Failure analysis of thin cast A357-T6 centre shell induced by casting defect

Kofi A. Annan[a], Richard Nkhoma [b] , Charles Siyasiya[a], Roelf Mostert[a]

[a]University of Pretoria, Department of Materials Science and Metallurgical Engineering, Private bag X20, Hatfield 0002, Pretoria, South Africa

[b]Malawi University of Science and Technology, Department of Engineering. Malawi

Highlights

- Failure of A357-T6 alloy component was identified to fail in a brittle manner.
- Increased porosity led to decrease in mechanical properties such as ductility.
- The crack initiated in the vicinity of porosity.

Abstract

Thin-walled Al-Si alloy precision casting components are used for various applications due to their excellent castability, corrosion resistance as well as high strength to weight ratio. It is very difficult to achieve all the set requirements due to complexity of thin-walled components through casting processes usually used in producing the aluminium alloy castings. A thin-walled shell, used as a housing unit for a component manufactured from A357-T6 alloy, failed prematurely during a torqueing process. The failed component was subjected to chemical analysis, microstructural analysis, visual examination and mechanical testing to identify the nature of the fracture and establish the primary cause of the failure. In the investigation, optical and electron microscopy, hardness and tensile tests were used to study the fracture. The examined fractured surface of the component revealed that, the fracture occurred in a brittle manner. The dominant and leading casting defect identified in the failed shell is porosity. The analysis of the results indicates that coarser grains and porosity defects led to decrease in ductility and thereby causing the shell to fail in a brittle manner.

Keywords: Microstructure; Porosity; Hardness; Failure; A357-T6 alloy

1. Introduction

Aluminium and its alloys are widely used in applications requiring high strength to weight ratio such as in aerospace and automotive industries [1]. Most of the components used in light weight requiring applications, are cast using various casting technologies such as aluminium sand, die, investment and permanent mould casting [2]. The casting of thin-walled component with improved physical and mechanical properties coupled with high productivity always possess a challenge to the casting industry [3], [4]. The predominant defects that are found in the Al-Si cast alloys includes porosity, segregation, surface bleeding, and inhomogeneity of grains and macroscopic bulking [5], [6], [7]. Among these, porosity is identified as the most disturbing defect due to its influence on the mechanical properties such as ductility, crack initiation and growth, fracture toughness and lack of pressure tightness [8],

[9]. Porosity, fundamentally results from shrinkage during solidification or the gas trap arising from the decrease in solubility of gases in the solid metal. Due to these defects most of the component manufacturers adopt specific heat treatment such as double heat treatment (T6) process to correct these defects [10], [11].

Thin strip casting with lower thickness have attracted increased interest due to the potential to achieve improved properties and high productivity [12]. Fatigue requirement of these alloys have increased owing to high-integrity shaped cast components that are subjected to repetitive cycle loading [8], [13]. The microstructural evolution characteristics and the defects present in the cast alloys have significant effect on the physical and mechanical properties of the alloy [14].

Service failure of components is largely due to fatigue accounting for nearly ninety percent (90%) of mechanical related failures [15], [16], [17]. Fatigue can be described as any failure that occurs under the influence of cyclic dynamic loading. Thus being a localized permanent structural change in any given material under fluctuating stress and strain conditions results in crack initiation and growth. It has been reported that porosity in Al-Si alloy is the key factor responsible for the control of fatigue properties in the alloy [18]. The pores in the Al-Si alloys are said to be the preferred site for crack initiation in the alloy even though the eutectic and intermetallic phases are also reported to contribute to the crack initiation in these alloys [19], [20]. Pores are found to act as high stress concentrators in the alloy matrix adjacent to the pore and thereby reducing the time for crack initiation [17], [19]. This basically leaves the fatigue life in the crack growth and cause the material to fail without warning. It has also been reported that numerous components made of A357-T6 alloys exhibits premature cracks [17], [19]. Studies have revealed that, casting pores largely remain the most influential defect on the number of cycles that lead to crack initiation in Al-Si-Mg alloys [15], [20]. The current investigation focuses on a thin-walled shell component that failed prematurely during torqueing. The failed component investigated in the current work is a centre shell cast from A357-T6 alloy that failed during torqueing. Chemical analysis, fractography and mechanical tests were used in the current work to identify and establish the cause of failure of the shell component. This paper presents the tests and analysis used to establish the type of failure and the root cause of the failure.

2. Materials and methods

2.1. Materials

Table 1 presents the spectrographic chemical analysis of the failed centre shell compared with the specification of alloys for such application. The results indicates that the material satisfied the chemical specification requirements.

Table 1. Chemical composition of the failed shell compared with standard requirements [21] of alloy for the application.

Alloy	Si	Fe	Cu	Mn	Cr	Ni	Zn	Pb	Ti	Sn	Al
EN10243	6.5–7.5	0–0.45	0–0.15	0–0.35	0–0.05	0–0.15	0–0.15	0–0.15	0.–0.20	0–0.05	Balance
Measured	6.80	0.12	0.03	0.006	0.002	0.003	0.007	0.003	0.16	0.001	Balance

2.2. Methods

Samples for microstructural examination were taken close and away from the fracture and prepared for analysis in accordance with ASTM E 3–11 [22]. The samples were metallographically prepared by grinding and polishing down to 1 µm and then etched with Keller's reagent. Another piece of the shell was taken and immersed in a paint removal solution for 10 min to remove coated paint on the surface of the alloy. The removal of the paint made it possible to get a true analysis of the distribution of the defects (porosity) in the material from the outer surface. The outer and the inner surfaces of the alloy without paint was then observed under JEOL SEM. The fractured surface of the shell was also observed under JEOL SEM.

Mechanical tests done in the current investigation were tensile and hardness tests. Three tensile test samples were taken from the transverse and three from longitudinal sections of the shell for the tensile tests. The tensile test was carried out to evaluate the effect of the defects on the tensile strength and the percentage elongation of the samples following the EN 10204:3 [21]. The Vickers hardness test of the shell was conducted following ISO 6507 [23]

3. Results and discussion

3.1. Visual examination

The failed component investigated in the current work was a centre shell used as a housing unit for a component. This shell failed prematurely during torqueing process. The applied pressure during the torqueing process was 0.04 MPa even though the operating pressure of the shell is 0.145 MPa. Fig. 1 presents the image of the failed centre shell used in the investigation showing the crack (arrowed) that was observed. The continuous crack line was visible to the naked eye as shown in the figure.

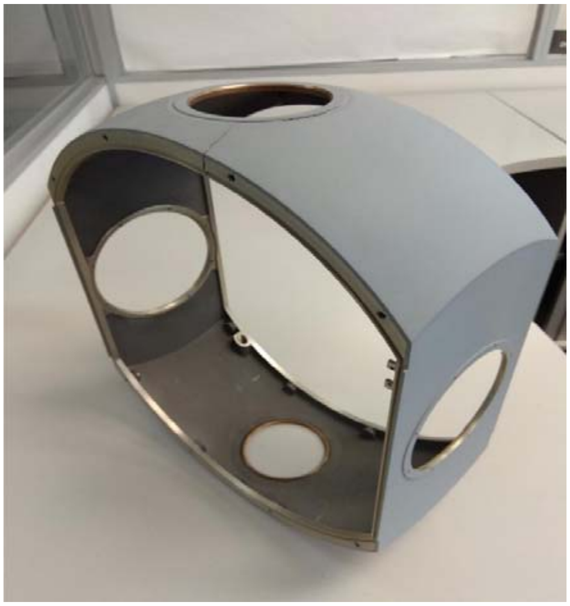

Fig. 1. Image of the fractured centre shell showing the crack.

The crack was carefully opened by inserting the shell in a G-clamp; physically separating it into two halves making the fractured surface visible. Upon exposing the crack, the surface was observed under stereo for detailed information concerning the crack. A stereo image of the fractured surface of the shell is shown in Fig. 2. As can be seen the fractured surface depicts typical brittle failure by crack initiation. A close examination indicated that the crack initiated at the edge of the ring and followed by catastrophic failure.

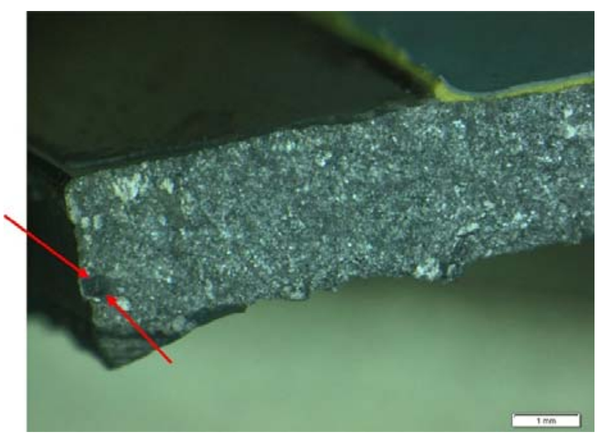

Fig. 2. Stereo image showing the fractured surface of the component and the point of crack initiation.

3.2. Microstructural observation and analysis

Fig. 3 shows an optical micrograph of the A357-T6 microstructure that was etched with Keller's reagent. Metallographic examination showed that the basic constituents of the cast A357 comprises of a primary Al matrix together with an Al + Si eutectic located between the secondary dendrite arms. The optical micrograph clearly shows evidence of porosity as indicated on the figure by arrows. The microstructure is hypoeutectic, consisting of primary phase (Al) and Al + Si eutectic between the dendrite arms which formed during the solidification process. The eutectic regions were also the favoured location for defects such as porosity. As shown in the Figure, it is evident that the white phase (Al) primary phase exhibits the dendrite morphology and the grey phases (Al + Si) eutectic in the grain boundary. It is also noted that the porosity occurred along grain boundaries appearing in a web-like structure that extends from porosity boundaries possibly resulting from eutectic solidification [5], [6], [16]. There was however no difference between the microstructure of the sample taken close to the crack and the one away from the crack as depicted in the Fig. 3a and b.

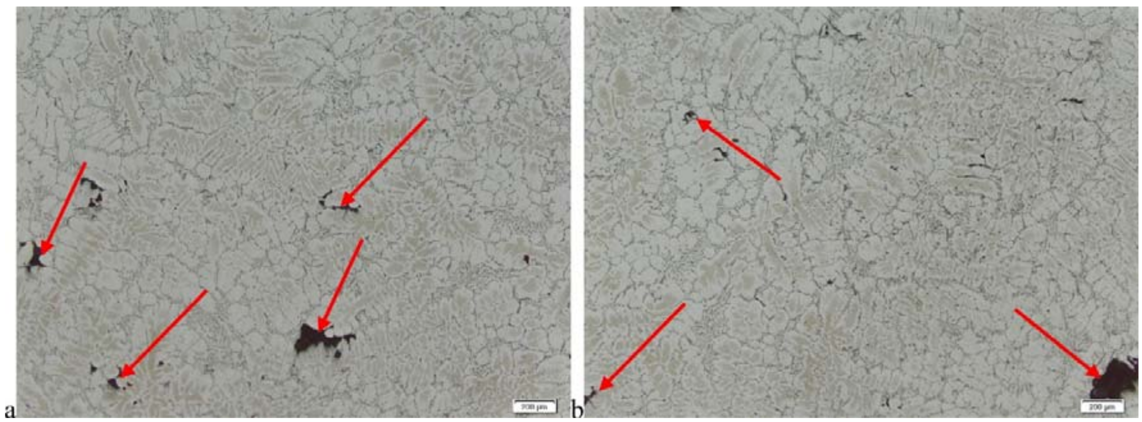

Fig. 3. Optical micrograph of the samples taken from the component a) close to the crack b) away from the crack.

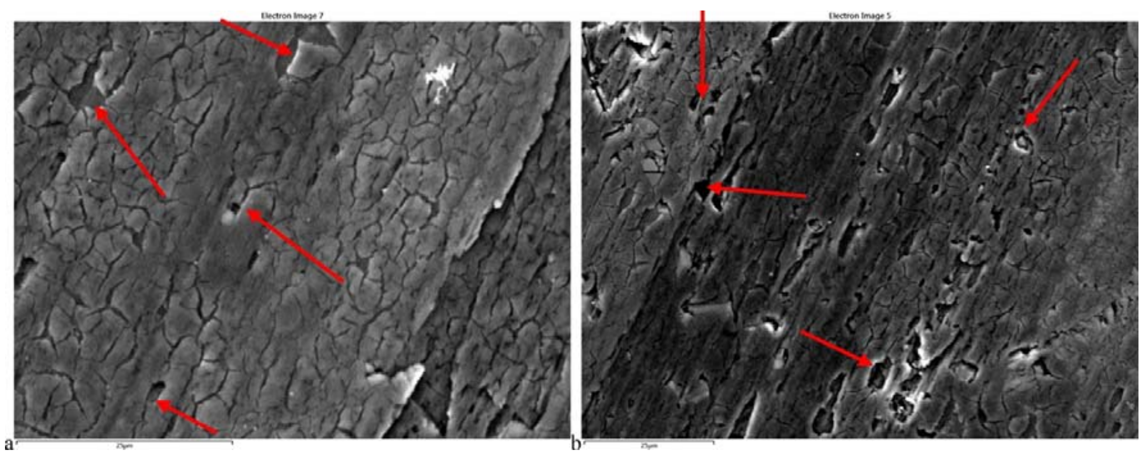

Fig. 4. SEM micrograph of the alloy without paint showing evidence of porosity from the a). Outside and b) inside of the component.

It is worthy to note that, the dendrite-shaped porosities are largely found to be distributed along the grain boundaries as shown in Fig. 3. Along the grain boundaries are found many tiny pores which are heavily distributed. Within the intergranular region and also along the grain boundaries of the Al matrix are the brittle Si eutectic particles. From the metallographic analysis done, it is clear that the major defects identified is the porosity. As seen, this porosity consists of interdendritic cavities along with chain of branches which exhibit some form of complexities in the microstructure. Fig. 4 shows micrograph of the perimeter of the shell with the paint peeled off observed under the JEOL 840A SEM. The image shows numerous porosity within the material. The micrographs presents detail of the randomly distributed pores which are irregular in shape.

Fig. 5 shows micrographs of the opened crack site showing the surface of the fracture analysed using SEM. The Figure shows a quasi-cleavage feature morphology indicating that the fracture clearly occurred in a brittle manner [14], [20]. Fig. 5a exhibits the presence of micro cracks generated in the material while 5b shows the dendritic “heads”. The fracture of the eutectic silicon particles created flat areas as shown on the micrograph in Fig. 5c. The sites showing micro cracks in Fig. 4a points to the fact that, there are other potential crack initiation sites as a results of casting quality [18]. The image clearly shows evidence of brittle dendrites in the material as in Fig. 4b. The path of the fracture is observed to be through the more brittle eutectic silicon particles which experienced some form of deformation as in Fig. 5c [15], [24]. The fracture pores occurred in the areas with eutectic Si particles in the interdendritic region. The initiated crack propagated along the solidification cells with segregation of eutectic particles leading to fracture and failure.

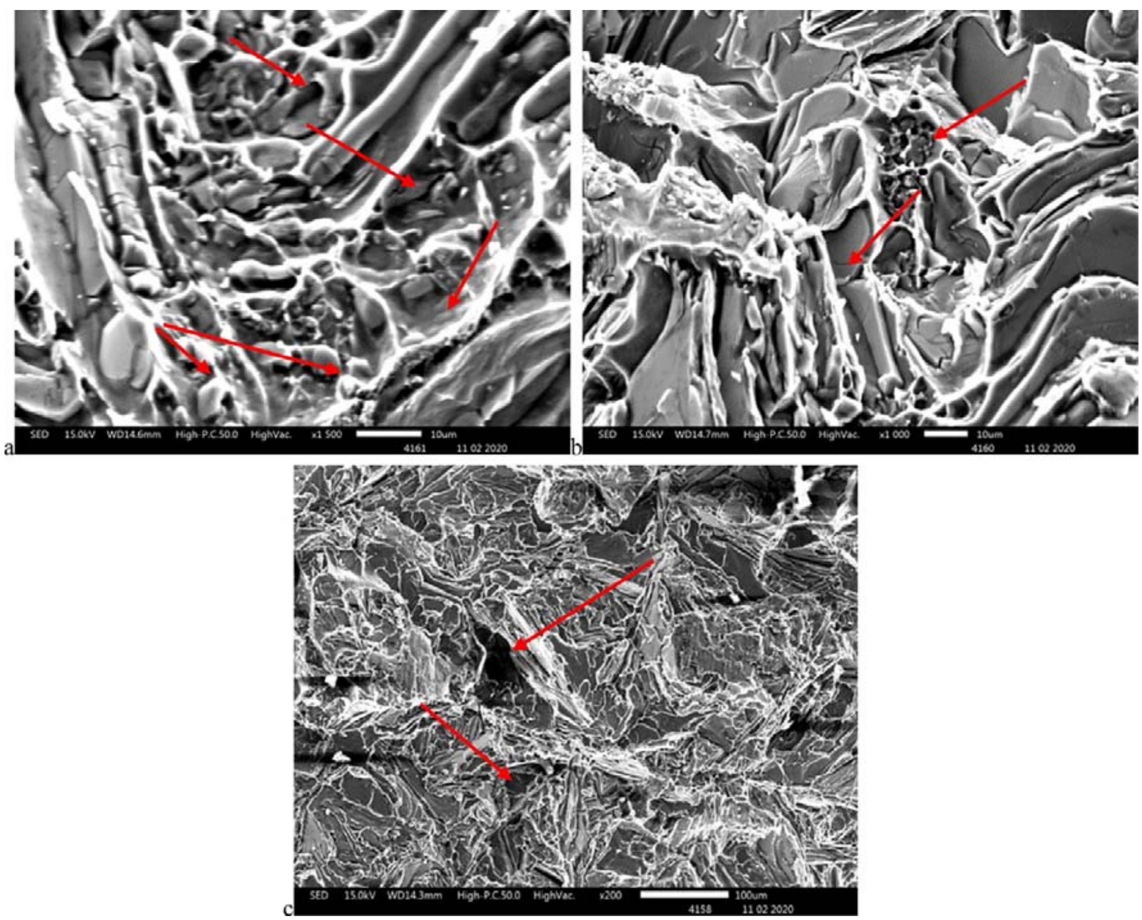

Fig. 5. SEM micrographs showing evidence of a). Micro cracks b) dendritic heads c) flattened areas.

The semi-quantitative EDS analysis technique employed provided a qualitative information on the material as shown in Fig. 6. The information obtained through the EDS confirms the dark portions identified in the optical and the SEM micrographs to the pores other than the composition of the alloy or artefacts.

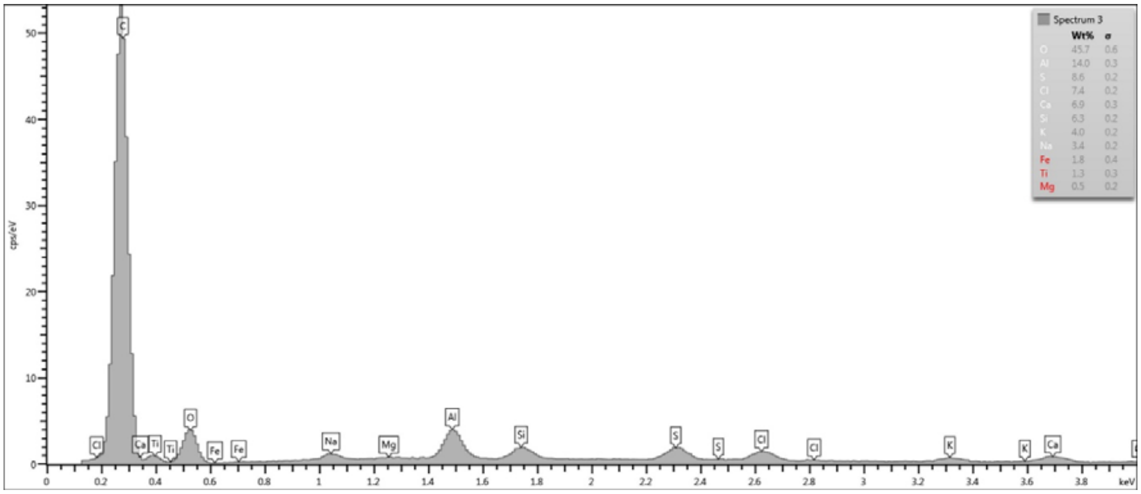

Fig. 6. EDS spectrum of the A357-T6 alloy confirming the presence of pores in the alloy.

It is evident from the stereo image and SEM analysis that the crack initiated from the pores located close to the sample surface, a mechanism described as failure dominant pores in aluminium alloys [17], [19].

3.3. Mechanical properties

Table 2 presents summary of the tensile test results consisting of the yield strength, UTS and elongation as well as the hardness test results. The results show that the yield strength, the ultimate tensile strength and the recorded hardness were all within acceptable limits according to the specification requirements. The elongation is however found to be below the required specification. This unacceptably low ductility is attributed to the presence of porosity in the material [9], [18].

Table 2. Measured mechanical properties of the alloy compared to compliance requirements.

Specimen	Yield strength (MPa)	UTS (MPa)	Elongation (%)	Hardness (HV)
Transverse section	170 ± 11	265 ± 15	1.35 ± 0.55	113 ± 12
Longitudinal section	185 ± 14	288 ± 22	1.45 ± 0.25	113 ± 11
Specified requirements	>165	>234	3.7–5.6	95

It is evident that, this failure is not a fatigue failed part but porosity related. Thus the porosity affected the ductility as demonstrated in the tensile test results as well as the irregular crack initiation and its propagation to failure [25]. Metallographic examinations showed large presence of porosity in the cast. The SEM analysis in Fig. 4 further showed microporosity and micro-cracks which are typical in Al cast alloys [14]. With presence of micro-cracks, the porosity made it easy for the initiated crack to grow quickly with little force applied leading to unannounced failure [25], [26], [27]. The porosity observed occurred as a result of the volume contraction during solidification leading to the observed shrinkage porosity. Another interesting observation is the web-like structure which is observed to occur along the intergranular boundaries areas which is able to initiate crack in the material [27], [8]. As shown in the optical and the SEM micrographs, the fracture in the studied cast component was actually initiated by the cracking of the Si areas with dendrites heads which are brittle silicon areas.

4. Conclusion

Following the tests conducted and the results analysis done, the following conclusions can be drawn:

- The examined fractured surface of the A357-T6 alloy show that, the fracture occurred in a brittle manner.
- The failure was not fatigue related but porosity as shown that the crack initiation and growth was purely reliant on the porosity which were dominant in the structure.
- The presence of porosity led to decrease in the mechanical properties of the alloy.
- The crack was initiated in the vicinity of casting porosity close to the surface of the shell and created a propagation path through the porosity sites.
- The identified presence of dendrites phases, micro-cracks and micro-porosity close to the surface is damaging in brittle failures

CRediT authorship contribution statement

Kofi A. Annan: Conceptualization, Formal analysis, Writing – review & editing. **Richard Nkhoma:** . **Charles Siyasiya:** Project administration. **Roelf Mostert:** Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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