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DAMAGE INVESTIGATION ON WELD ALUMINUM COMPONENT OF A COMPRESSOR AFTER-COOLER

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Abstrak

Studi ini dilakukan pada sebuah alat penukar kalor kompresor yang mengalami kebocoran pada bagian sambungan las komponen yang terbuat dari paduan aluminium tanpa pengerasan perlakuan panas. Tujuan dari studi ini adalah menentukan jenis dan faktor penyebab serta mekanisme kegagalan/kerusakan dalam kaitannya dengan struktur metalurgi yang terjadi. Dalam studi ini sejumlah pengujian telah dilakukan meliputi pemeriksaan visual dan makroskopik, pengujian metalografi dan kekerasan, serta analisa SEM (*scanning electron microscope*) yang dilengkapi dengan EDS (*energy dispersive spectroscopy*). Hasil studi yang diperoleh menunjukkan bahwa jenis kegagalan yang terjadi pada alat penukar kalor kompresor adalah korosi antar-butir akibat peristiwa sensitisasi yang terjadi. Disamping itu, kerusakan yang terjadi kemungkinan juga dipengaruhi oleh cacat las yang terbentuk yaitu berupa porositas gas.

Kata Kunci: Alat penukar kalor kompresor, investigasi kerusakan, korosi antar-butir, paduan aluminium tanpa pengerasan perlakuan panas, sensitisasi, cacat las (porositas)

Abstract

This study was carried out on a compressor heat exchanger (after-cooler) which leaked in the welded joint of a component made of non-heat-treatable aluminum alloys. The purpose of this study is to determine the type, cause, and mechanism of failure/damage in relation to the metallurgical structure that occurs. In this study, several tests were carried out including visual and macroscopic examinations, metallographic and hardness testing, and SEM (scanning electron microscope) analysis equipped with EDS (energy dispersive spectroscopy). The results show that the type of failure that occurs in the compressor after-cooler is intergranular corrosion due to the sensitization that occurred in the microstructure. In addition, the damage that occurs may also be influenced by the weld defect in the form of gas porosity.

Keywords: *Compressor heat exchanger (after-cooler), damage investigation, intergranular corrosion, non-heat treatable aluminum alloys, sensitization, welding defect (porosity)*

1. INTRODUCTION

As compressor heat exchanger (after-cooler) components are generally made of medium-strength aluminum alloys such as the AA5xxx and AA3xxx. Besides that, these aluminum alloys are also widely used for components in car air conditioners and other structural applications because they have a good combination of strength and formability[1],[2]. Such properties can be achieved by the mechanism of solid solution hardening and enhanced by deformation due to the high strain hardening behavior [3],[4]. The AA5xxx is the aluminum alloys in which magnesium (Mg) used as the principal alloying element, while the AA3xxx is the aluminum alloys in which manganese (Mn) used as the principal alloying element [5]. For further improvement in properties such as good weldability and high corrosion resistance, the alloys are also added with other solute elements in small amounts and/or modified by processing routes [6],[7]. Although by addition of other solute elements may have produced different types of intermetallic phases and could increase the strength of the alloys, however, they may lead to a higher susceptibility to localized corrosion [8],[9]. Due to the limited solubility of Mg or Mn in the aluminum matrix in both alloys at lower temperatures, the alloys become supersaturated and the excess alloying atoms together with other solute atoms would precipitate and form various intermetallic phases, preferentially at grain boundaries [1]-[2],[9]. Under certain conditions, either during fabrication/welding or in extended service at high temperatures, the solubility of principal alloying elements in the aluminum matrix will further decrease because they may interact with the existing intermetallic phases and form other new precipitates. This condition may result in a different concentration between the grains and the grain boundaries and makes the alloys sensitized and susceptible to intergranular corrosion, stress corrosion, or pitting corrosion [2],[8]–[9]. Many recently published works stated that the type of intermetallic phases that may play an important role in the intergranular corrosion and other localized corrosion on the non-heat-treatable aluminum alloys include Mg_2Si, Al_3Mg_5, Al_6 (Mn, Fe), Al_6 Mn, etc [1]-[2],[8].

The failed compressor after-cooler that used in this study consists of two separated pressure chambers, one is used to cool the hot stream of pressurized air from the compressor and the second is used to cool the hot stream of compressor lubricating oil. From the design and manufacture datasheet, it was mentioned that the failed compressor after-cooler is made of non-heat-treatable aluminum alloys of AA5xxx and AA3xxx, and fabricated by brazing and welding. In this study, the effect of welding that may have led to sensitization and intergranular corrosion of the after-cooler component was also evaluated in relation to the service fluid and environmental condition that occurs during operation.

2. Materials and Methods

The present work aims to study the damage mechanism that has caused a compressor after-cooler to leak. Figure 1 shows a leaked compressor after-cooler used in the present study. The after-cooler is equipped with two separated pressure chambers, namely compressor air cooler and compressor lubricating oil cooler. The operating data of the compressor after-cooler is as follows: duty of 897 BTU/min., and maximum working pressure of 150 psi. As indicated in Fig. 1, the leak is located at the oil cooler around the corroded area on the weld joint between the inlet header and the sidebar/parting sheet.

The design and construction of the failed after-cooler is a typical brazed aluminum plate-fin heat exchanger [10]. As seen in Figs. 1, 2, and 3, the after-cooler consists of a block (core) of alternating layers (passages) of corrugated fins. These corrugated fins consist of heat transfer fins to heat exchange the cooling air from the forced draft fan, and distributor fins to heat exchange the hot streams of pressurized air or compressor lubricating oil. The block is bounded by cap sheets at both sides, whereas all the layers that carrying the pressurized hot air or compressor hot lubricating oil are connected by headers with nozzles which are directly attached by welding on to the brazed core at the sidebars and parting sheets across the ports. From Fig.s 2 and 3, the header looks only joined using an external single fillet weld without any internal fillet weld. According to the ALPEMA [10]-[11], typical materials used for the construction of brazed aluminum plate-fin heat exchangers are non-heat-treatable aluminum alloys of AA3003 type for core matrix (fins, parting sheets, sidebars, and cap plate), and AA5083 type for header and nozzle.

As seen in Figs. 1 to 3, the after-cooler inlet nozzles are aimed to enter the pressurized hot air or compressor hot lubricating oil flow into the after-cooler, while the after-cooler outlet nozzles are aimed to remove the pressurized cold air or compressor cold lubricating oil flow out of the after-cooler. The pressurized hot air or compressor hot lubricating oil is collected in the port of inlet headers before being distributed through each passage containing distributor fins. On the way from the inlet header to the outlet header, the pressurized hot air or compressor hot lubricating oil flow within the passages containing distributor fins experiences heat loss due to heat exchange from the passages containing heat transfer fins. The extended surface of the heat transfer fins is cooled using ambient airflow driven by a forced draft fan.

A close-up view of the failed after-cooler shown in Fig. 4 reveals that the oil leak located on the linear crack that formed on the parting line of weld joint between inlet header and sidebar/parting sheet.

In this study, several specimens were prepared from the sectional parts of the failed after-cooler shown in Figures 2 and 3 for several laboratory examinations and analysis. Macroscopic examination on some damaged surface of the after-cooler was performed using a stereomicroscope. In addition, a metallographic examination was also performed using an optical microscope at various magnifications. The metallographic samples were mounted using epoxy and prepared by grinding, polishing, and etching. The etchant applied was Keller solution [12]. A hardness survey was also carried out on the same samples for the metallographic examination using the Vickers hardness method at a load of 2 kg (HV2). Moreover, examination of some damaged surfaces of the after-cooler was also performed using SEM (scanning electron microscopy) to determine the damaged surface topography and the nature of the failure. The SEM was also equipped with an EDS (energy dispersive spectroscopy) analysis to detect the presence of any corrosion by-product.

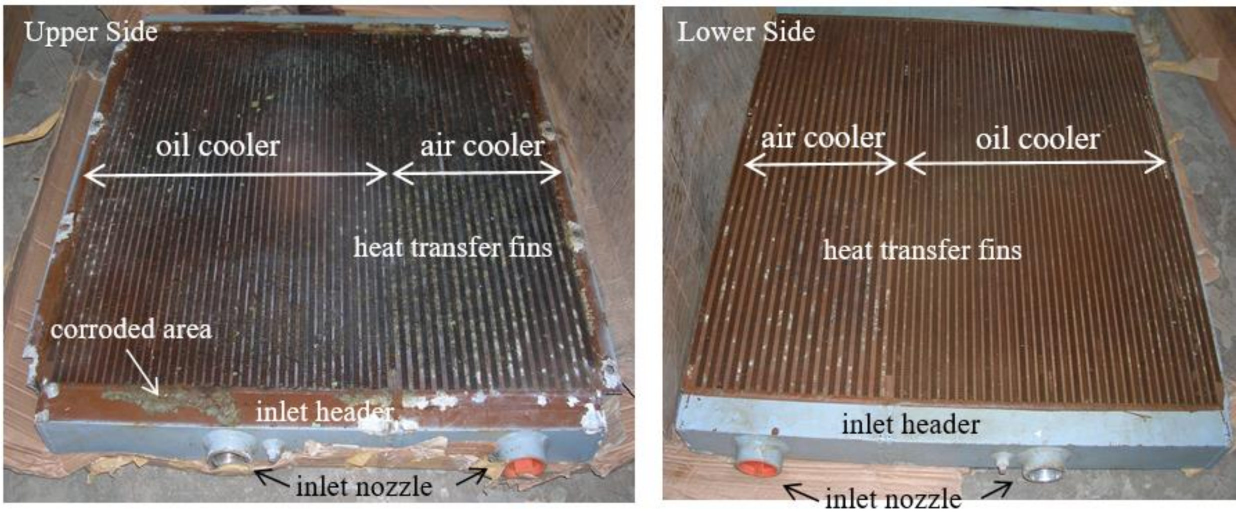


Figure 1. The leaked compressor after-cooler used in the present study, showing its upper side and lower side, respectively

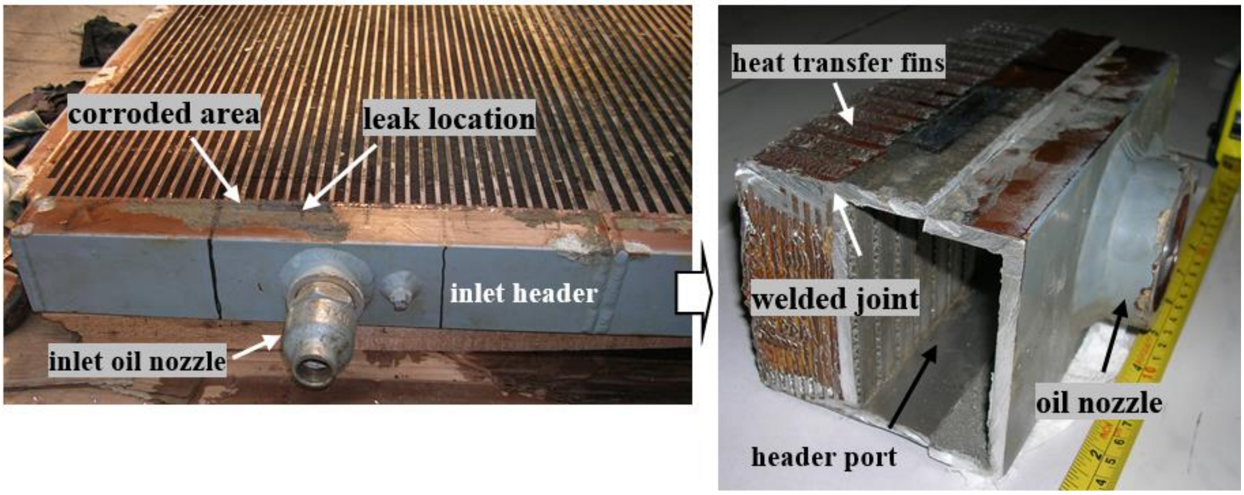


Figure 2. Cutting-off some parts of the compressor after-cooler around the leak location for samples preparation

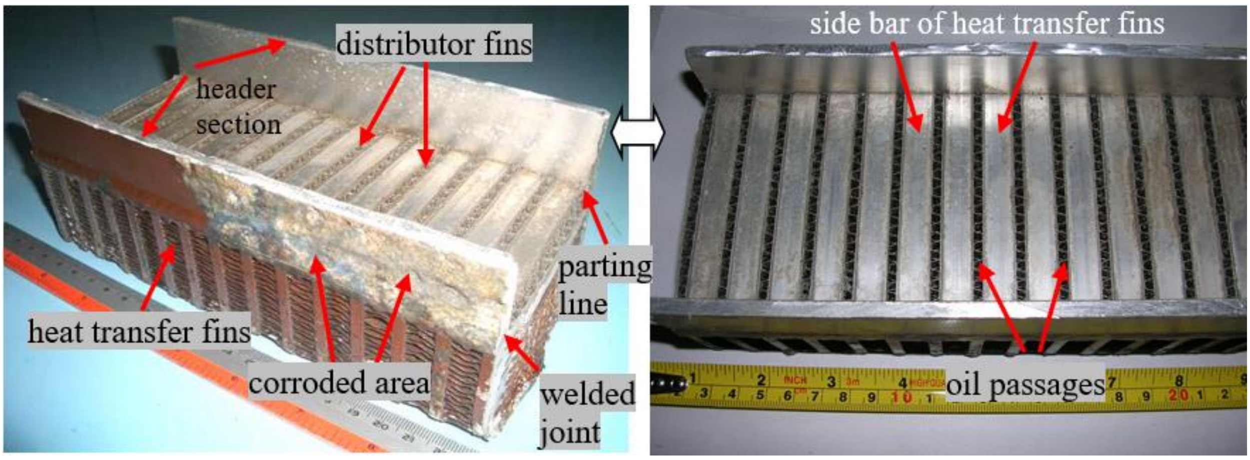


Figure 3. Close up view of the inside header port, showing several oil passages containing distributor fins and parting line of the weld joint between the header and sidebars/parting sheets

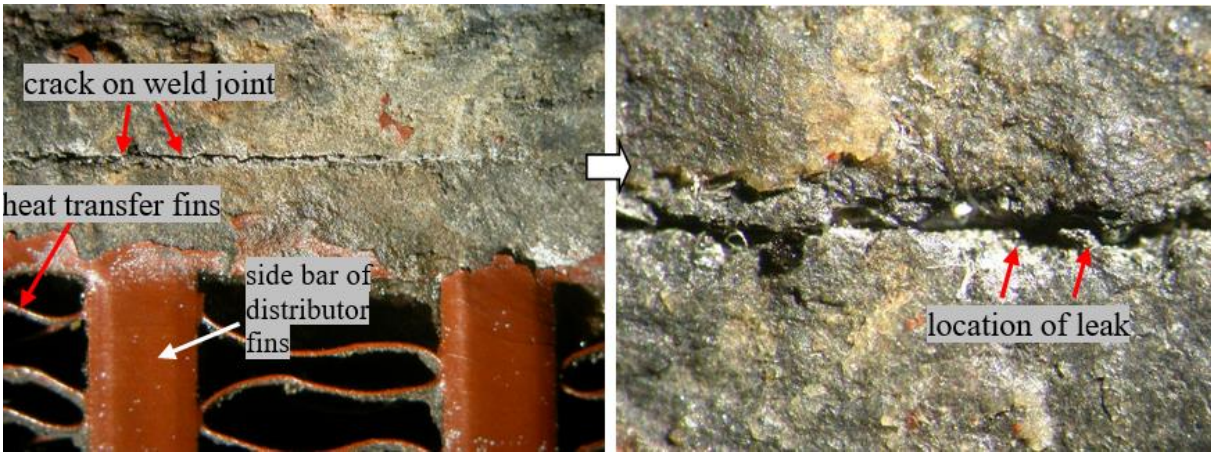


Figure 4. Close up view of the corroded surface around the weld joint of the leaked compressor after-cooler

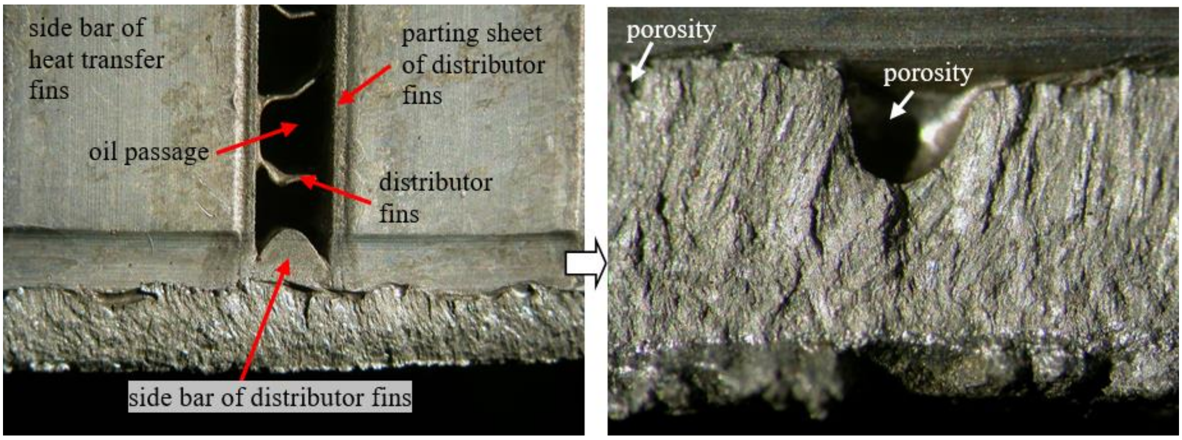


Figure 5. Fracture surface of the weld joint between header and sidebar/parting sheet

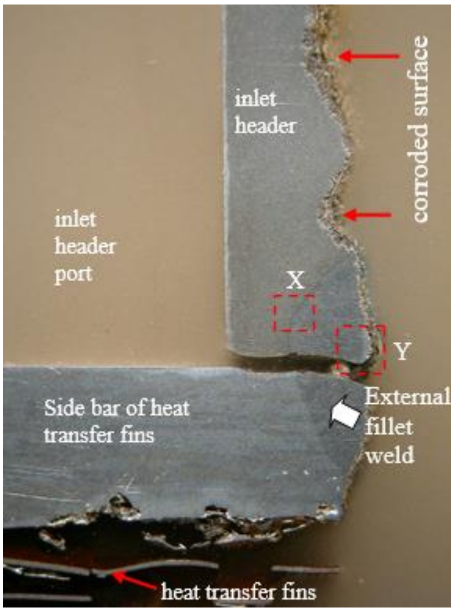


Figure 6. Cross section of a polished and etched specimen obtained from the leaked weld joint between header and sidebar/parting sheet

3. Results and Discussions

3.1. Visual and Macroscopic Examination

The results of the macroscopic examination obtained from the leaked area on the weld joint between the inlet header and the sidebar/parting sheet of the compressor after-cooler (see Fig. 4) are presented in Fig. 5. It can be seen from Fig. 5 that most of the weld fracture surface contained several voids due to gas porosity. In addition, the corrosion seems to have entered into the weld fracture surface. Besides that, the application of one single fillet weld may have further reduced the load-carrying capacity of the weld joint between the inlet header and the sidebar/parting sheet and therefore it was prone to cracking.

3.2. Metallographic Examination and Analysis

Figure 6 shows a cross-section of a polished and etched specimen obtained from the leaked weld joint between the inlet header and the sidebar of the after-cooler/oil cooler. The specimen shows a fracture line lied along the parting line between the header and the sidebar of heat transfer fins. The crack leading to the fracture was likely originated from the corroded weld surface. Microstructures obtained from the specimen shown in Fig. 6 are presented in Fig. 7 at different locations. In the weld joint of the header side shown in Fig. 7, the microstructures obtained are located around the WM (weld metal), HAZ (heat affected zone), and around the BM (base metal HAZ). The microstructure of weld metal generally shows a dendritic type, while the microstructure of the header material at its base metal shows typical wrought aluminum alloy microstructure containing fine particles of the intermetallic second phases [1],[2],[8]–[9]. Similarly, the microstructure obtained from the weld metal shown in Fig. 5 also apparently exhibits several large voids or porosity (see Fig. 8). This further confirms that the fillet weld between the inlet header and the sidebar/parting sheet of the compressor after-cooler contained some amount of weld defect. In addition, the microstructures are shown in Fig. 9 also exhibit the area with heavy damage of external corrosion. The corrosion damage on the weld metal surface in general shows typical interdendritic corrosion. This interdendritic corrosion may have been caused by sensitization that occurred on the weld metal due to formation of a number of intermetallic phases during welding process or in service at extended high-temperature exposure [1]-[2],[8]-[9].

Another specimen of metallographic examination was also obtained from the leaked weld joint between the inlet header and the parting sheet of distribution fins (see Fig. 9). The microstructures obtained are very much similar to those observed from the previous microstructures shown in Figs. 7 and 8. The fracture shown in Fig. 9 was most likely originated from the corroded weld surface that was heavily damaged by interdendritic corrosion and progressed into the internal port of the inlet header through the parting line between the header and the parting sheet of distributor fins. Similarly, the extended crack or fracture that occurred was most also likely influenced by some weld defect (porosities) that formed in the weld joint between the header and the parting sheet.

Details of the microstructure obtained from the corroded surface area of the inlet header are depicted in Fig. 10. It is seen that most of the header surface was severely affected by intergranular corrosion. Similar to the microstructures shown in Figs. 7, 8 and 9, this intergranular corrosion was most likely caused by sensitization due to the formation of some intermetallic phases at the grain boundaries [1]-[2],[8],[9].

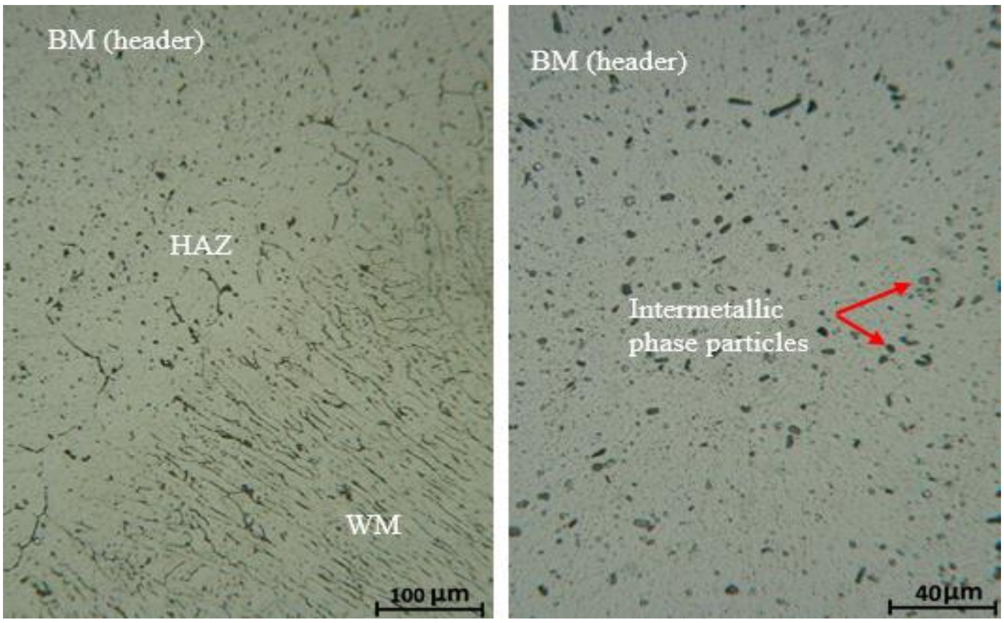


Figure 7. Microstructure obtained from the weld joint between header and sidebar/parting sheet at location X as indicated in Figure 6 (etched with Keller solution). Note BM is base metal, HAZ is heat-affected zone, and WM is weld metal

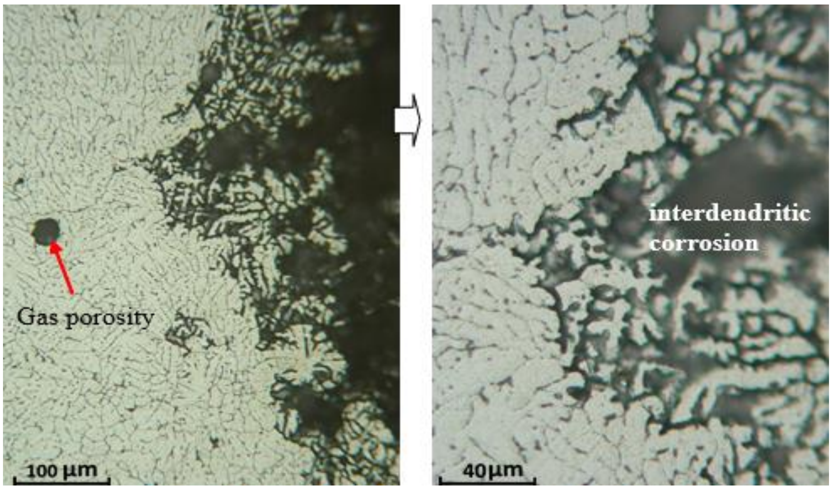


Figure 8. Microstructure obtained from the corroded weld metal of the header side at location Y as indicated in Figure 6 (etched with Keller solution)

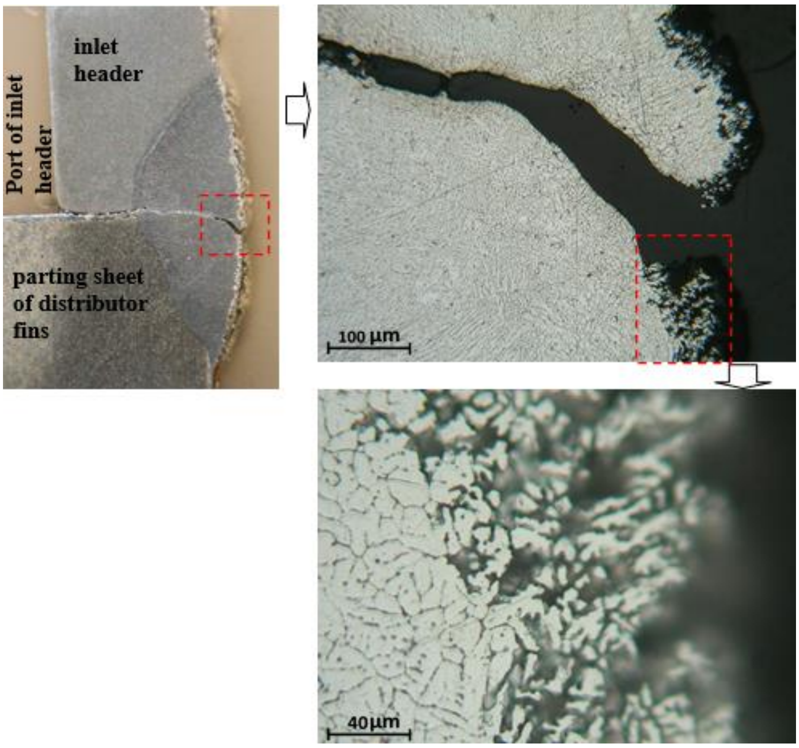


Figure 9. Microstructure obtained from the weld joint between header and parting sheet of distributor fins at location as indicated (etched with Keller solution)

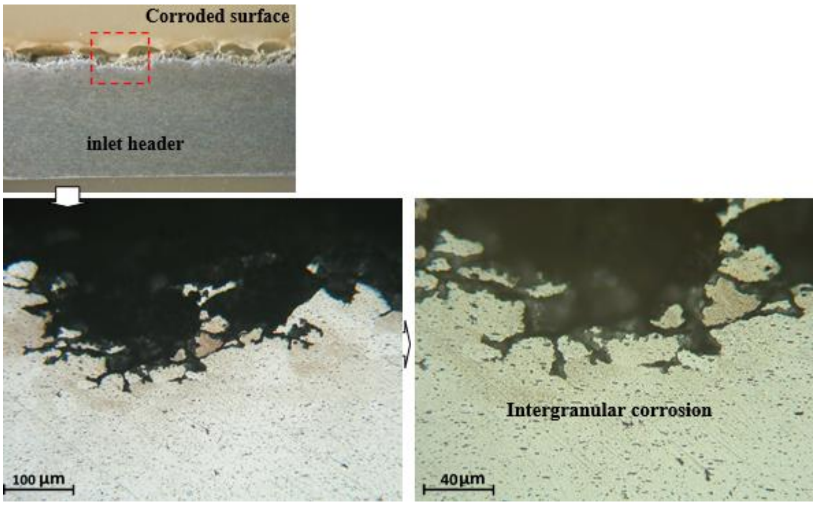


Figure 10. Microstructure obtained from the corroded area of the header surface at location as indicated (etched with Keller solution)

3.3. Hardness Test and Analysis

The hardness test was performed on the same metallographic specimen at different test locations (see Table 1). The results obtained show that the header base metal has hardness values in the range of 87.4-102 HV, i.e, slightly lower than its HAZ which is in the range of 94.6-105 HV. The hardness values of the weld metal are around 64.4 to 84.1 HV. Furthermore, the sidebar or parting sheet materials have hardness values in the range of 23.2-34.1 HV, i.e. lower than the hardness values of the sidebar or parting sheet material at its respective HAZ (24.4-59.3 HV). The higher hardness values obtained from the header material compared to the hardness values of the sidebar/parting sheet material indicated that both materials are made from different aluminum alloys. As mentioned in the ALPEMA standard [10]-[11], the header material is usually made of an aluminum alloy AA5083 type, whereas the sidebar/parting sheet material is usually made of an aluminum alloy AA3003 type. Both of these aluminum alloys belong to the non-heat-treatable alloys [5].

Table 1. Hardness survey (HV) obtained from various test locations of the metallographic sample shown in Figure 11

Test Location	Hardness (HV)
1	87.4
2	102.0
3	94.6
4	105.0
5	64.4
6	84.1
7	23.2
8	34.1
9	24.4
10	59.3

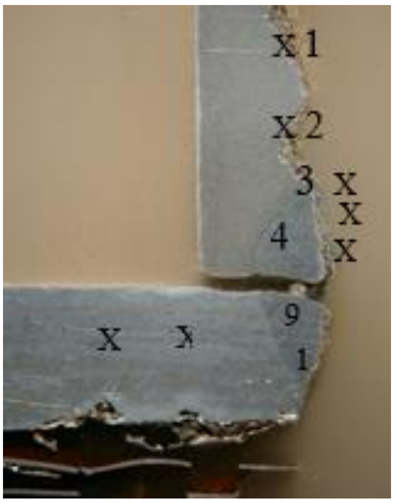


Figure 11. Various test locations for hardness survey

3.4. SEM Fractography and EDS Analysis

SEM fractography obtained from the fracture surface of the leaked after-cooler are presented in Fig. 12. The fractography obtained show the fracture surface of the weld joint between the header and the sidebar/parting sheet that contained many porosities. These porosities in some extent may have contributed to the crack or fracture formation. The crack seemed to initiate from the corroded surface of the weld joint and propagated into the weld defect (porosity) where the crack may have come to stop. However, the crack may have further continued to the nearest parting line between the header and the sidebar to complete the crack path. As seen clearly in Fig. 12, a large porosity appears to fill with some inclusions.

The EDS spectrum of elements obtained from the header fracture surface shown in Fig. 12 that experienced corrosion damage shows some major elements such as aluminum (Al), carbon (C), and oxygen (O) (see Fig. 13). The oxygen content obtained is much likely affected by the oxide formation due to corrosion (as corrosion product). Whereas the high carbon content found in the EDS spectrum may be influenced by some leakage of compressor hot lubricating oil that entered into the oil cooler. In addition to those elements, there are also other elements observed in the EDS spectrum such as magnesium (Mg), silicon (Si), sodium (Na), chloride (Cl) and calcium (Ca). Both elements of Mg and Si are the alloying elements of the aluminum alloy AA5xxx. The source of Na and Cl was most likely coming from the seawater and/or its moisture or maybe present from other aqueous environments. Figure 14 also shows the EDS spectrum of elements representing the corresponding composition of inclusion that formed inside a large porosity shown in Fig. 12. The inclusion is a typical aluminum oxide that likely formed from the filler metal used during welding.

Another result of the EDS analysis obtained from the corroded surface area located around the edge of the header and the weld fracture surface is presented in Fig. 15. Most of the result obtained indicated that oxygen (O) and carbon (C) along with aluminum (Al) and its alloying elements such as Si, Mg, Fe, Zn and some sulfur (S), chloride (Cl) and calcium (Ca) were detected on much of the corroded surface scale/corrosion product.

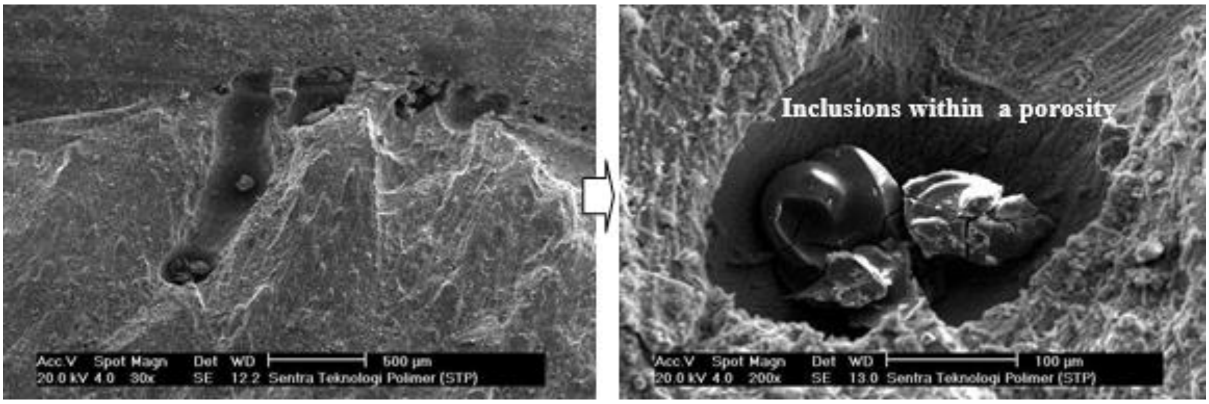
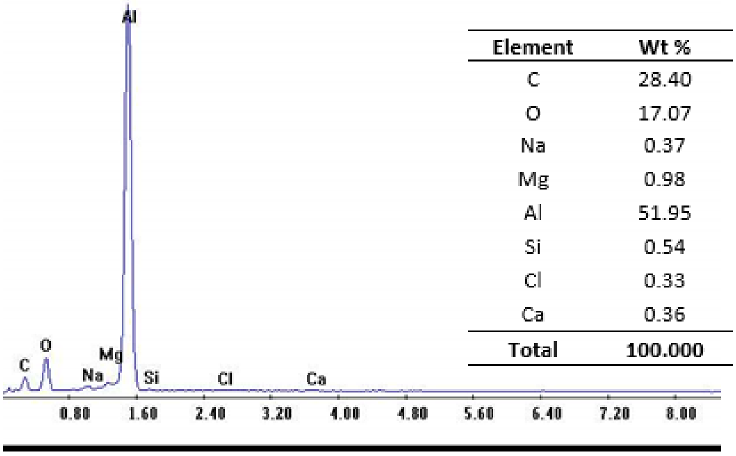
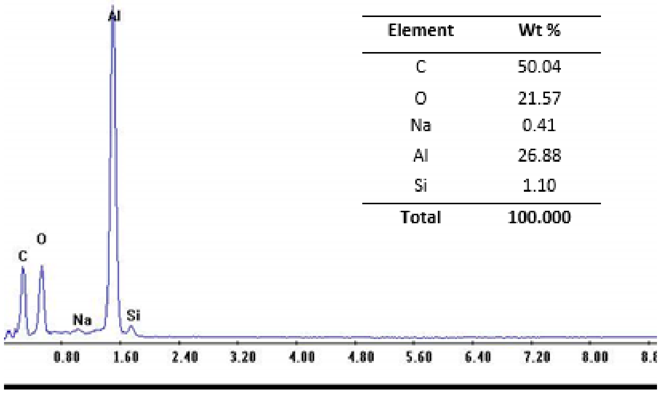


Figure 12. SEM micro fractography of the through fracture surface obtained from the leak area of the weld joint between the header and the sidebar/parting sheet, showing some inclusions within the weld defect



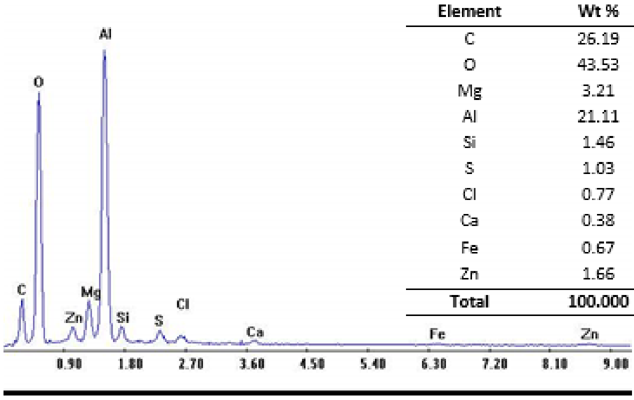
Element	Wt %
C	28.40
O	17.07
Na	0.37
Mg	0.98
Al	51.95
Si	0.54
Cl	0.33
Ca	0.36
Total	**100.000**

Figure 13. EDS spectrum of elements obtained from the header fracture surface shown in Fig. 12



Element	Wt %
C	50.04
O	21.57
Na	0.41
Al	26.88
Si	1.10
Total	**100.000**

Figure 14. EDS spectrum of elements obtained from the inclusion formed in the weld defect (porosity) shown in Fig. 12



Element	Wt %
C	26.19
O	43.53
Mg	3.21
Al	21.11
Si	1.46
S	1.03
Cl	0.77
Ca	0.38
Fe	0.67
Zn	1.66
Total	**100.000**

Figure 15. EDS spectrum of elements obtained from the corroded header surface shown in Fig. 10

Based on the test results obtained from the EDS analysis, metallographic examination and hardness test, the material used for the header, sidebar, and parting sheet of the failed after-cooler are typical of wrought aluminum alloys. Some difference in hardness values observed on the header material in comparison with the sidebar and the parting sheet material is probably influenced by the difference in the chemical composition of the material. The header material is likely made of aluminum alloy AA5xxx series, while the sidebar/parting sheet material is probably made of aluminum alloy AA3xxx series. These two aluminum alloys belong to the non-heat-treatable alloys which are well known to have good properties for brazing and welding [6],[10]-[11].

The weld joint failure of the after-cooler in the present study was most likely caused by the combination of external corrosion (intergranular/interdendritic corrosion) and some welding defects (porosity) formed at the parting joint between the header and the sidebar/parting sheet of the corrugated fins. This may have led the compressor after-cooler to leak. The crack propagation would be accelerated in combination with the external corrosion that occurred on the weld joint surface that may have significantly reduced the effectiveness of the weld joint area. The external corrosion would have resulted from the high Cl and/or S levels obtained on the most corroded/fracture surfaces of the failed after-cooler (see Figs. 13 and 15). Chloride is the most important halide ion that has the greatest effect in accelerating attack in most aluminum alloys [3]. The source of this chloride could be coming from the natural constituent of the marine environment or other environments. The external corrosion observed in the present study is a typical intergranular or interdendritic corrosion (see Figs. 8 to 10). Some aluminum alloys that contain an appreciable amount of soluble alloying elements, primarily magnesium, silicon, copper, and zinc, are known susceptible to intergranular/ interdendritic corrosion [1], [2], [8]–[9].

The aforementioned mechanism of external corrosion and weld defect would cause a lowering of the load-carrying capacity of the weld joint and hence initiated failure of the weld joint during operation. Crack propagation may have also been accelerated by cyclic stresses induced by the internal pressure of the oil stream/flow or by flow-induced vibration of the after-cooler during operation.

In addition to the external corrosion and weld defect, the premature failure of the compressor after-cooler was also likely caused by insufficient weld design as the weld joint between the header and the sidebar/parting sheet of the after-cooler only used a single fillet weld. The application of another fillet weld on the inside parting line between header and sidebar/parting sheet may improve the load-carrying capacity of the weld joint structure, and hence it may increase the operating life of the after-cooler significantly.

4. CONCLUSIONS

The results of the EDS (energy dispersive spectroscopy) analysis, metallographic examination, and hardness test of the material used for both the header and the sidebar/parting sheet of the corrugated fins are likely according to the material specification of the non-heat-treatable wrought aluminum alloys of AA5xxx and AA3xxx series, respectively.

According to the fracture morphology and mode of failure, the leaked after-cooler under investigation had experienced a combination effect of the external corrosion and welding defect (porosities). Most of the external corrosion was concentrated on some particular area of the header/weld joint surface where the leak was found. The external corrosion was a typical interdendritic/intergranular corrosion and very much likely caused by some aqueous environment containing corrosive agents such as Cl, Na, and/or S.

The most possible source of Cl and/or Na content was the marine environment or from other environments. Sulfur (S) as being other corroding agents towards the acceleration of interdendritic/intergranular corrosion of the header/weld joint was also found in the corroded area. The source of S that had only contaminated some particular area of the header/weld joint surface of the failed after-cooler may be coming from the compressor hot lubricating oil.

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