.07	0.00–0.10
Cr	0.19	0.20–0.40
Mo	0.04	0.00–0.10
Cu	0.26	0.60–1.00
Fe	Bal.	Bal.

Table 1.
Elemental composition of the fractured brake disc (wt.%).

4.2.4 Microstructure analysis

The microstructure of a material depends on its elemental composition and the processing technique used. Even at the same nominal constituents, the effect of the processing method can produce several other microstructural features in different metallic materials. Light optical and scanning electron microscopes were used to examine the brake rotor samples for their microstructure constituents. **Figure 6a** displays the LOM micrograph of the etched sample, and the SEM micrograph of the disc is presented in **Figure 6b**. The microstructure, shown in **Figure 6a**, displays no traces of free cementite, but 0.15% free ferrite (by phase volume fraction) was observed. It is also evident in **Figure 6** that the GCI disc contains graphite flakes, which conforms with the requirements according to the European Standard (EN ISO 945–1:2008) for GCIs rotor [28]. Based on this standard, the rotor microstructure should primarily consist of pearlite in its matrix and a maximum of 5% and 2% free ferrite and free cementite, respectively, by phase volume fractions. Also, the graphite morphology should be mainly Type-A with flakes size 3–4 according to the SS-EN ISO 945–1:2008 standard (**Figure 6b**). It is apparent in **Figure 6** that the matrix is principally pearlite

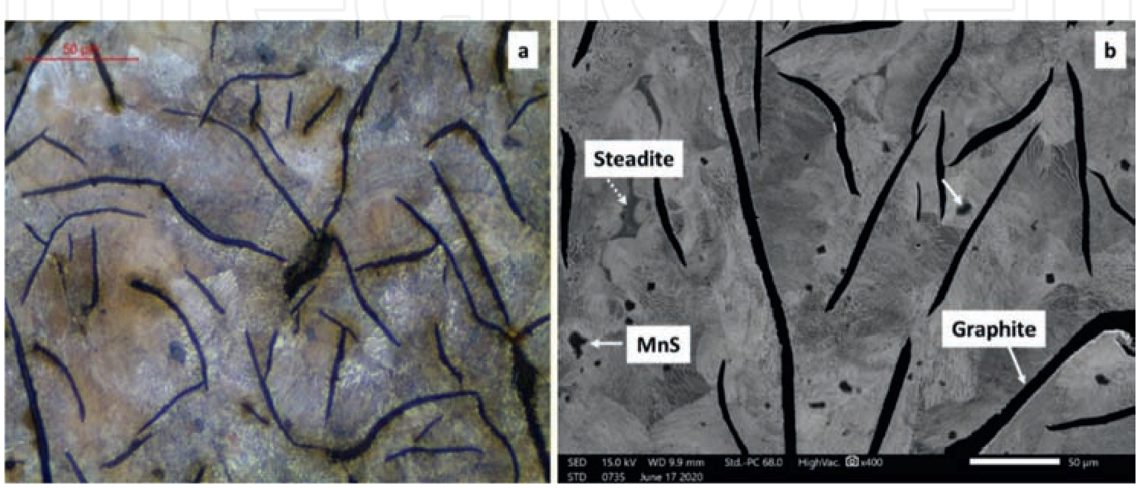

Figure 6.
Light optical (a) and SEM (b) micrographs of the rotor.

with a few manganese sulphide (MnS) particles and traces of steadite. It can be concluded from this study that there were no inconsistencies in the microstructure constituent of the failed disc, and therefore conforms with the microstructural specification for the disc material.

4.3 Fractographic examination

The aims of conducting fractographic analyses are to identify the origin and the propagation direction of a crack. This analysis is often performed using a combination of low and high-magnification microscopes. With the aid of a stereomicroscope, the origin/cause of a failure can be detected. At the same time, a scanning electron microscope can reveal detailed features and the identity of the failure cause. As shown in **Figure 7a**, the region identified as "Old fracture" is the fracture surface created during the in-service of the rotor, while the one marked as "New fracture" is the surface made during the splitting process. The "Old" fractured surface was critically inspected using a stereomicroscope to identify the failure's origin and root cause, as illustrated in **Figure 7a**. A thorough examination of the cracked surface showed some microstructural features variation from the primary matrix microstructure. The broken arrows in **Figure 7a** indicated some whitish gray phases, presumed to be corrosion

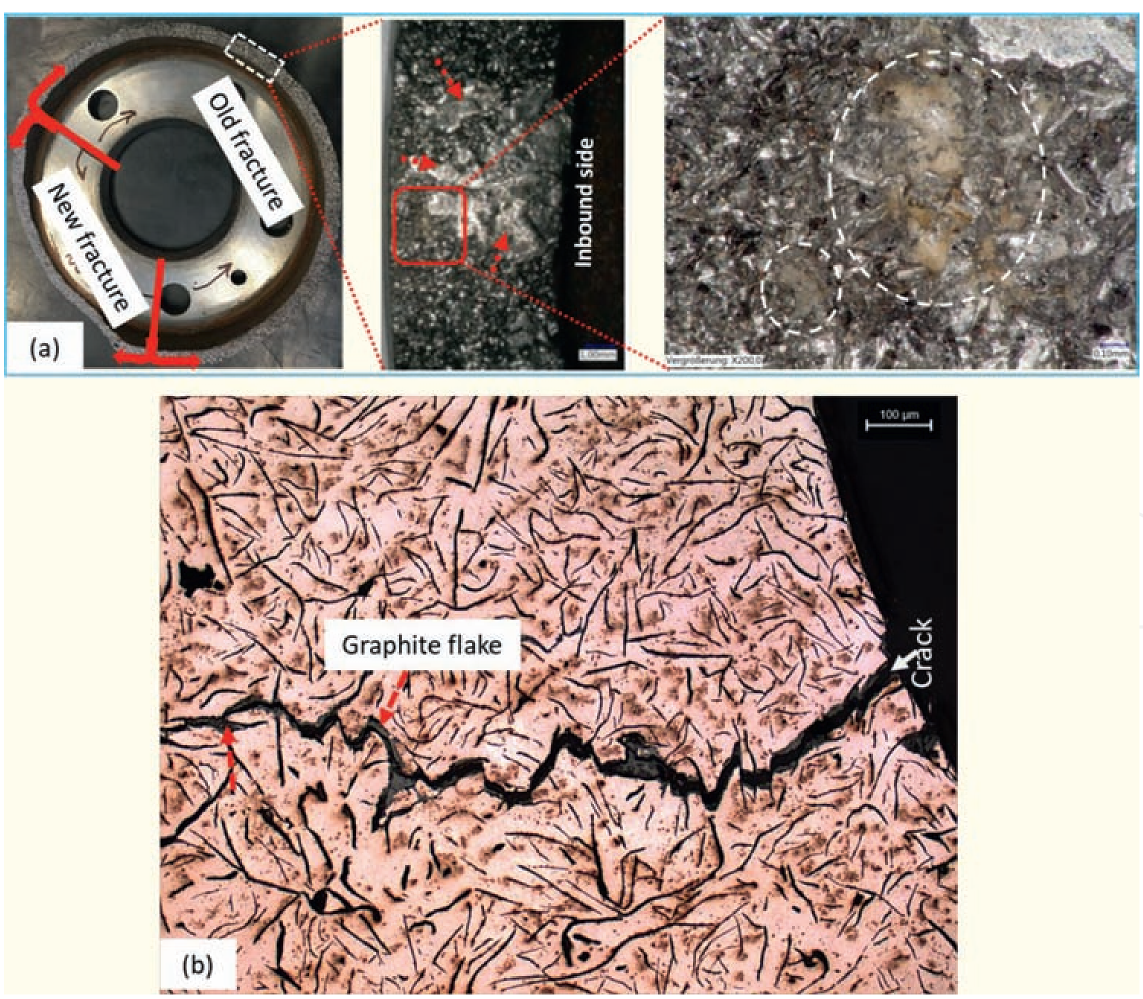

Figure 7.
(a) Stereomicroscope analysis showing fracture surface features. The broken arrows indicate corrosion products; the circled areas indicate foreign structures; and (b) a micrograph showing the propagation of cracks along the graphite-pearlite interface.

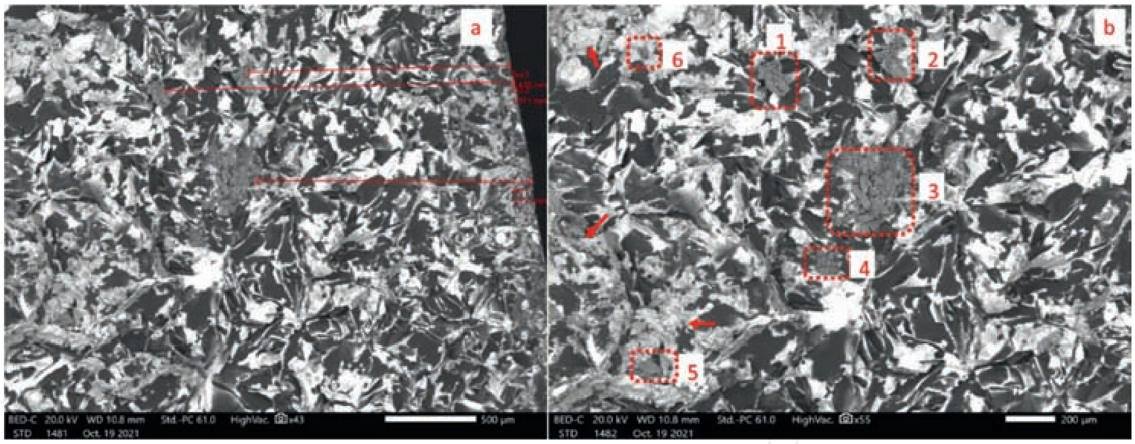

Figure 8.
SEM micrographs of the rotor's fracture surface.

products. The region marked with a solid rectangle was further magnified to reveal its microstructural make-up. However, some distinct phases were noticed in the magnified micrograph (areas highlighted in broken circles), which were further examined through an SEM-EDS analysis for identification. Additionally, a metallographic sample was extracted from the region around the fracture and observed under the optical microscope, revealing that the crack, having initiated, propagated circumferentially along the flaky graphite-pearlite interface, as illustrated in **Figure 7b**.

Figure 8 displays the SEM micrographs of the rotor's fracture surface. Different phases with varying textures can be identified from the micrographs. An inspection of the crack surface showed a relatively rough texture with a significant amount of oxidized products and foreign bodies inclusion, as displayed in **Figure 8**. The dark gray is the graphite phase, while the whitish-colored areas are the oxidized pearlite matrix due to the penetration of corrosive agents into the fractured surface leading to the corrosion of the cracked surface. Besides, some areas were recognized with a distinct appearance from the major constituent phases, as shown in **Figure 8b**. These critical features are labeled 1–6 (**Figure 8b**) and further investigated at high magnification to reveal their details. **Figure 9** presents the high magnification of some of the distinct microstructure features identified on the cracked surface of the rotor. A high number of foreign inclusions were also identified, some highlighted in **Figure 8b**. The foreign inclusions occasionally appear as a blocky (**Figure 9**, images 3–6) or lumpy (**Figure 9**, images 1, 2 and 7) structure. The location of the inclusions is approximately 1.620 ± 0.237 mm away from the disc in-board radial perimeter, as indicated in **Figure 8a**. **Figure 8** also displays that the cracked surface portrays layered structures suggesting brittleness, a characteristic fracture behavior exhibited by GCI materials [11, 29]. A network of fine microcracks can be seen on the fracture surface and even in the vicinity of the inclusions (**Figure 8**). Numerous microcracks are observed around these inclusions (**Figure 9**), suggesting potential nucleation sites for crack initiation.

However, an SEM-EDS spot and elemental mapping analysis were employed to identify the origin and composition of the foreign inclusions shown in **Figure 9**. The results of these analyses are presented in **Figures 10–13**. Furthermore, a close examination of the EDS analysis of Spots a and c in **Figure 10** reveals that the foreign materials in micrographs 3 and 5 (**Figure 9**) are silica sand (SiO_2) inclusions. The shape of the sand inclusions is comparatively regular, as seen in the figure. However, some other oxides can be observed admixed with the silica as represented in the EDS microanalysis of **Figure 10d** and the SEM-EDS elemental mapping of micrograph 3 (**Figure 11**).

DOI: http://dx.doi.org/10.5772/intechopen.107950

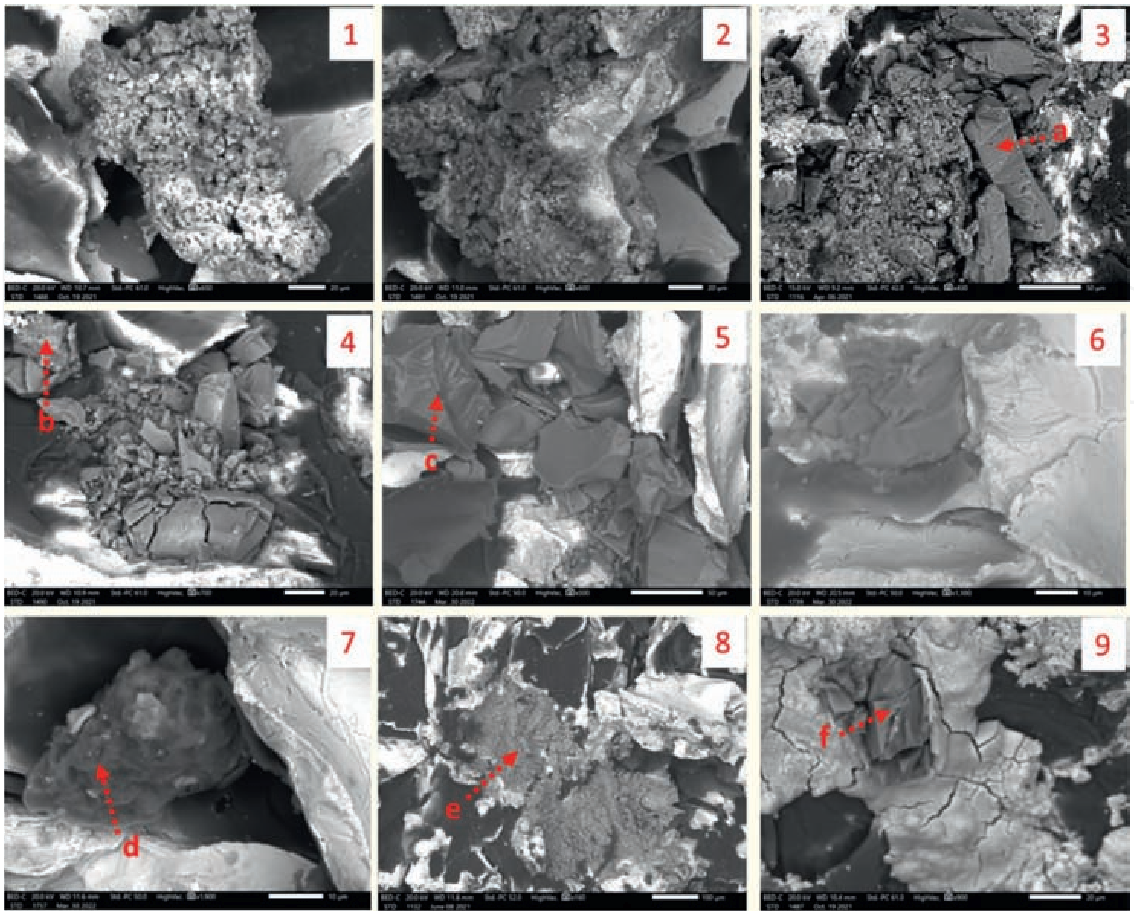

Figure 9.
SEM micrographs of the inclusions found on the fracture surface of the rotor.

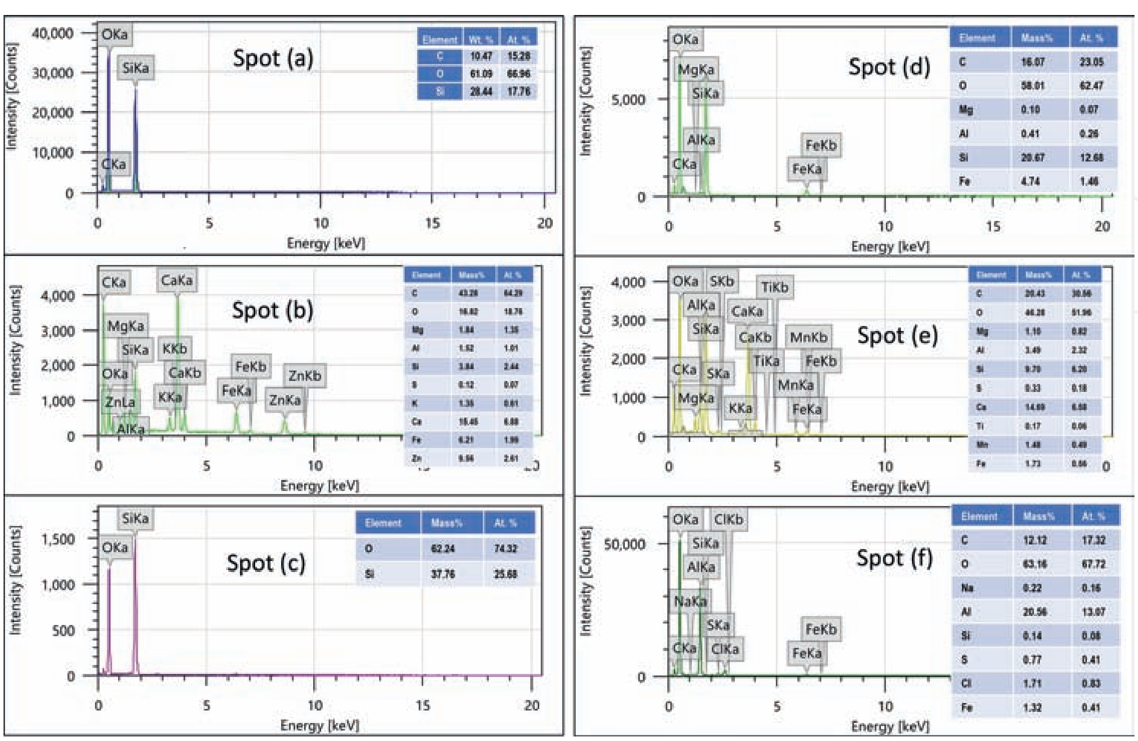

Figure 10.
*SEM-EDS spectra of spots (a-f) indicated in **Figure 9**.*

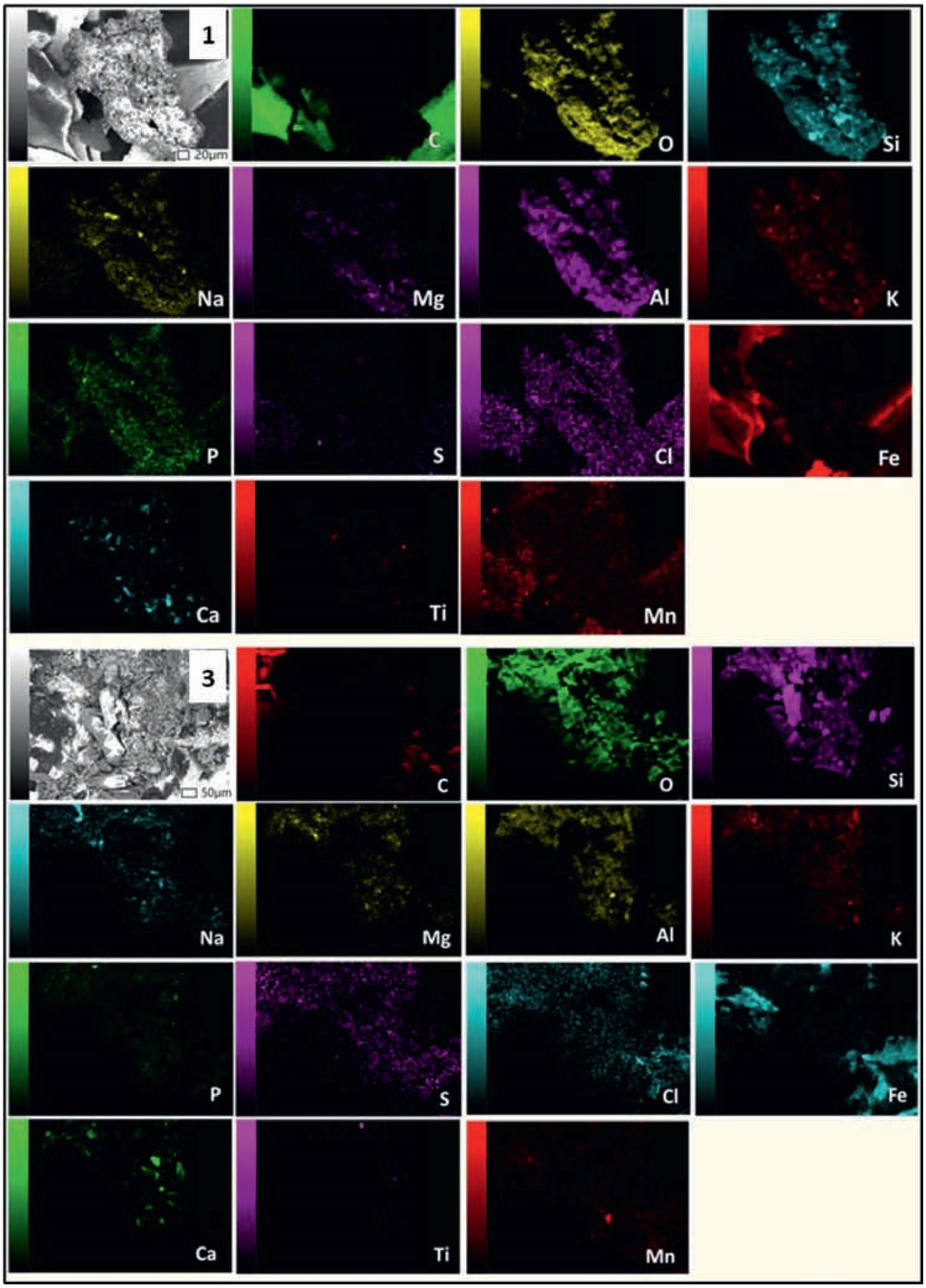

Figure 11.
SEM-EDS elemental mapping of micrographs 1 and 3 of ***Figure 9*****.**

Silica sand with binders is generally used for making mold and core in the iron casting process and can be differentiated from slag because it comprises a single phase (**Figure 10a** and **c**). The presence of silica inclusions can be attributed to the entrapment of mold material during metal pouring due to the erosion of or loose mold

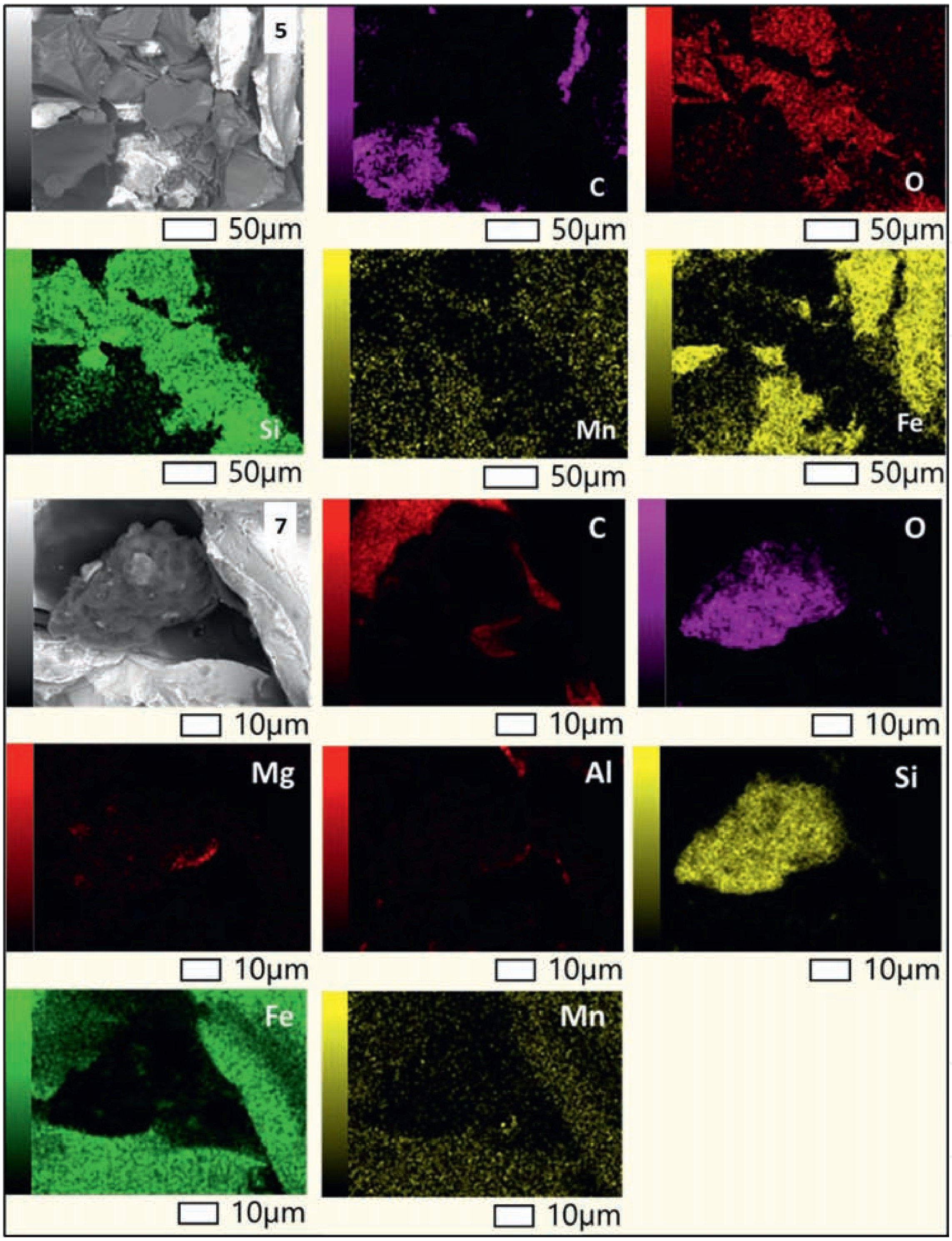

Figure 12.
SEM-EDS elemental mapping of micrographs 5 and 7 of ***Figure 9****.*

material. By analyzing the EDS microanalysis of spots b, e-f (**Figure 10**) and comparing it with the elemental mappings shown in **Figure 11** (micrograph 1) and 12 (micrograph 7), it can be seen that some of these lumpy inclusions are the oxides rich in calcium, silicon, zinc and aluminum with traces of admixture oxides of Mg, Ti, Mn, Na, K and Fe. The analysis also reveals minor phosphorous, sulphide and chloride concentrations (**Figure 10b, e, f, 11** and **13**).

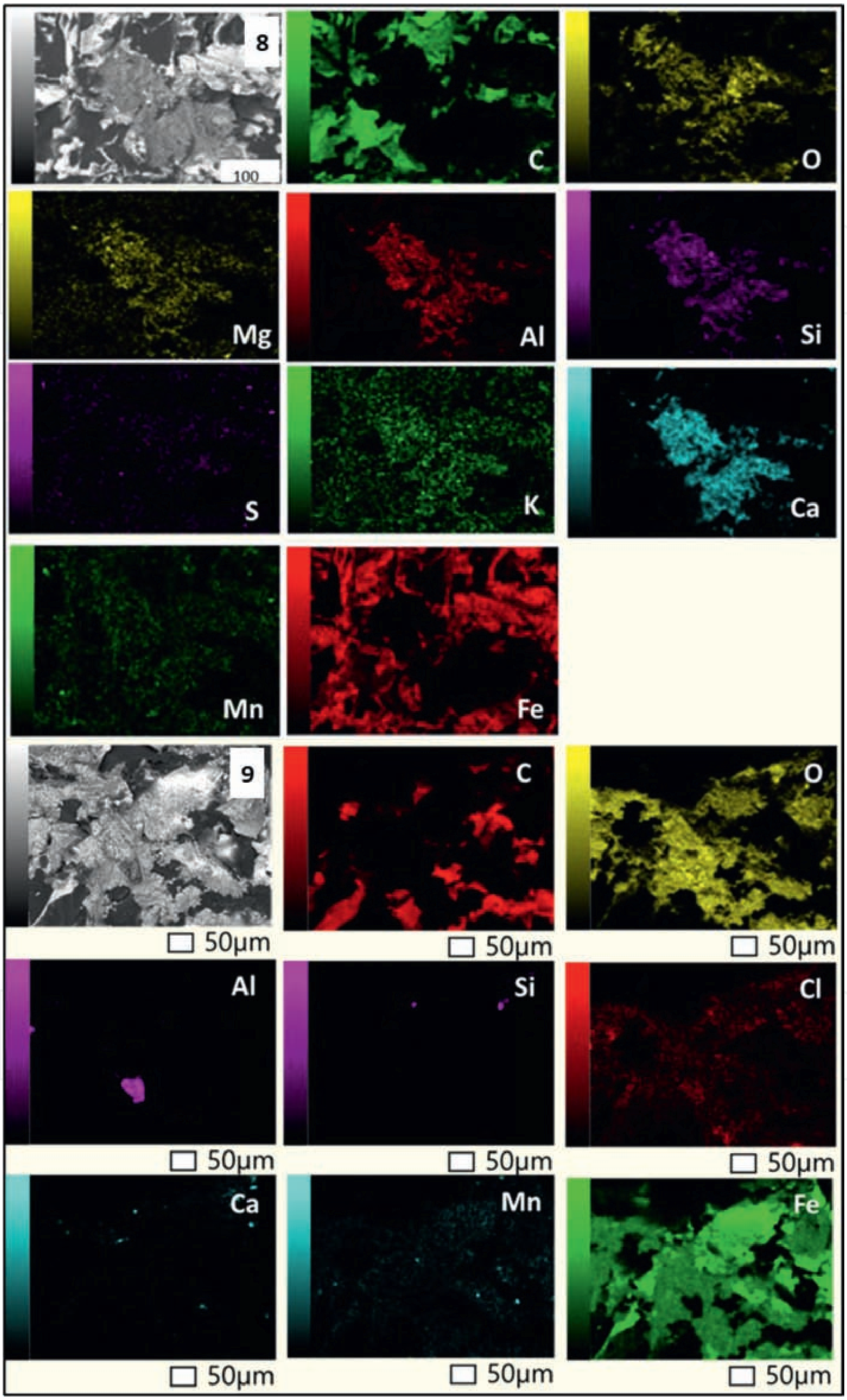

Figure 13.
SEM-EDS elemental mapping of micrographs 8 and 9 of ***Figure 9*****.**

The fractographic examination conducted on the failed rotor has identified indigenous and exogenous inclusions on the disc's cracked surface. The inclusions from external sources like slag, dross, ferroalloys, flux materials, ladle lining, and entrapments from eroded mold, core and refractory materials are categorized as exogenous. Those native or inherent in the molten metal treatment process are known as indigenous inclusions. Indigenous inclusions are the products of the liquid melt reactions with deoxidizers such as silicon, manganese, and aluminum particles or during desulphurization, creating some residual oxide inclusions in the casting [22]. However, previous studies have recognized ferroalloys as a significant source of inclusions in steel and cast-iron castings [11, 30]. Ferroalloys are pre-alloyed raw materials bonded with iron used in the treatment of molten iron and steel to produce castings with desired chemical composition. In general, the primary applications of ferroalloys in iron and steel makings include (i) alloying sources to enhance the mechanical properties and functional characteristics of iron and steel products (e.g., FeCr, FeMo, FeTi, FeMn, FeW), (ii) deoxidizers such as FeSi, FeMn, SiMn and FeAl, and (iii) reducing agents such as FeSi which can be used as a reducing agent to produce FeMo, FeV and other alloys [30]. Unfortunately, several impurities accompanied ferroalloys production, including H, N, O, S and P and other trace elemental impurities such as Mg, Al, Ti, V, Ca, etc. In the cast-iron melting process, FeSi ferroalloys are the common source of silicon addition to the molten iron to decrease its melting point, improve fluidity, and promote graphitization. These FeSi alloys are the source of Al and Ca impurities, which can significantly affect the quality of the castings by forming oxide inclusions. Unfortunately, these inclusions provide excellent nucleation sites for microcracks during cooling, which is why they were consistently found within microcracks [30]. Earlier studies [31] have shown that the predominant composition of slag formed from spheroidal and lamellar irons processing consists of several oxides, including FeO, MnO, SiO_2, Al_2O_3 and MgO. In a similar investigation, Jonczy [32] concluded that the dominant component of the cast iron slag is silica (62.04%) in addition to 11.03% of Al_2O_3, 10.38% of MnO, 6.32% of MgO, 5.37% of CaO with the admixture of iron, sodium, potassium, barium and sulfur oxides. The chemical composition of slag can vary greatly depending on the level of impurities in the starting raw materials (e.g., pig iron and scraps) and other additives (e.g., flux agents and ferroalloys). For instance, the slags formed using steel scrap-based charges showed the highest zinc and aluminum contents and created a crystalline $ZnAl_2O_4$ (gahnite) phase in addition to other admixture oxides (e.g., SiO_2, Al_2O_3, CaO, MgO and MnO). These high zinc and aluminum contents are due to the use of galvanized steel scrap as raw material (Zn and potentially Al) and of FeSi and SiC as additives (Al) [31]. This probably explains the high concentrations of Zn, Al and Ca found in some of the inclusions identified in **Figure 10(b, e** and **f)**.

The SEM-EDS elemental mappings shown in **Figures 11** and **13** depict the existence of chloride ions on the cracked surface of the rotor, which is also corroborated by the EDS microanalysis presented in **Figure 10f**. It can be observed that the chloride ions covered the entire disc's fractured surface, suggesting that the chloride ions possibly originate from an outside source, such as road salt. During winter, calcium and sodium chloride salts are generally used for roadway de-icing, thereby creating a high concentration of chloride ions on the motorways. Salt solution on the road can easily penetrate the crack surface of the rotor (**Figure 4**) and hasten the corrosion of the fracture surface (**Figure 8**). Chloride ions are a highly corrosive agent that serves as a catalyst and exacerbates the deterioration of steel and cast-iron components [11]. Analysis of the disc's fractured surface showed that the rusty products were only noticed in the pearlitic matrix areas, as displayed in **Figure 9**, micrographs 6–9, since graphite does not corrode.

4.4 Failure root cause and prevention

Failures of components are frequently activated by defects introduced during manufacturing [33]. Due to the prevalence of manufacturing defects, critical components are usually subjected to a thorough inspection to prevent defective parts from entering service, and sometimes this effort is unsuccessful. Several shortcomings are associated with the casting operations, which are potential causes of product failure. For example, it is well known that core or subsurfaces discontinuous, including voids, blowholes, shrinkage cavities, pipes and porosities created during ingot solidification, are identified sources of imperfections during succeeding manufacturing steps or in service as these weak points initiate cracks in the components that eventually lead to their failure [34]. The oxide inclusions in castings could indirectly induce crack initiation by enhancing local stress concentration, promoting cleavage fracture and detrimental to the fracture toughness of the components [12]. Nonmetallic inclusions also create discrepancies such as thermal expansion mismatch, stiffness mismatch, chemical mismatch, and ductility mismatch [22, 35], which ultimately impair the cast products' mechanical properties and service performance. It is therefore imperative to understand the impact of inclusion defects on the structural integrity and the fracture toughness of cast parts about their interaction with the main characteristics of fracture mechanics, including defect crack size, loading and material toughness.

As illustrated in **Figure 14**, nonmetallic inclusions in the rotor's swan neck reduce the disc's adequate thickness. The design thickness in the rotor neck region is 6.62 ± 0.01 mm, but the inclusions defects were positioned at approximately 1.620 ± 0.237 mm away from the rotor inner radial perimeter. During the braking regime, the disc swan neck can be exposed to cyclic compressive or tensile loads (**Figure 14**). However, inclusions in the neck region would reduce the swan neck's design load-bearing capacity, consequently

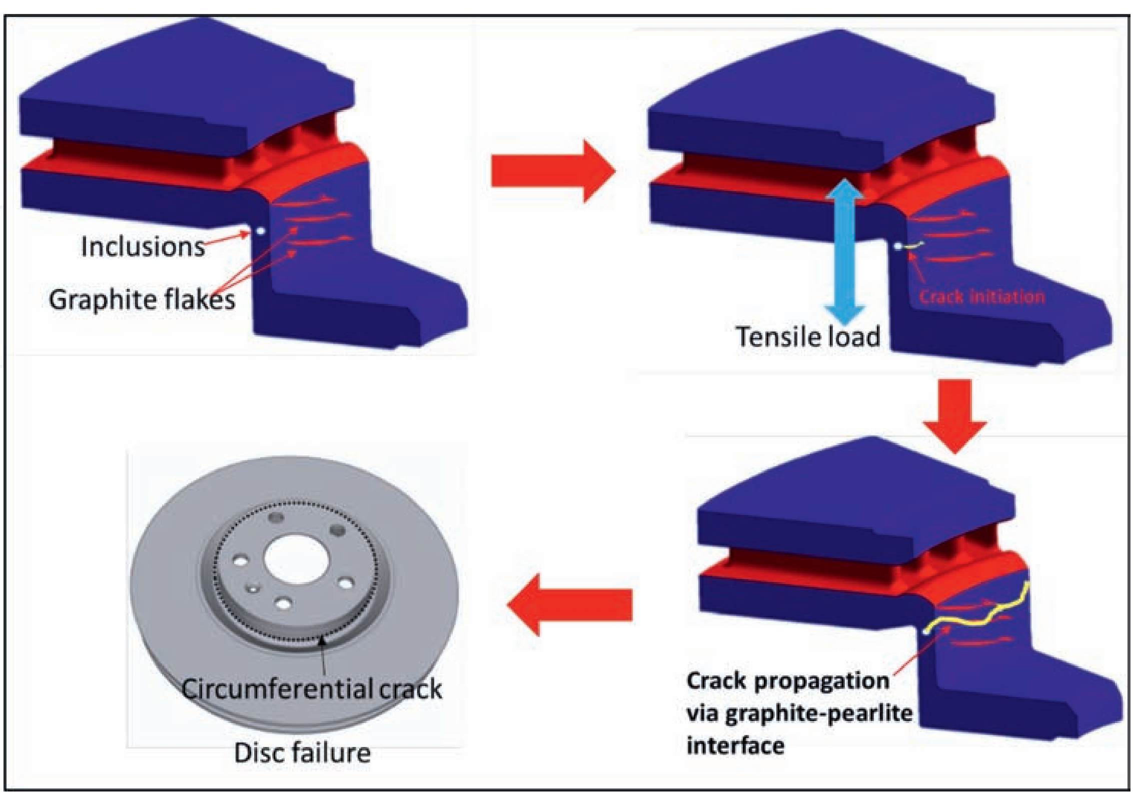

Figure 14.
A schematic illustration of the mode of failure of the rotor.

subjecting this region to higher stress during service. Due to the high thermal expansion potential of the inclusion particles, they would disintegrate into smaller particles [11, 35] and produce cavities that generate microcracks around the inclusion particles (**Figure 9**). Also, during the application, the brake rotor continuously experiences thermal (heating and cooling) and mechanical loadings that cause local concentrations of strain, induce residual stresses and initiate microcracks because of the thermal expansion mismatch between the inclusion particles and the pearlitic matrix. These microcracks propagate further through the interface between the graphite-pearlitic matrix (**Figure 7b**) and ultimately cause the rotor's failure.

After understanding and establishing the failure root cause(s), it is essential to formulate corrective or preventive measures/actions to forestall future recurrence. Judging from the various inspections performed on the failed rotor, the outcomes indicated that the inclusions (sand and slag materials) embedded in the rotor's swan neck during the casting process were responsible for its premature failure. This observation indicated that the failure root cause originated from the rotor manufacturing, implying that the preventive recommendations should be focused on the casting process to ensure quality castings. Therefore, the following strategies should be strictly implemented and practiced by the metal casters for casting quality enhancement and to avert nonmetallic inclusions during the following casting operations.

i. Mold design and preparation: Good gating design and adequate compaction of the molding sand during mold preparation are the initial steps to ensure quality casting. However, the gating system and the mold cavity should be free of sharp corners to minimize erosion wear. When assembling the mold, any loose sand particles around the down sprue or at the bottom of the sprue should be eliminated to prevent sand entrapment during mold filling.

ii. Melt preparation and pouring: Melt cleanliness is paramount to sound castings. Metal casters should implement a comprehensive approach to preventing slag particles from getting entry into the mold cavity by using suitable purifying additives (fluxing and floating agents) that protect liquid iron from further oxidation during melting and allow the slag to flow on top of the molten iron for easy removal before the pouring operation. A ceramic screen should be integrated into the gating system to separate slag material from entering the mold during melt pouring. Besides, a bottom-poured ladle should be used to eliminate slag entrapment. Melt pouring should be done to minimize turbulent flow during mold filling.

iii. Quality control management: Metal casting is a complex process that requires standard quality assurance management. A poorly managed quality control system in the foundry industry would impair the quality of castings. Therefore, metal casters should rigorously inspect the quality of all the casting processes and castings to diminish products' imperfections. An in-line nondestructive evaluation (NDE) solution (radiographic and ultrasonic inspections) should be developed and implemented in the foundries for the early discovery of cast imperfections such as nonmetallic inclusions, gas porosity, cracks, shrinkage porosity, and other casting irregularities to ensure a 100% quality assurance of their products. Continuous training of foundry workers regarding quality inspection in all facets of casting operations should be implemented, and negligent attitudes among foundry workers should be discouraged.

5. Conclusions

This chapter highlights the impact of nonmetallic inclusions on the quality and performance of a cast product and how this can ultimately cause premature component failure. The practical application of root cause analysis methods in resolving failure problems is discussed using a failed automotive brake rotor as a case study. The investigation concluded that the automotive brake rotor failed prematurely due to the influence of nonmetallic inclusions in the swan neck of the rotor. The inclusions were concentrated at approximately 1.620 ± 0.237 mm away from the disc's inner radial perimeter, reducing the design thickness of the rotor's swan neck. A cluster of inclusions in the rotor's neck region provided stress concentration and crack initiation sites. Multiple microcracks were initiated within and around the oxide inclusions and propagated through the interface between the flaky graphite and the pearlitic matrix. Examination of the rotor's hardness, chemical composition and microstructure suggested that the failed disc had been produced from the appropriate gray cast iron material and met the specification requirements; and that there were no deficiencies or abnormalities found with the disc material. The evaluation revealed that nonmetallic inclusions were the primary cause of the failure, and preventive recommendations were provided to forestall future recurrence and ensure high-quality castings.

Acknowledgements

The component investigated in this publication was provided by the Quality Control Unit, Automotive Components Floby.

Conflict of interest

The author declares no 'conflict of interest' regarding the work published in this paper.

Notes/thanks/other declarations

Thank you.

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