

The Effect of Silicon Deficiency on Material Properties of Nodular Cast Iron

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Abstract

The brittle failure of a crankshaft was investigated. The chemical composition and material properties of the crankshaft were analyzed. The hardness profile indicated that the manufacturer used the crankshaft as cast without heat treatment. The chemical composition and material parameters were compared with those found in the literature for similar applications. The yield strength, tensile strength, and hardness values observed for the crankshaft were lower than those observed in other crankshafts in the literature. The chemical analysis revealed that the Si composition deviated from the composition in the literature for a typical crankshaft material. Furthermore, low modularity and irregular nodule distribution were observed. The main reason for this failure was the poor mechanical properties arising from the chemical composition, processing, and inoculation characteristics.

Keywords: *crankshaft, nodular cast iron, fracture, forging, metallographic structure, mechanical properties, case hardening*

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Introduction

Modern automobiles and their components are manufactured to meet high standards that ensure continuous operation without failure. In most cases, components of automobiles may fail with a warning that allows the operators to replace them without much trouble. However, unexpected failures are still being reported in vital automotive components, hindering the entire operation of a vehicle and potentially leading to fatal accidents and injuries to vehicle occupants and pedestrians.

Analyses from different perspectives of automotive component failures are important. One important reason for these analyses is to ensure that a failure is not recurring, which can lead to many other vehicles failing during service. If it is only an isolated event, the reason for such failures is of interest to ensure the safety of passengers and pedestrians. Heyes (1998) reported that most of such failures occur in parts related to engines, and the main reason is abuse (29%, while the second reason is related to manufacturing or design).

The crankshaft is considered the heart of a piston engine. The crankshaft converts the reciprocating motion of the piston to rotary motion. The crankshafts are subjected to torsion combined with rotary bending stresses. In this paper, a case of crankshaft failure is presented.

Possible sources for the failure of crankshafts can be categorized as operating or mechanical sources. The main operating sources are operating in the absence of oil or defective oil lubrication, high operating oil temperature, and improper use of the engine, such as over revving or overloading. The main mechanical sources are misalignment, stress concentration, improper heat treatment, improper material composition, incorrect design, excessive vibration, improper clearance, and incorrect size bearings (Silva, 2003). Crankshafts of internal combustion engines are subjected to a complex stress state and are prone to fail prematurely for various reasons. The effect of Chemical Composition on material parameters of a crankshaft made of nodular cast iron is presented in this paper. The engine is a four-stroke four-cylinder gasoline engine with a displacement of 1498 cc, developing a power of 52 kW at a rate of

4800 rev/min. At the time of failure, the engine undergoes a full load performance test on an engine dynamometer.

Review of Literature

A literature review was carried out specifically on the failures of crankshafts made of nodular cast iron. The main mechanisms, material compositions, and physical properties of previously reported failures were studied. Keskin & Aydin (2010) analyzed the physical and chemical properties of a crankshaft against the manufacturer-specified properties. There were no metallurgical defects apart from a slightly increased carbon content. The reason identified for the failure was thermal fatigue. The micro hardness values changed from 502 to 930 HV. As per the manufacturer's specifications, the yield strength and tensile strength should be greater than 440 MPa and 800 MPa, respectively. The investigators observed the yield strength to be 485 MPa and the tensile strength to be 860 MPa, which was following the manufacturer's specifications. Furthermore, the elongation was 4%, which was following the manufacturer's specification of a minimum value of 2%. Referring to the literature, Keskin & Aydin (2010) identified the material investigated as EN-GJS-800-2. Osman (2006) analyzed the failure of a crankshaft made of ductile cast iron. The test results showed that the material was EN-GJS-700-2 ductile cast iron. The scholars identified that the absence of a hardened case in the fillet region initiated a crack leading to failure.

As per the specifications for EN-GJS-700-2, the proof strength and tensile strength should be greater than 420 MPa and 700 MPa, respectively. The investigators observed the yield strength to be 450 MPa and the tensile strength to be 765 MPa, which was following the specification for the material. Furthermore, the elongation was 3%, which was following the manufacturer's specification of a minimum value of 2%. Furthermore, the specified hardness for EN-GJS-700-2 was in the range of 225 HB–350 HB. The hardness observed during the investigation was 295 HB, which was well accepted.

An investigation on the failure of a crankshaft from a four-cylinder engine made of nodular cast iron grade EN-GJS-800-2. The analysis of the chemical composition revealed that the composition complied with the requirement for that of EN-GJS-800-2 nodular ductile cast

iron. Upon testing of mechanical properties, it was revealed that even though the tensile strength and yield strength complied with the requirement, the hardness was less than that specified for EN-GJS-800-2. The elongation was 5.89%, whereas the specification dictated that it should be greater than 2%. The reason for failure was identified as inadequate lubrication and overload on the engine causing crack initiation. The low nodularity and low hardness of the material were identified as causes for the propagation of fatigue cracks.

Farrahi et al. (2011) investigated the failure of a four-cylinder diesel engine crankshaft made of EN-GJS-700-2 ductile cast iron and concluded that the failure was a brittle fracture. The scholars did not find any mismatch between the material compositions and physical parameters with the specified material. However, the researchers proposed evaluating the design and manufacturing processes to optimize the fillet rolling process by changing the parameters. This recommendation was adopted by the manufacturer, and no further fracture has been reported since.

Xu & Shi (2020) analyzed the failure of a nodular cast iron crankshaft made of EN-GJS-800-2. The researchers found that the material properties and chemical composition matched the specifications of the material. However, the failure was attributed to shrinkage and surface cracks in the casting process.

Materials and Methods

The initial estimate was that the crankshaft failed due to excessive loading. The material composition, failure morphology, and physical parameters of the crankshaft material were investigated.

The chemical composition of the crankshaft was analyzed using spark emission spectrometric analysis. The composition is given in Table 1.

Table 1. Chemical composition of the crankshaft material (%)

C	Si	Mn	S	P	Cr	Ni	Cu	Mg	Ce
3.7	1.77	0.36	0.004	0.099	0.01	0.02	0.01	00	0.01

Table 2 presents a summary of the physical properties of the investigated crankshaft. The magnitudes were much lower than those observed for typical nodular cast iron crankshaft material encountered during the literature review.

Table 2. *Material properties comparison with literature*

Parameter	value
Yield strength (MPa)	210
Tensile strength (MPa)	387
Elongation (%)	3

The hardness values for EN-GJS-700-2 and EN-GJS-800-2 were in the range of 225–350 HB, whereas a hardness in the range of 197–210 was observed for the investigated crankshaft. The variation in hardness for the crankshaft is shown in Figure 1. The nominal diameter of the crank pin journal was 40 mm.

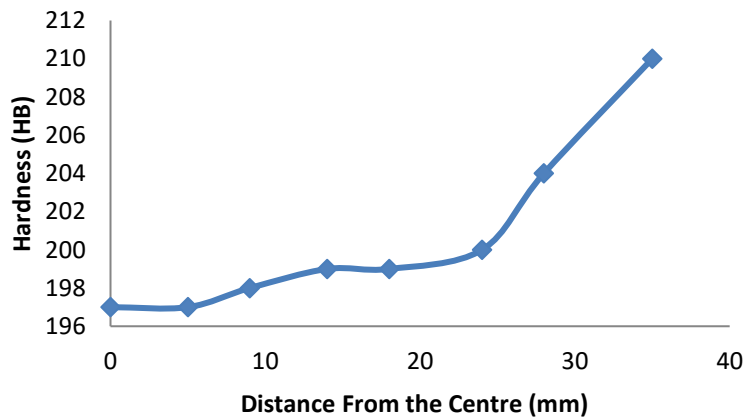


Figure 1. Hardness profile

The hardness profile indicated that the manufacturer used the crankshaft as cast without heat treatment. A specimen obtained in the vicinity of the failure was observed using optical microscopy after etching with a 2% Naital solution. A typical structure that could be observed is shown in Figure 2.

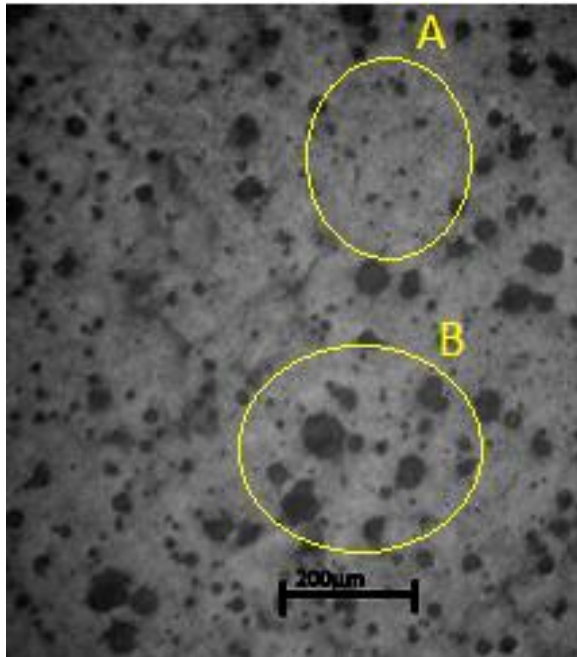


Figure 2. Microstructure of the material (2% Nital)

Optical microscopy revealed the material was nodular cast iron with a ferrite matrix. The failed section of the crankshaft was analyzed using optical imaging. The failed section is shown in Figure 3.

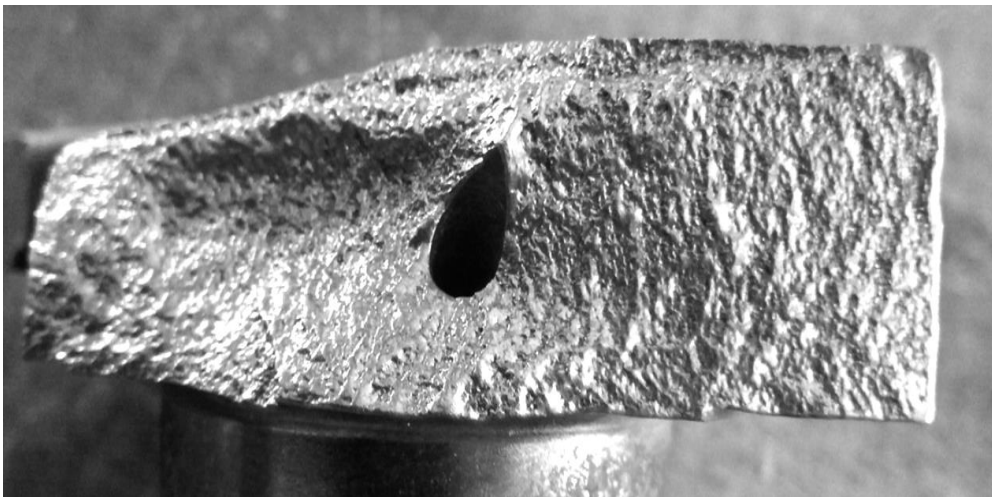


Figure 3. Damage profile

Discussion

From the literature review, it is evident that high-strength nodular cast iron grades EN-GJS-700-2 and EN-GJS-800-2, where the tensile strengths are in the region of 700–800 MPa and the yield strengths are in the range of 430–450 MPa, have been predominantly used to manufacture crankshafts for automobile engines. However, the crankshaft investigated has very low tensile strength and yield strength values of 210 MPa and 387 MPa, respectively. The microscopic analysis revealed large variations in nodule size and nodule distribution. A comparison of the chemical compositions of the investigated crankshaft and the crankshaft from the literature is shown in Table 3.

Table 3. Comparison of the chemical compositions of the investigated crank shaft and the crankshaft found in the literature (%)

Element	EN-GIS-800-2 [Ali Keskin and Kadir Aydin (2010)]	EN-GIS-700-2 [Osman A (2006)]	Crankshaft analyzed
C	3.2–4.7	3.2–4.1	3.7
Si	1.8–2.8	1.8–2.80	1.77
Mn	0.10–1.0	0.10–1.00	0.36
S	0.035 (max)	0.040 (max)	0.004
P	0.040 (max)	0.035 (max)	0.099
Cr	0.080–1.20	-	-
Ni	-	0.05–0.20	-
Cu	0.80–1.20	0.80–1.20	0.01

When the composition of each element is compared with the composition of the standard material, the analyzed crankshaft complies with the requirements, except for the silicon content. The silicon content is less than the recommended value for that observed in the literature for crankshafts made of nodular cast iron (Keskin & Aydin, 2010) All cases analyzed have silicon contents above 2%. The case presented by Keskin & Aydin (2010) has a silicon content of 2.58%. A decrease in the graphite content can be seen with a decrease in the Si content (Riposan & Skaland, 2017). Silicon is considered an important factor influencing carbon equivalent levels. Silicon decreases the solubility of carbon in molten iron and supports graphite formation during the cooling process to the end of solidification.

Aliakbari (2021) analyzed the von Mises stresses of six crankshaft failures where the stress ranges from 186 to 236 MPa. The literature review reveals that the nodular cast iron used to manufacture crankshafts should have a yield strength of at least 400 MPa. The yield strength of the material investigated is only 210 MPa.

Increased fractions and increased mean diameters of graphite nodules tend to increase the fracture toughness (Benedetti et al., 2018). High strength can be achieved by promoting a ferritic microstructure. Silicon acts as a ferritic stabilizer which promote the ferritic microstructure thus increasing the strength (Arshad et al., 2018; Soivio, 2018).

Gumienny, (2013) has studied five different samples of ductile cast iron that is being used in the industry. The silicone composition of all samples varied within the range of 2.37% to 2.61%. González-Martínez et al., (2018) have shown that at silicon concentrations between 5.0-5.2 wt% ductile cast irons achieve the highest UTS which is in the range of 628 MPa to 719 MPa. Further, they have shown that beyond 5.2 wt%, silicone decline the ductility of cast iron. The above facts substantiate the fact that the low concentration of Silicone affected the strength of the sample investigated.

For the case presented, the microstructure reveals a low fraction and small diameter nodules with low nodularity. These characteristics are evident from the lower fracture toughness experienced by the material

of the crankshaft under investigation. Furthermore, defects that can be suspected to be shrinkage porosities are visible. Shrinkage pores are responsible for crack initiation (Borsato et.al, 2018). Khalil-Allafi, & Amin-Ahmadi (2011). have investigated the effect of Silicone concentration on the microstructure, shrinkage volume and porosity defects. They have revealed that higher silicon levels from 2.1% to 3.3% enhance graphite nodule formation and reduce the porosity defects and shrinkage volume.

Wang et al., 2013 have studied the effect of shrinkage porosities on tensile strength of ductile cast iron. They have revealed that with the increase of shrinkage porosities the tensile strength decreases linearly. Further, shrinkage porosities affect the elongation thus reducing the ductility. Microstructure analysis reveals many small diameter nodules in the range of 5–10 μm . Nodules that are smaller than approximately 5 μm in diameter are mainly classified as inclusions or micro porosities (Pedersen & Tiedje, 2008). Furthermore, the reduced degree of nodularity significantly reduces the strength and ductility. Figure 2 shows two distinct regions identified as A and B, where region A has very small nodules and region B has comparatively large nodules.

In the process of making ductile cast iron, specially formulated alloys are added to molten metal. This process is called liquid treatment. During processing, inoculation is carried out to increase the nodule count. In ductile iron processing, increasing the nodule count is an important goal because a high nodule count is associated with a high as-cast ferrite/pearlite ratio (Riposan & Skaland, 2017).

Typical alloys used for inoculation are based on ferrosilicon, which contains several other elements, such as calcium, aluminum, barium, strontium, and cerium. Inoculation is affected by the quality of the charge material, such as pig iron, steel scrap ratio, and re-carburizers (Riposan & Skaland, 2017).

Conclusions

Analyses of automotive component failures were important to ensure that the failure was not a recurring failure that could lead to many

other vehicles failing under service and to ensure the safety of passengers and pedestrians.

The analysis revealed that the material properties of the crankshaft were inferior to those encountered in the literature. The yield stress, tensile strength, and hardness values were approximately 50% lower than those reported by other researchers.

There exist a strong relationship of Si concentration with strength, microstructural defects and formation of shrinkage pores.

Chemical analysis revealed a deficiency in Si concentration that deteriorated physical properties.

The crankshaft was used as cast without heat treatment. A proper heat treatment could increase the mechanical properties, thus increasing the fatigue strength.

The failure could be attributed to the low material quality and deterioration of physical properties.

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