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

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Abstrak

Studi Kerusakan Sambungan Las Komponen Aluminium Sebuah Alat Penukar Kalor Kompresor

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 microscopy) 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 *gas porosity*.

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

Abstract

This study was carried out on a compressor heat exchanger (after-cooler) which had a leak 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 a number of tests were carried out including visual and macroscopic examinations, metallographic and hardness testing, and SEM (scanning electron microscopy) 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 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

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 amount 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 the 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, 10]. Under certain conditions, either during fabrication/welding or in extended service at high temperatures, the solubility of principal alloying element 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 become sensitized and susceptible to intergranular corrosion, stress corrosion or pitting corrosion [2, 8-10]. In 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 data sheet, 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 with the service fluid and environment condition that occur during operation.

2. MATERIALS AND METHOD

The present work aims to study 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 psig. As indicated in Figure 1, the leak is located at the oil cooler around the corroded area on the weld joint between the inlet header and the side bar/parting sheet.

Design and construction of the failed after-cooler is a typical brazed aluminium plate-fin heat exchanger [11]. As seen in Figures 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 together by headers with nozzles which are directly attached by welding on to the brazed core at the side bars and parting sheets across the ports. From Figures 2 and 3, the header looks only joined using an external single fillet weld without any internal fillet weld. According to the ALPEMA [11,12], 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, side bars and cap plate), and AA5083 type for header and nozzle.

As seen in Figures 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 are 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 enchange from the passages containing heat transfer fins. The extended surface of the heat transfer fins are cooled using ambient airflow driven by a forced draft fan.

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

In this study, a number of 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 damage surface of the after-cooler was performed using a stereo microscope. In addition, 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 [13]. 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 on some damage surface of the after-cooler was also performed using scanning electron microscopy (SEM) to determine the damage surface topography and nature of the failure. The SEM was also equipped with an energy dispersive spectroscopy (EDS) analysis to detect the presence of any corrosion by-product.

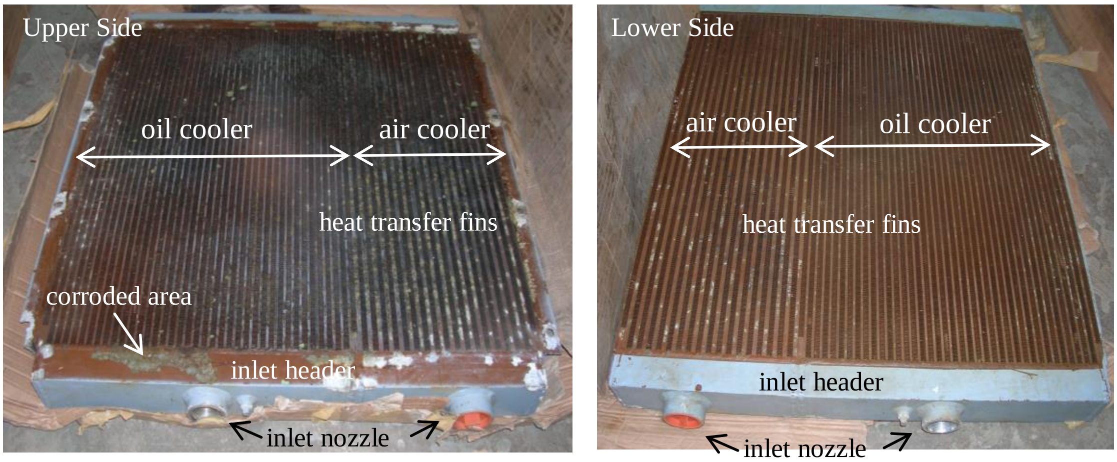


Figure 1. The leaked compressor after-cooler used in the present study, showing its upper side and lower side, respectively.

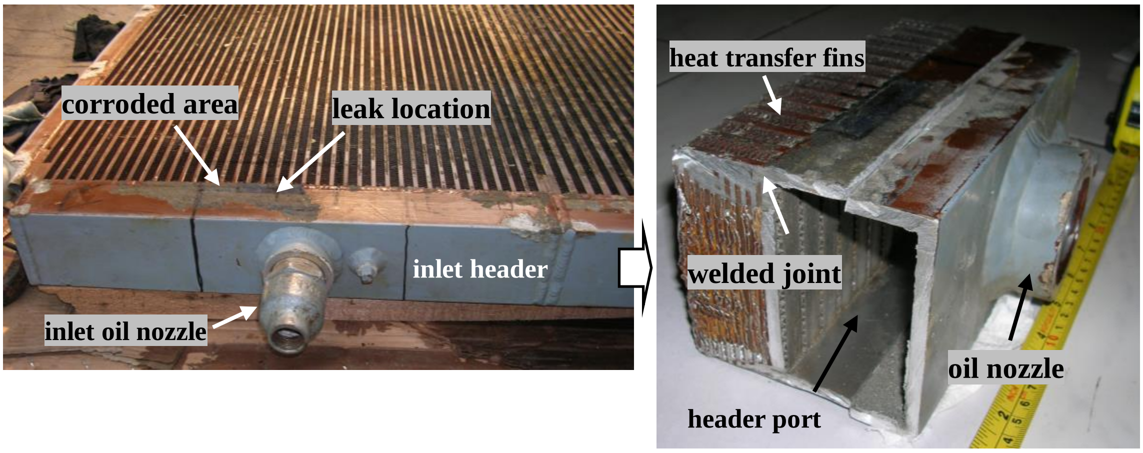


Figure 2. Cutting-off some parts of the compressor after-cooler around the leak location for samples preparation

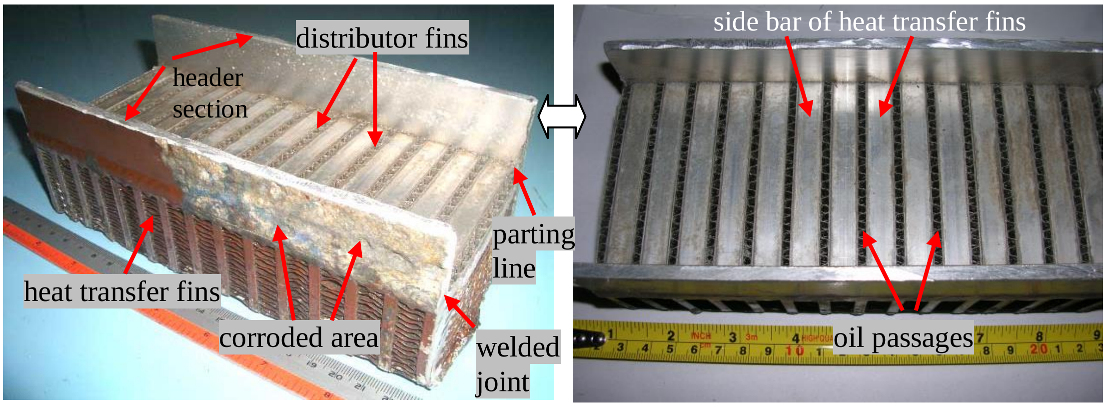


Figure 3. Close up view of the inside header port, showing a number of oil passages containing distributor fins and parting line of the weld joint between header and side bars/parting sheets.

3. Results

3.1. Visual and Macroscopic Examination

The results of macroscopic examination obtained from the leaked area on the weld joint between the inlet header and the side bar/parting sheet of the compressor after-cooler (see Figure 4) are presented in Figure 5. It can be seen from Figure 5 that most of the weld fracture surface apparently contained a number of voids due to gas porosity. In addition, the corrosion seems to have entered into the weld fracture surface. Beside 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 side bar/parting sheet and therefore it was prone to cracking.

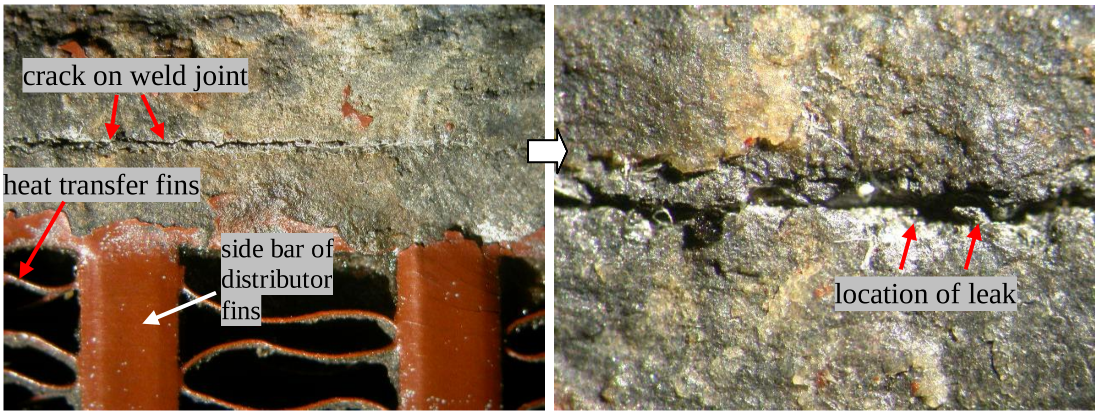


Figure 4. Close up view of the corroded surface around the weld joint of the leaked compressor after-cooler.

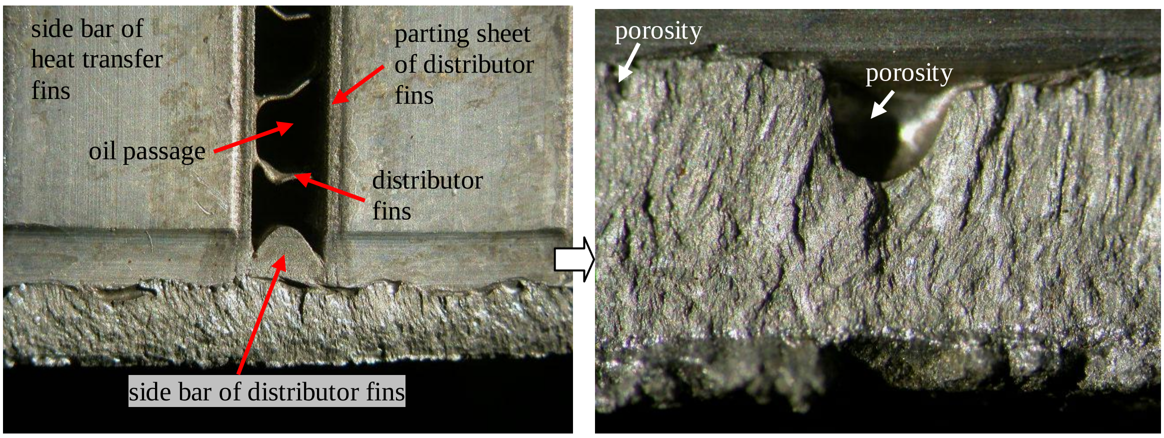


Figure 5. Fracture surface of the weld joint between header and side bar/parting sheet

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 side bar of the after-cooler/oil cooler. The specimen shows a fracture line lied along the parting line between the header and the side bar of heat transfer fins. The crack leading to fracture was likely originated from the corroded weld surface. Microstructures obtained from the specimen shown in Figure 6 are presented in Figure 7 at different locations. In the weld joint of the header side shown in Figure 7a, the microstructures obtained are located around the weld metal (WM), heat affected zone (HAZ) and around the base metal (BM). 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 [1,2,8-10]. Similarly, the microstructure obtained from the weld metal shown in Figure 5 also apparently exhibits a number of large voids or porosity (see Figure 7b). This further confirms that the fillet weld between the inlet header and the side bar/parting sheet of the compressor after-cooler contained some amount of weld defect. In addition, the microstructures shown in Figure 7b 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, 10].

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 Figure 8). The microstructures obtained are very much similar with that observed from the previous microstructures shown in Figure 7. The fracture shown in Figure 8 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 occurred was most also likely influenced by some weld defect (porosities) that formed in the weld joint between header and the parting sheet.

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

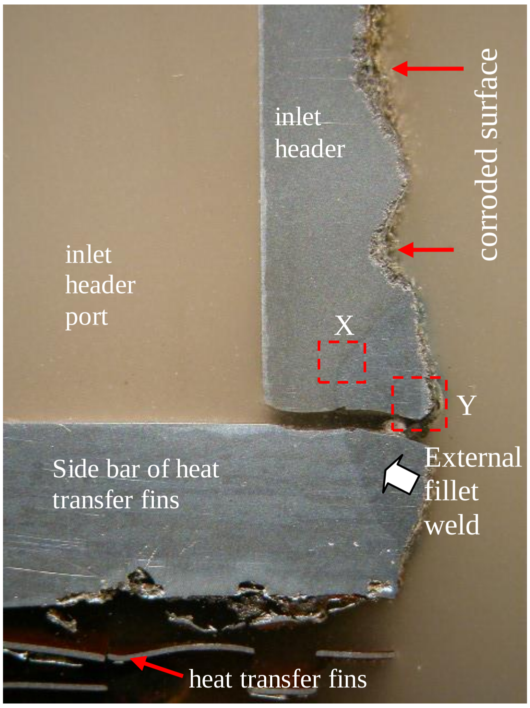


Figure 6. Cross section of a polished and etched specimen obtained from the leaked weld joint between header and side bar/parting sheet

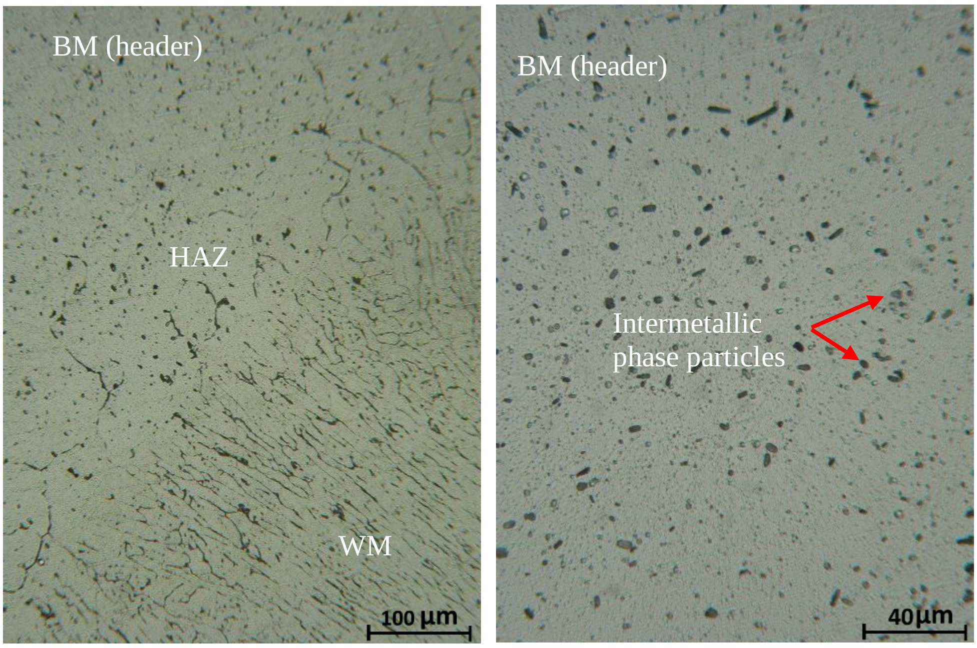


Figure 7a. Microstructure obtained from the weld joint between header and side bar/parting sheet at location X as indicated in Figure 6 (etched with Keller solution). Note BM is base metal, HAZ is heat-affected zone, and WM is weld metal.

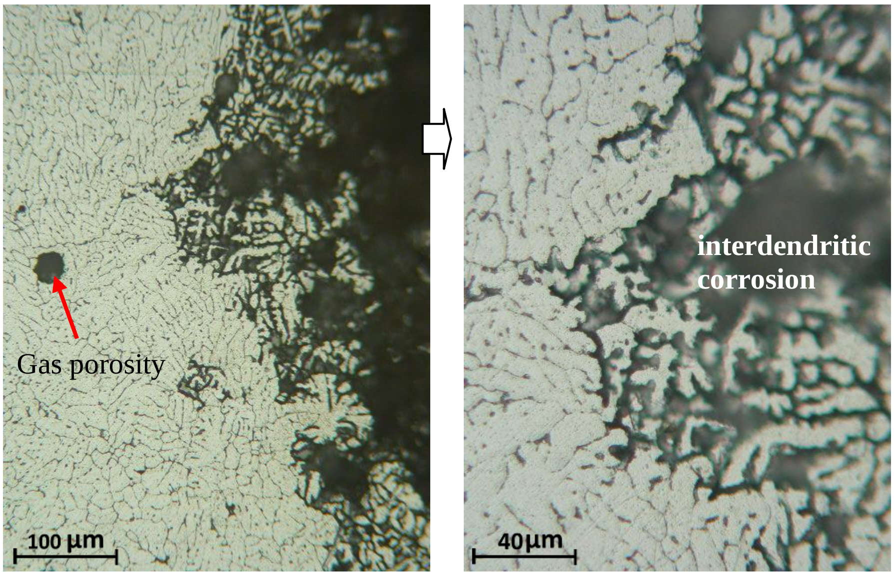


Figure 7b. Microstructure obtained from the corroded weld metal of the header side at location Y as indicated in Figure 6 (etched with Keller solution)

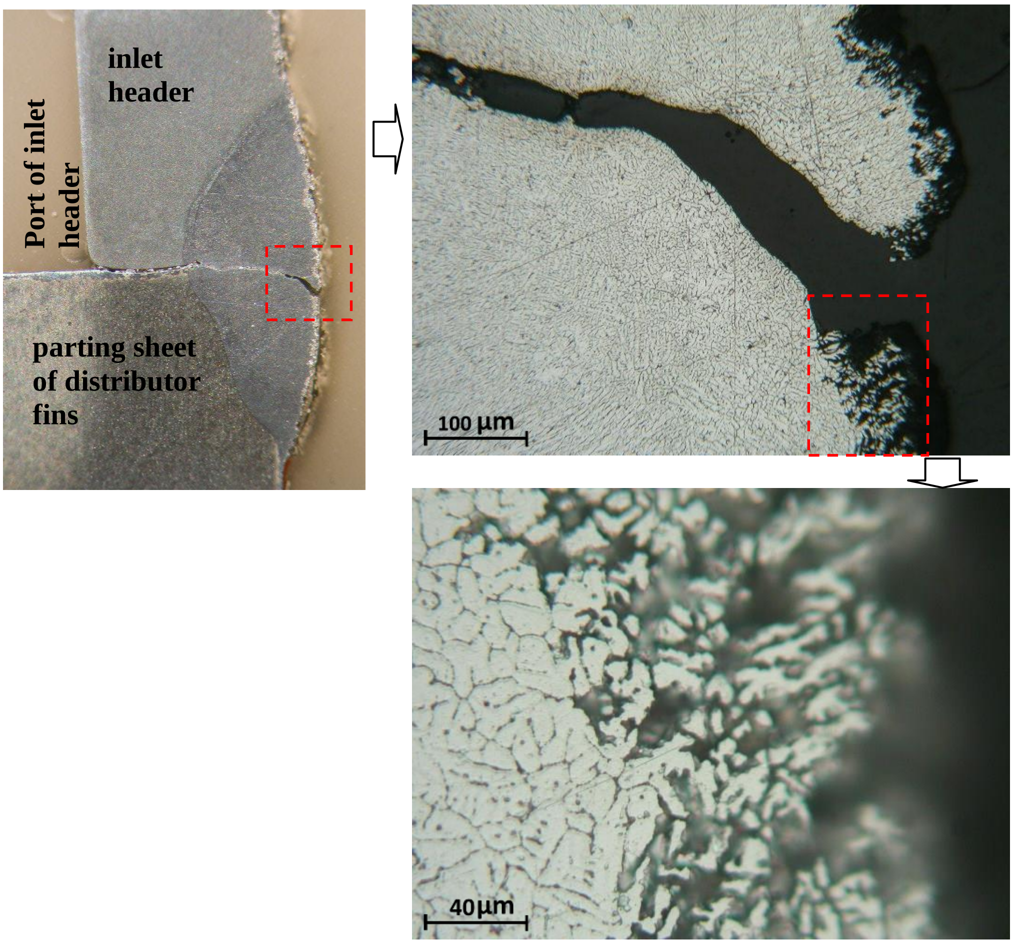


Figure 8. Microstructure obtained from the weld joint between header and parting sheet of distributor fins at location as indicated (etched with Keller solution)

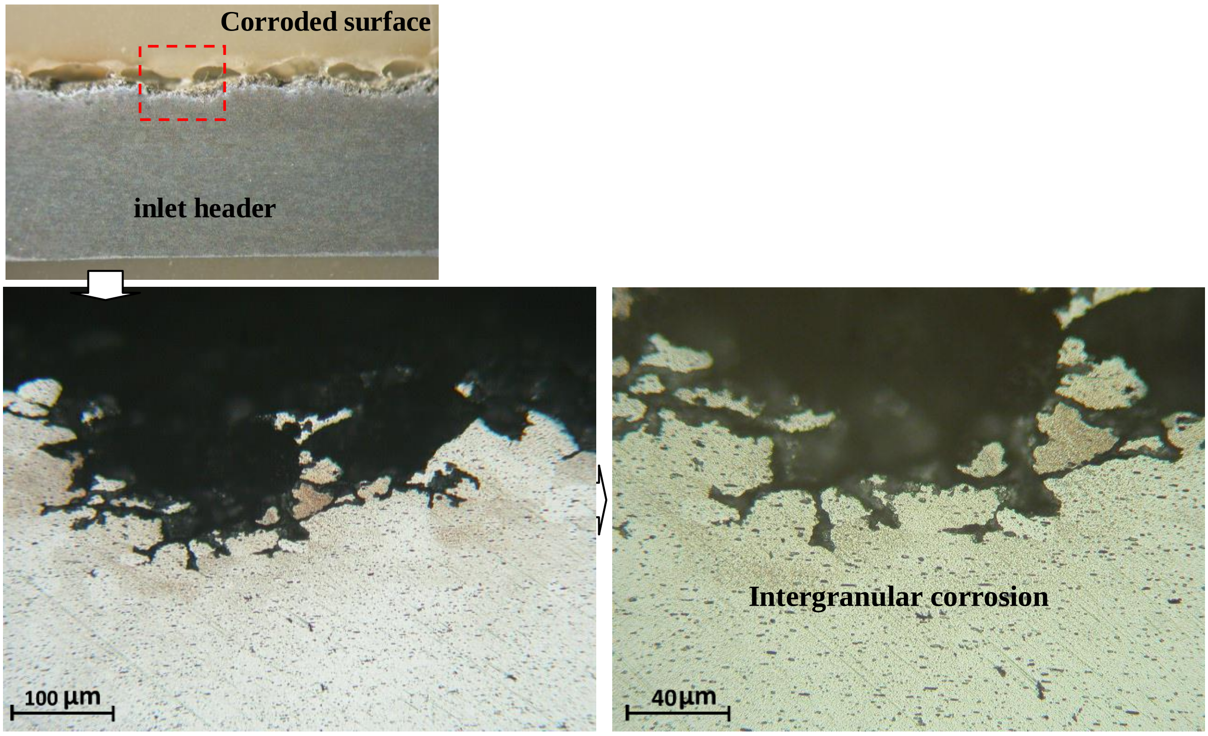


Figure 9. Microstructure obtained from the corroded area of the header surface at location as indicated (etched with Keller solution)

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 side bar or parting sheet materials have the hardness values in the range of 23.2-34.1 HV, i.e. lower than the hardness values of the side bar 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 side bar/parting sheet material indicated that both materials are made from different aluminum alloys. As mentioned in the ALPEMA standard [11,12], the header material is usually made of an aluminum alloy AA5083 type, whereas the side bar/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 10.

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

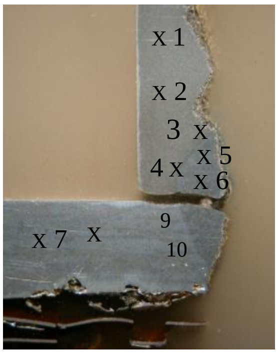


Figure 10. Various test locations for hardness survey

3.4. SEM Fractography and EDS Analysis

SEM fractographs obtained from fracture surface of the leaked after-cooler are presented in Figure 11. The fractographs obtained show the fracture surface of the weld joint between the header and the side bar/parting sheet that apparently contained a number of 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 header and the side bar to complete the crack path. As seen clearly in Figure 11, a large porosity appears to fill with some inclusions.

The EDS spectrum of elements obtained from the header fracture surface shown in Figure 11 that experienced corrosion damage shows some major elements such as aluminum (Al), carbon (C) and oxygen (O) (see Figure 12). 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 may be present from other aqueous environment. Figure 13 also shows the EDS spectrum of elements representing the corresponding composition of inclusion that formed inside a large porosity shown in Figure 11. The inclusion is a typical aluminum oxide that likely formed from the filler metal used during welding.

Other 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 Figure 14. 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.

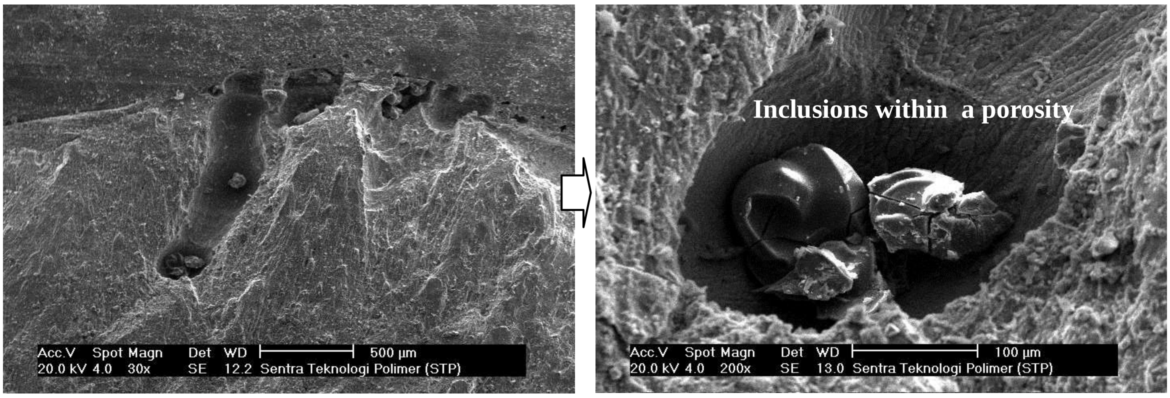
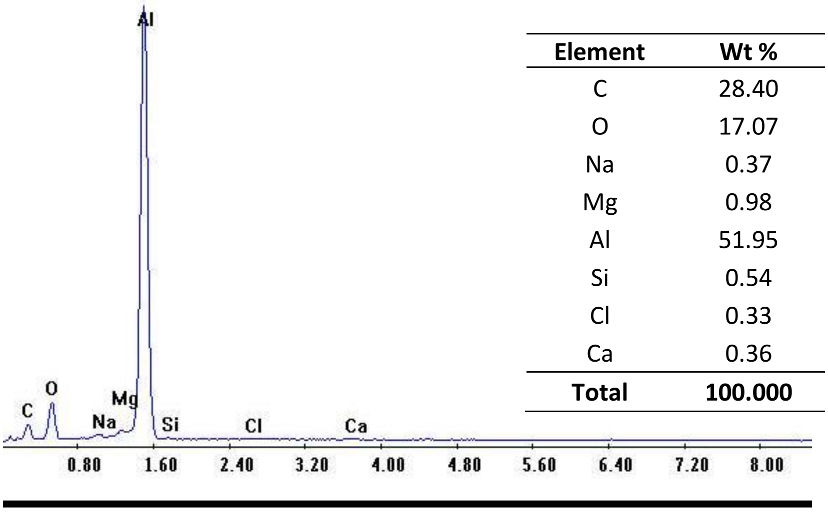
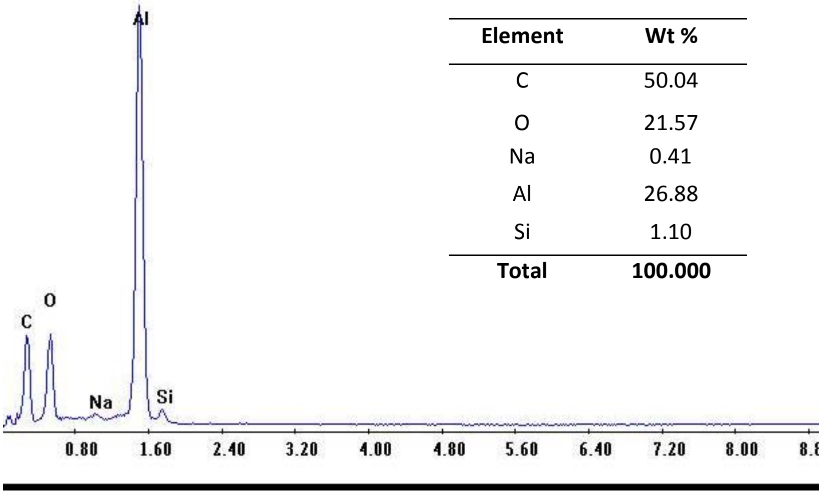


Figure 11. SEM microfractograph of the through fracture surface obtained from the leak area of the weld joint between the header and the side bar/parting sheet, showing some inclusions within the weld defect.



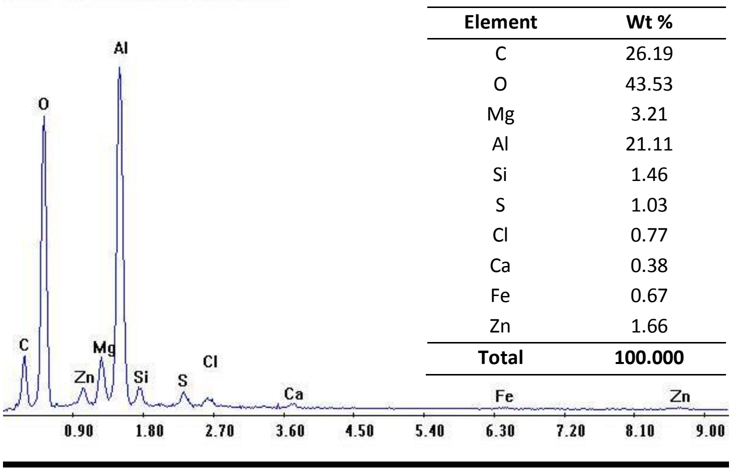
Element	Wt %
C	28.40
O	17.07
Na	0.37
Mg	0.98
Al	51.95
Si	0.54
Cl	0.33
Ca	0.36
Total	**100.000**

Figure 12. EDS spectrum of elements obtained from the header fracture surface shown in Figure 11.



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

Figure 13. EDS spectrum of elements obtained from the inclusion formed in the weld defect (porosity) shown in Figure 11.



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 14 EDS spectrum of elements obtained from the corroded header surface shown in Figure 9.

4. DISCUSSION

Based on the test results obtained from the EDS analysis, metallographic examination and hardness test, the material used for header, side bar and parting sheet of the failed after-cooler are basically typical of wrought aluminum alloys. Some difference in hardness values observed on the header material in comparison with the side bar and the parting sheet material is probably influenced by the difference in chemical composition of the material. The header material is likely made of aluminum alloy AA5xxx series, while the side bar/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, 11, 12].

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 side bar/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 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 Figures 12 and 14). 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 marine environment or from other environment. The external corrosion observed in the present study is a typical intergranular or interdendritic corrosion (see Figures 7 to 9). Some aluminum alloys that contain appreciable amount of soluble alloying elements, primarily magnesium, silicon, copper and zinc, are known susceptible to intergranular/ interdendritic corrosion [1, 2, 8, 9, 10].

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 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 side bar/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 side bar/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.

5. CONCLUSIONS

The results of the EDS analysis, metallographic examination and hardness test of the material used for both of the header and the side bar/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 were 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 agent 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 on 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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REFERENCES

[1] M. Yoshino, S. Iwao, M. Edo, and H. Chiba, "Mechanism of intergranular corrosion of brazed Al-Mn-Cu alloys with various Si content", *Materials Transactions*, vol. 58, issue 5, pp. 768-775, 2017

[2] W. Wei, *Study of sensitization in AA 5083 aluminum alloy*, Ph. D Thesis Faculty of Science and Engineering, University of Manchester, 2017

[3] O.M. Alyousif and R. Nishimura, "The effect of applied stress on environment-induced cracking of aluminum alloy 5052-H3 in 0.5 M NaCl solution", *Int. J. Corrosion*, vol. 8, pp 1-5, 2012

[4] Y. Oya, Y. Kojima and N. Hara, "Influence of silicon on intergranular corrosion for aluminum alloys", *Materials Transactions*, vol. 54, No. 7, pp. 1200-1208, 2013

[5] J.R. Davis, *Aluminum and Aluminum Alloys*, ASM International, pp. 351-416, 2001

[6] L. Radovic, M. Bucko and M. Miladinov, "Corrosion behavior of TIG welded AlMg6Mn alloy", *Scientific Technical Review*, vol. 66, no.2, pp. 10-17, 2016

[7] Y. Kailin, S. Hai wang, R. Yu Chen, T. Sheng Hsieh, L. Tsai, and C. Chin Chiang," The effect of heat treatment on the sensitized corrosion of the 5383-H116 Al-Mg alloy", *Materials*, 10, 275, pp. 1-9, 2017

[8] V.S. Sinyavskii, V.V. Ulanova and V.D. Kalinin, "On the mechanism of intergranular corrosion of aluminum alloys," *J. Protection of Metals*, vol. 40, no. 5, pp. 481-490, 2004

[9] Y. Oya, Y. Kojima and N. Hara, "Influence of silicon on intergranular corrosion for aluminum alloys," *J. Japan Institute of Metals*, vol. 78, no.1, pp. 52-59, 2014

[10] S. Kumari, S. Wenner, J.C. Walmsley, O. Lunder, and K. Nisancioglu, "Progress in understanding initiation of intergranular corrosion on AA 6005 aluminum alloy with low copper content", *J. Electrochemical Society*, vol 166, no. 11, pp. C3114-C3123, 2019

[11] *The Standard of The Brazed Aluminum Plate-Fin Heat Exchanger Manufacturers' Association (ALPEMA)*, Second Edition, 2000

[12] J. R. Thome, "The new 3rd edition of the ALPEMA plate-fin heat exchanger standards", *Heat Transfer Engineering*, vol. 31, no. 1, pp. 1-2, 2010

[13] M. Warmuzek, *Metallographic Techniques for Aluminum and Its Alloys*, Metallography and Microstructures, ASM

Handbook, vol. 9, ASM International, p. 711-751, 2004