STUDY OF INTERGRANULAR CORROSION ON NON-HEAT TREATABLE ALUMINUM ALLOYS IN A COMPRESSOR AFTER-COOLER

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Abstrak

Studi Korosi Antar-Butir pada Paduan Aluminium Tanpa Pengerasan Perlakuan Panas pada Sebuah Alat Penukar Kalor Kompresor

Studi ini dilakukan pada sebuah alat penukar kalor kompresor yang mengalami kebocoran pada bagian sambungan las komponennya yang terbuat dari paduan aluminium tanpa pengerasan perlakuan panas. Tujuan dari studi ini adalah menentukan jenis dan faktor penyebab serta mekanisme kegagalan 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 mekanisme kegagalan yang menyebabkan terjadinya kebocoran pada sambungan las paduan aluminium komponen alat penukar kalor kompresor adalah korosi antar-butir akibat peristiwa sensitisasi yang terjadi dan akibat faktor lingkungan yang terkait. Disamping itu, kerusakan yang terjadi kemungkinan juga dipengaruhi oleh cacat las berupa *pinholes*.

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

Abstract

This study was carried out on a compressor heat exchanger (after-cooler) which had a leak in the welded joint of its components made of non-heat treatable aluminum alloys. The purpose of this study is to determine the type and cause, and mechanisms of failure associated with the metallurgical structure that occurs. In this study a number of tests have been 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 of the study obtained indicate that the failure mechanism that causes leakage in the aluminum alloy welding joints of the compressor heat exchanger component is intergranular corrosion due to sensitization and the related effect of environmental factors that occur. In addition, the failure may also be affected by welding defect in the form of pinholes.

Keywords*: Compressor heat exchanger (after-cooler), intergranular corrosion, non-heat treatable aluminum alloys, sensitization, weld defect (pinholes).*

1. INTRODUCTION

The medium strength of non-heat treatable aluminum alloys such as AA5xxx and AA3xxx are widely used for heat exchangers in air compressor after-cooler, automobile air conditioner and others in structural applications due to different 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) is the principal alloying element, while the AA3xxx is the aluminum alloys in which manganese (Mn) is the principal alloying element [5]. In addition to the principal alloying element, 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]. By addition of other solute elements, although they may have produced different types of intermetallic phases in the alloys and could increase the strength, however they may lead to a higher susceptibility to the localized corrosion [8,9]. Due to the limited solubility of Mg or Mn in aluminum matrix of both alloys at lower temperatures, the alloys become supersaturated and the excess alloying atoms together with other solute atoms would precipitate to form various intermetallic phases, preferentially at grain boundaries [1-2, 10]. Under certain conditions, either during fabrication/welding or in service at extended high temperature exposure, the solubility of principal alloying element in the aluminum matrix will further decrease because some of them will joint or interact with the existing intermetallic phases or form other intermetalic phases of new precipitates preferentially at the grain boundaries. This condition induces a concentration difference 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 it was stated that the type of intermetallic phases that may play an important role in the intergranular corrosion and other localized corrosion in the non-heat treatable aluminum alloys include Mg_2Si, Al_3Mg_5, Al_6 (Mn, Fe), Al_6 Mn, etc [1,2,8].

In relation with the intergranular corrosion caused by sensitization on the non-heat treatable aluminum alloys as mentioned above, a failure case on a compressor after-cooler was studied. This compressor after-cooler is a typical brazed aluminum plate-fin heat exchanger. 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 on the weld joint 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 frequently caused a compressor after-cooler to leak. Figure 1 shows a leaked compressor after-cooler that was used for the present study. The after-cooler was equipped with two separated or independent pressure chambers, namely compressor air cooler and compressor lubricating oil cooler. 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. Heat transfer fins are used to heat exchange the cooling air from the forced draft fan, while distributor fins are used 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 hot pressurized air or hot compressor 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, it can be seen that the header is only welded from the outside of the side bar/parting sheet using a single fillet joint and no such fillet weld is given at the internal parting line between the header and the side bar/parting sheet. 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 or nozzle.

As seen in Figures 1 to 3, the after-cooler inlet nozzles are aimed to enter the hot pressurized air or hot compressor lubricating oil flow into the after-cooler, while the after-cooler outlet nozzles are aimed to exit the cold pressurized air or cold compressor lubricating oil flow out of the after-cooler. The hot pressurized air or hot compressor 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 hot pressurized air or hot compressor 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 is cooled using ambient air flow driven by a forced draft fan.

A close up view of the failed after-cooler around the leak location is given in Figure 4. It is seen that the location of oil leak on the after-cooler is a 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 cut away from the sectional part 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 performed using an optical light microscope at various magnifications. The metallographic samples were mounted using epoxy and prepared by grinding, sanding, 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 as received failed compressor after-cooler that was used for the present study

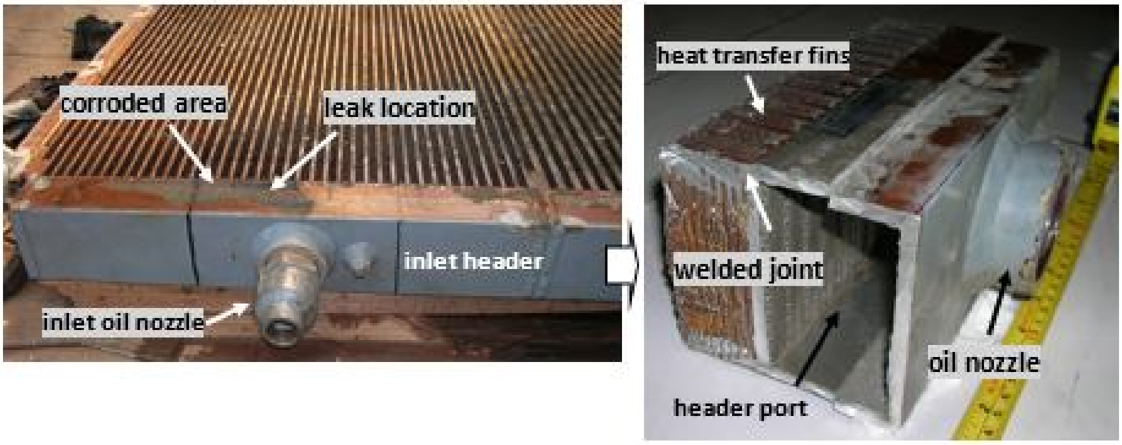


Figure 2. Cutting-off the failed after-cooler around the leak location for sample preparation and examination

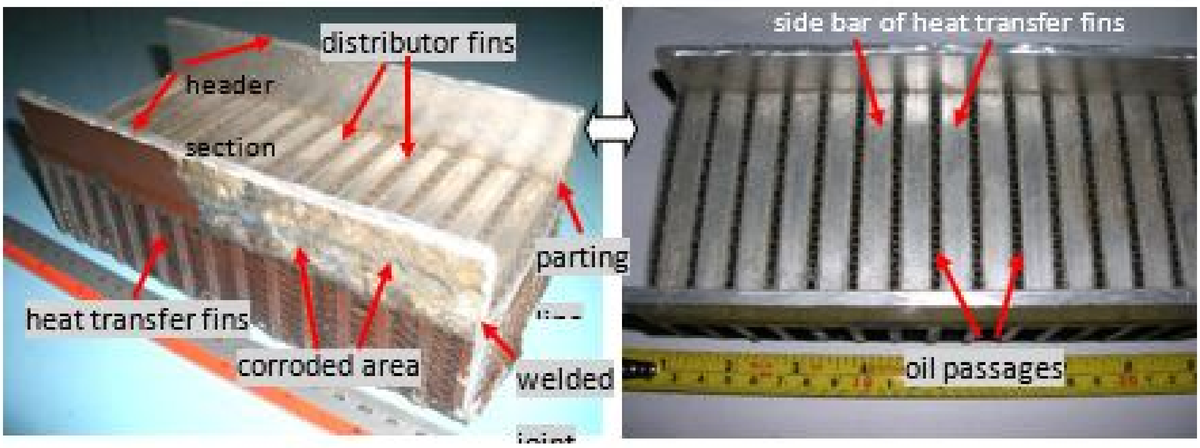


Figure 3. Close up view of the inside header port, showing a number of oil passages containing distributor fins and parting line of the weld joint between header and side bars/parting sheets

3. RESULTS

3.1. Visual and Macroscopic Examination

The results of macroscopic examination obtained from some leaked area on the weld joint between the inlet header and the side bar/parting sheet of the compressor after-cooler shown in Figure 4 are presented in Figure 5. It can be seen from Figure 5 that most of the weld surface fracture apparently contained a number of pinholes due to gas porosity. In addition, some corrosion attack was also indicated to have entered into some surface fracture of the weld. 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.

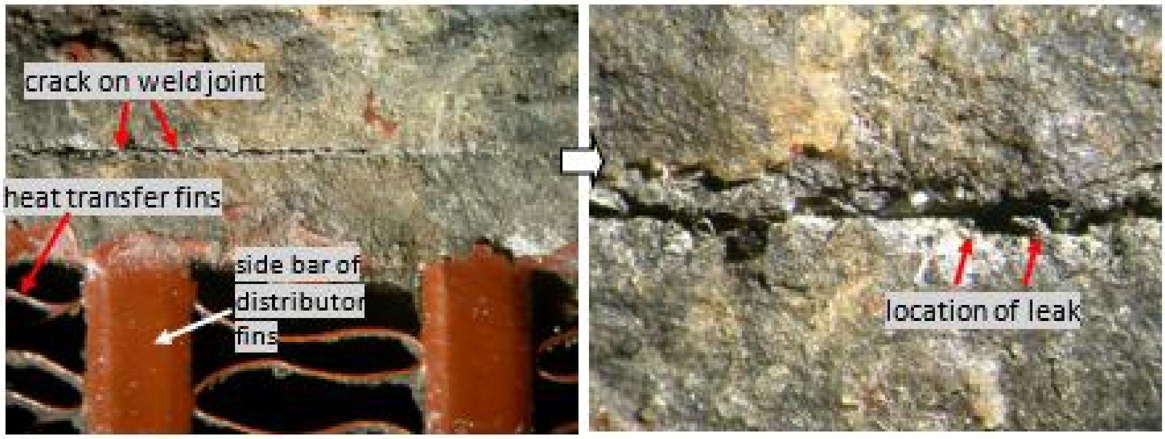


Figure 4. Close up view of the corroded surface area around the weld joint that caused the after-cooler to leak

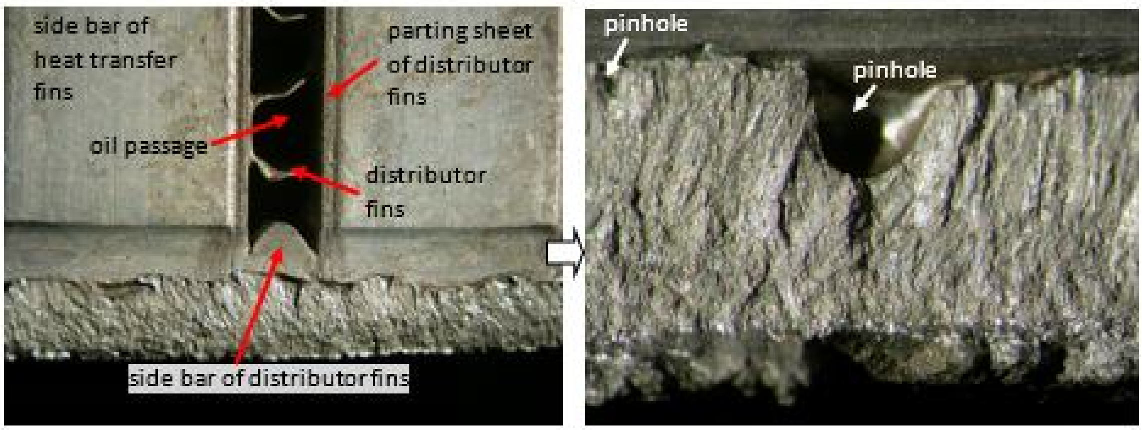


Figure 5. Surface fracture of the weld joint between header and side bar/parting sheet

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 fracture may have been originated from the heavily corroded weld surface. Microstructure 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 intermetallic second phase particles [1,2,8-10]. Similar to the macrostructure shown in Figure 5, the microstructure obtained from the weld metal also apparently exhibits a number of large pinholes (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 some 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 for metallographic examination was 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 which 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 fracture may have also been related with some weld defect (pinholes) that formed in the weld joint between header and the parting sheet.

Details of microstructure obtained around the corroded surface area of the inlet header are clearly presented 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].

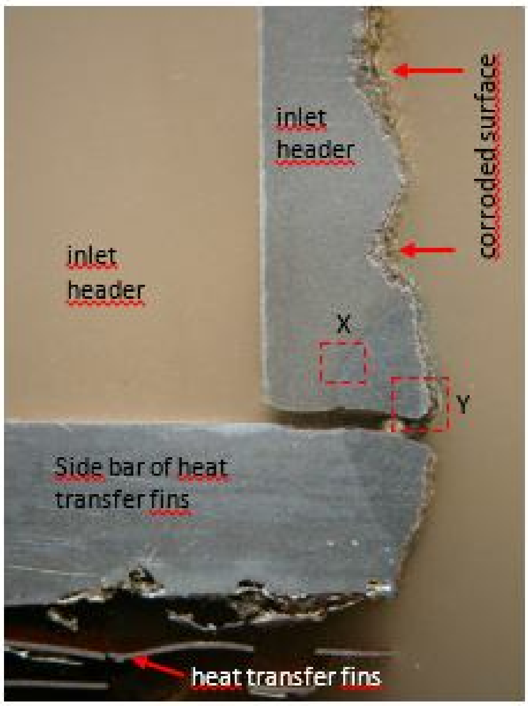


Figure 6. Cross section of a polished and etched specimen obtained from the leaked weld joint between header and side bar/parting sheet

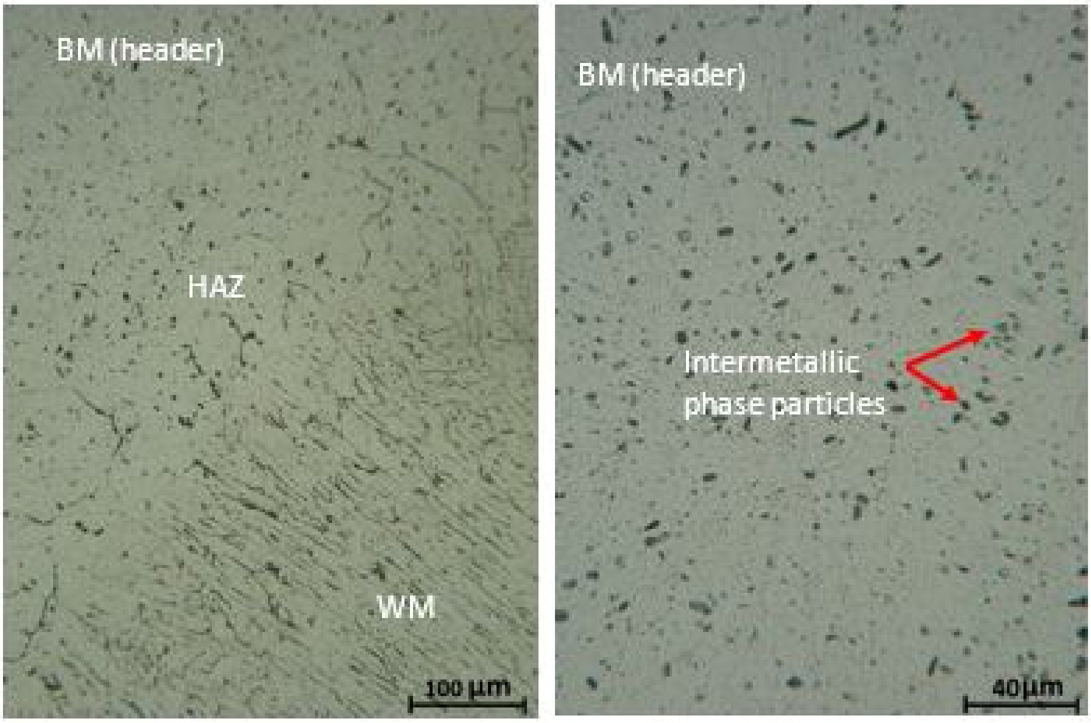


Figure 7a. Microstructure obtained from the weld joint between header and side bar/parting sheet at location X as indicated in Figure 6 (etched with Keller solution). Note BM is base metal, HAZ is heat-affected zone, and WM is weld metal.

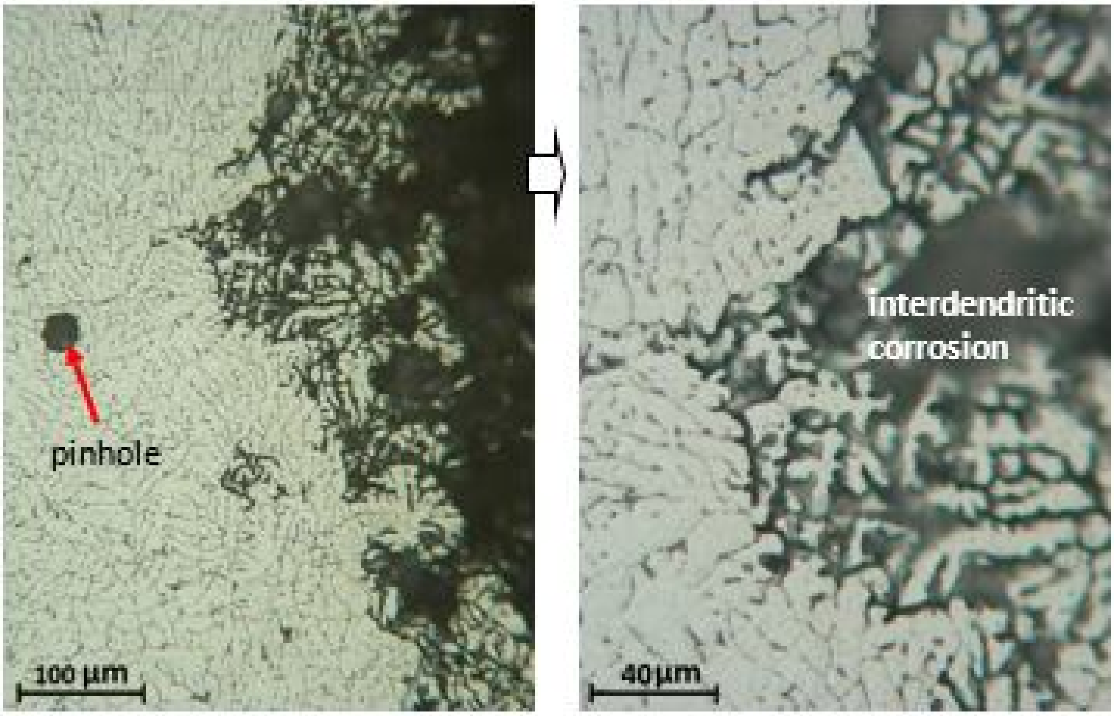


Figure 7b. Microstructure obtained from the weld metal area at header side at location Y as indicated in Figure 6 (etched with Keller solution)

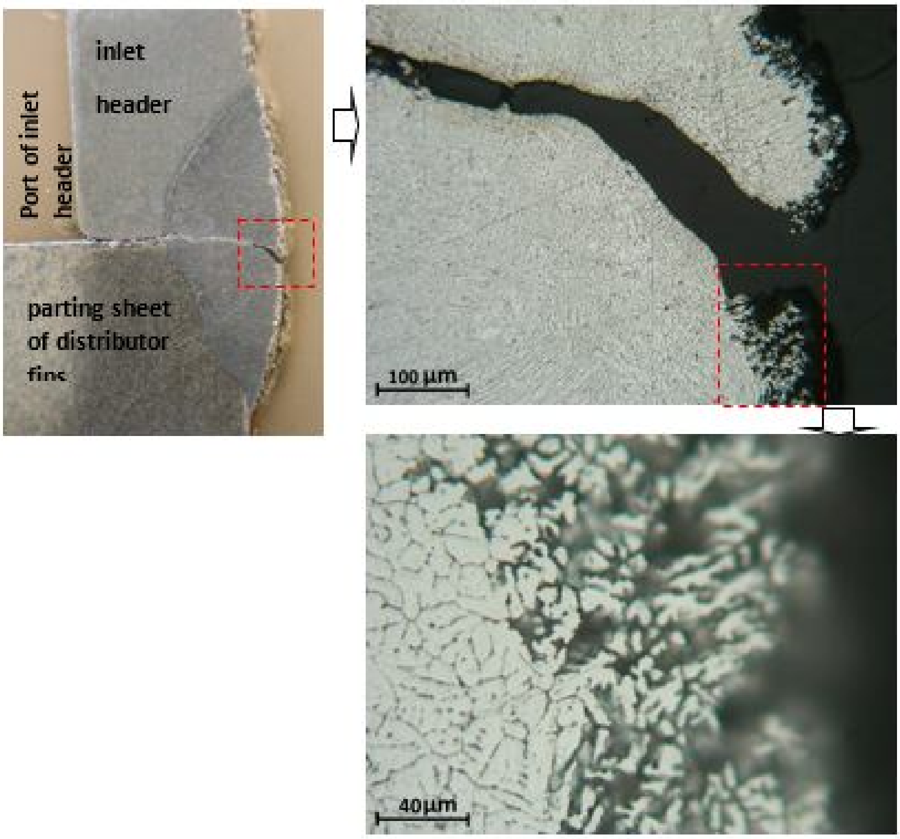


Figure 8. Microstructure obtained from the weld joint between header and parting sheet of distributor fins at location as indicated (etched with Keller solution)

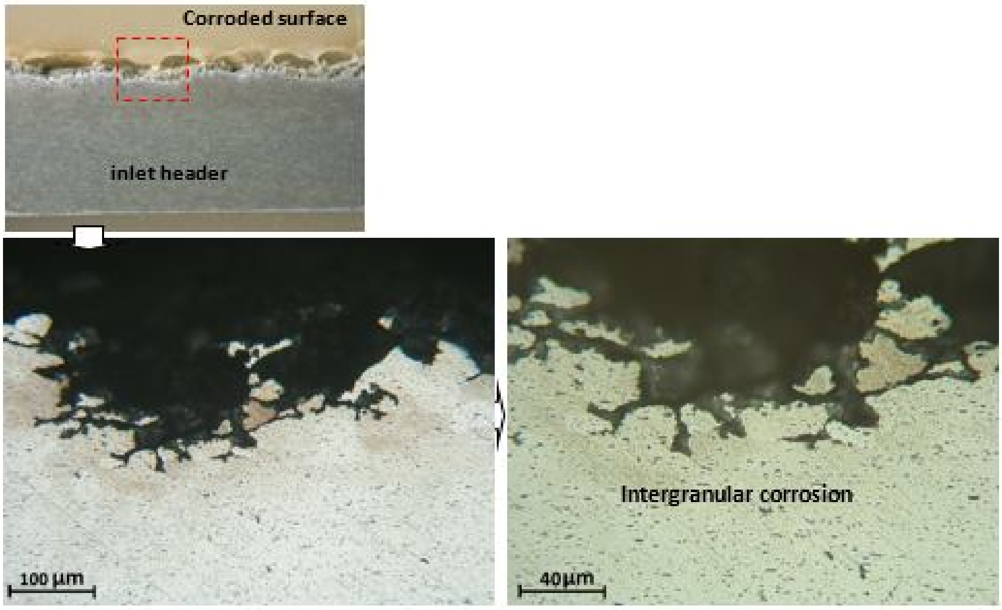


Figure 9. Microstructure obtained from the corroded area of the header surface at location as indicated (etched with Keller solution)

3.3. Hardness Test and Analysis

The hardness tests were performed at different test locations on the cross section around the leaked area. The results obtained show that the header base metal has hardness values in the range 87.4-102 HV, i.e, slightly lower than the hardness values of the header metal at its HAZ which its hardness values in the range 94.6-105 HV. Whereas 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 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].

3.4. SEM Fractography and EDS Analysis

SEM fractographs obtained from surface fracture of the failed after-cooler are presented in Figure 10. The fractographs obtained show the surface fracture of the weld joint between the header and the side bar/parting sheet that apparently contained a number of pinholes. These pinholes in some extent may have contributed to the crack or fracture formation. The crack may have been initiated from the corroded surface of the weld joint and progressed inward to the pinhole area where a high stress concentration may have present. As seen clearly in Figure 10, one large pinhole was filled with some inclusions.

The EDS spectrum obtained from the header surface fracture shown in Figure 10 that experienced corrosion damage shows some major elements such as aluminum (Al), carbon (C) and oxygen (O) (see Figure 11). 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 hot compressor 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 sea water and/or its moisture contamination, or may be present in other aqueous environment as a contaminant. Figure 12 also shows EDS spectrum of elements representing the corresponding composition of inclusion that formed inside a large pinhole shown in Figure 10. Basically, the inclusion is a typical aluminum oxide that formed from the filler metal during welding.

Other result of EDS analysis was also obtained from some corroded surface area located around the edge of the header and close to the weld surface fracture (see Figure 13). 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.

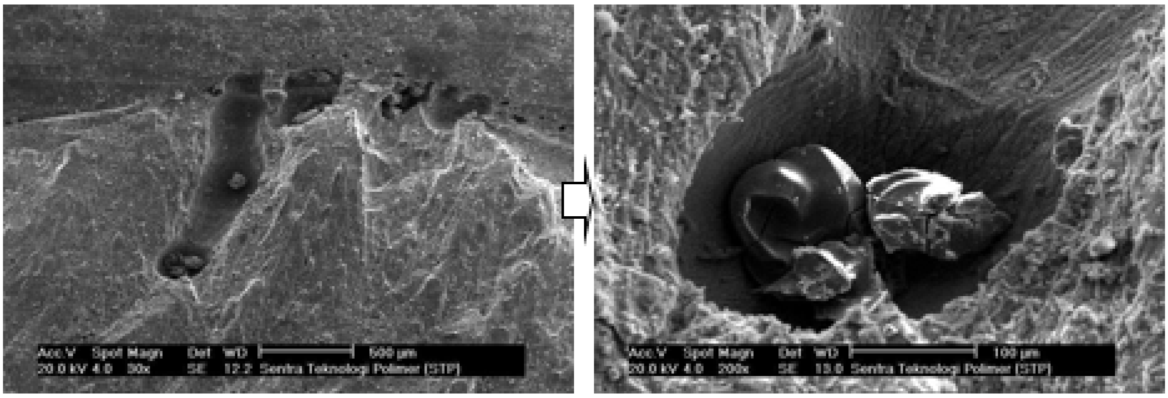
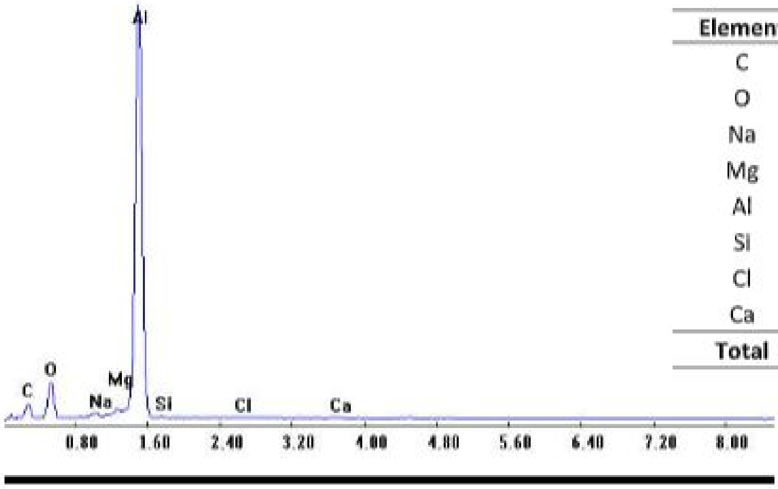
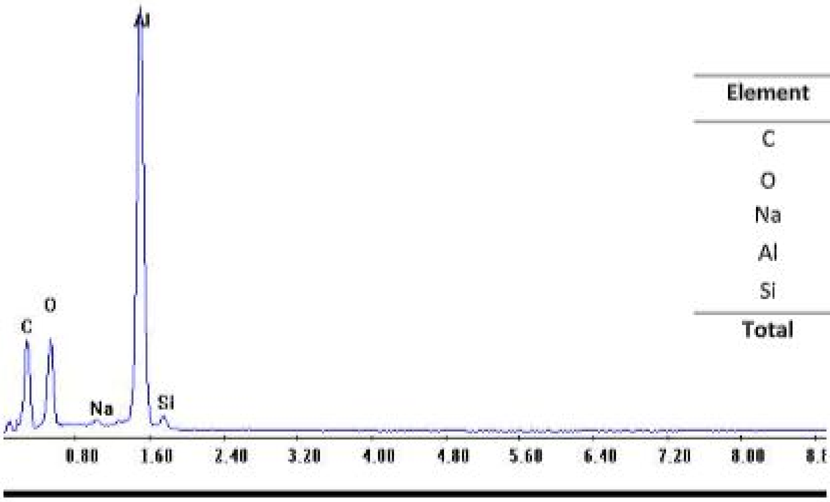


Figure 10. SEM fractographs of surface fracture obtained from the leak area of the weld joint between the header and the side bar/parting sheet.



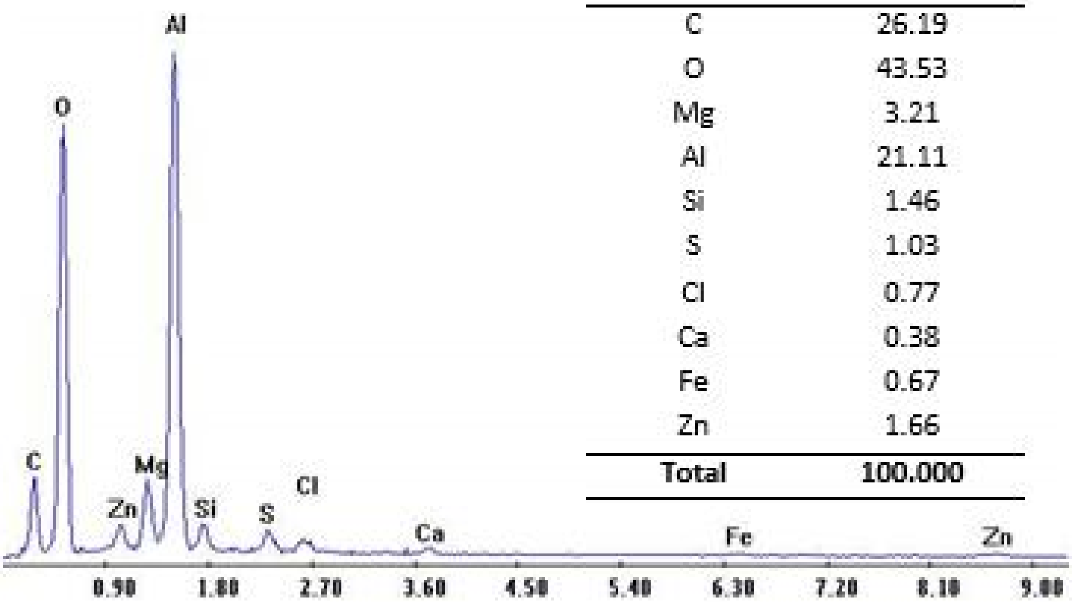
Element	Wt %
C	28.40
O	17.07
Na	0.37
Mg	0.98
Al	51.95
Si	0.54
Cl	0.33
Ca	0.36
Total	**100.000**

Figure 11. EDS spectrum of element representing the corresponding composition of the header surface fracture shown in Figure 10.



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

Figure 12. EDS spectrum of elements representing the corresponding composition of inclusion formed inside a pinhole shown in Figure 10



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 13 EDS spectrum of elements representing the corresponding composition of some corroded surface of the header.

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 affected by the difference in chemical composition of the material. The header material is likely made of aluminum alloy AA5xxx series, while the side bar and 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 attack (intergranular / interdendritic corrosion) and some welding defects (pinholes) formed at the parting joint between the header and the side bar/parting sheet of the corrugated fins and this may have led the after-cooler to leak. The crack propagation would be accelerated in combination with the external corrosion attack occurred on the weld joint surface that may have significantly reduced the effectiveness of the weld joint area. The external corrosion attack 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 11 and 13). 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 environments as a contaminant. The external corrosion attack 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 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 external corrosion and weld defect, the premature failure of the 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 EDS analysis, metallography and hardness test of the material used for both of the header and the side bar/parting sheet of the corrugated fins are very much close to the material specification of non-heat treatable wrought aluminum alloys of AA5xxx and AA3xxx series, respectively.

According to the crack/fracture morphology and mode of failure, the leaked after-cooler under investigation had experienced a combination effect of some external corrosion and weld defect (pinholes). Most of the external corrosion attacks 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 as a contaminant. 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 as corrosion product. The source of S as other corrosive agent that had only contaminated on some particular area of the header/weld joint surface of the failed after-cooler may be coming from the leaked lubricating oil.

Acknowledgements

The author wishes to express his gratitude to the Head and Members of Department of Mechanical Engineering, Faculty of Industrial Technology of the National Institute of Science and Technology (ISTN) for their support and encouragement in publishing this work.

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