Failure Analysis on Stainless Steel Tubing of a Lube Oil Console for Gas Generator

by

Mohd Izuddin Bin Ismail
8066

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

JULY 2010

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CHAPTER 1
PROJECT BACKGROUND

1.1 Background of Study

The author has completed the industrial internship program at MTBE/Polypropylene (M) SDN BHD for a period of eight months. During the industrial internship period, the author has experienced a various type of equipment failure. The author has chosen the "Failure Analysis on Stainless Steel Tubing of a Lube Oil Console for Gas Generator" as the title for Final Year Project (FYP) that must be completed during the final year period.

MTBE Reactor Effluent Compressor is driven by a gas generator. **KC 201 GG** is the equipment number for the gas generator which is functioned as the driver or prime mover for the MTBE Reactor Effluent Compressor. The exhaust for the gas generator is attached to a 3 stage power turbine that coupled to the Low Pressure (LP) and High Pressure (HP) Reactor Effluent Compressor. The gas generator consists of 17 stages compressor blade in the gas generator compressor blade and 3 stages of gas turbine. It is an Avon model gas generator manufactured by Rolls Royce **(refer to Appendix 1)**. It is located in a compartment that filled with carbon dioxide during running process to avoid any fire started at the GG.

The gas generator uses 3 ball bearings along its shaft. The bearings were lubricated by hydraulic oil which is Aero shell 500. The gas generator has its own lube oil console **(refer to Appendix 2)** which consists of lube oil pump, lube oil reservoir, Pressure Safety Valve (PSV), lube oil cooler and stainless steel tubing as the transfer medium. The lube oil pump is a gear types operated based on the positive displacement principle. The operating temperature and pressure for the lube oil is 45°C (114°F) and 500 kPa (80 psiG). It was reported that the gas generator trip due to lube oil level low alarm. It was observed that the lube oil tubing broken at the fitting side **(refer to Appendix 4 & 5)** and caused the lube oil leak **(refer to Appendix 3)**.

1.2 Problem Statement

1.2.1 Problem identification.

The stainless steel tubing that carries the hydraulic oil for the Gas Generator was broken at the fitting and ferrule location that caused the hydraulic oil in the tubing to leak to the atmosphere.

1.2.2 Significant of the project.

Resulting from this failure, the Gas Generator was tripped due to low level of the hydraulic oil in the oil reservoir. The Generator cannot run without the hydraulic oil or it can cause catastrophic failure to the equipment and cause a lot of money to be spent. The spillage of the high pressure hydraulic oil maybe hazardous to the operator or anybody in the plant. The failure must be analyzed and solved to prevent this failure from occurring in the future and cause many other problem related to this kind of failure.

1.3 Objectives

1. To study the characteristics and properties of austenitic stainless steel.

2. To apply various type of examinations and tests to inspect the microstructure of the fail material and the fine one.
3. To develop a methodology of failure analysis process in a step-by-step analysis procedures.
4. To identify the potential causes of the failure by performing the failure analysis studying the failure mode in order to determine the type of failure.
5. To propose solution to prevent the failure from occurring in the future.

1.4 Scope of Study

The whole project would start with the knowledge gathering and theoretical studies. This project involves of investigating the microstructure and properties of the stainless steel especially austenitic type which is 300 series. This project also involves various types of testing and examination in order to study the material in an overall view. In addition, data collection and management skills can be applied upon finishing the failure analysis as well as critical thinking and problem solving ability.

1.5 Relevancy and Feasibility of the Project

This project is relevant enough as the sample material is collected and selected from the real industrial equipment and the failure occur based on the flaw and faulty of the equipment. The failure analysis that will be carried out is also possible to be done using precision and high technology testing equipment for inspection and investigation of the sample material properties and microstructure.

CHAPTER 2

LITERATURE REVIEW

2.1 Failure Analysis Overview

Failure analysis is the process of collecting and analyzing data to determine the cause of a failure and how to prevent it from recurring. It is an important discipline in many branches of manufacturing industry, such as the electronics industry, where it is a vital tool used in the development of new products and for the improvement of existing products. It relies on collecting failed components for subsequent examination of the cause or causes of failure using a wide array of methods, especially microscopy and spectroscopy. The NDT or nondestructive testing methods are valuable because the failed products are unaffected by analysis, so inspection always starts using these methods [1].

It starts with the preliminary examinations or observations which mean the fail sample is observed using naked eye. In this process, the findings at the failure scene cannot be negligible. It is because the failure cannot occur by itself; it must be related to another equipment or component that is a must to find out before any further investigation. Assumptions of the failure also necessary usually done by Root Cause Analysis. After data gathering and preliminary examination done and before the sample is to be destroyed using destructive testing, the photo of the specimen must be taken for further analysis and prove. Then we can destroy the specimen in order to do some tests to prove that the failure occur because of what we assume before.

2.2 Ishikawa Diagram

The **Ishikawa Diagram**, also known as the Fishbone Diagram or the Cause-and-Effect Diagram, is a tool used for systematically identifying and presenting all the possible causes of a particular problem in graphical format. The possible causes are presented at various levels of detail in connected branches, with the level of detail increasing as the branch goes outward, i.e., an outer branch is a cause of the inner branch it is attached to. Thus, the outermost branches usually indicate the root causes of the problem. [2]

The basic concept in the Cause-and-Effect diagram is that the name of a basic problem of interest is entered at the right of the diagram at the end of the main “bone". The main possible causes of the problem (the effect) are drawn as bones off of the main backbone. The "Four-M" categories are typically used as a starting point: "Materials", "Machines", "Manpower", and "Methods". Different names can be chosen to suit the problem at hand, or these general categories can be revised.

The key is to have three to six main categories that encompass all possible influences. Brainstorming is typically done to add possible causes to the main "bones" and more specific causes to the “bones" on the main "bones". This subdivision into ever increasing specificity continues as long as the problem areas can be further subdivided. The practical maximum depth of this tree is usually about four or five levels. When the fishbone is complete, one has a rather complete picture of all the possibilities about what could be the root cause for the designated problem. [2]

2.3 Failure background

On 20th February 2009, the tubing for the lube oil console of the Gas Generator at Area 200, MTBE/Polypropylene (M) Sdn. Bhd. snapped and caused the lube oil to leak to the atmosphere (refer to Figure 2.2). When the lube oil was leaking, the lube oil level in the lube oil reservoir is lowering until the low level alarm was triggered. When the lube oil level is very low, the second alarm also triggered and the Gas Generator control shutdown was occurred on 21st February 2009 at 1810 hrs due to hydraulic oil leak. The cost for the plant shutdown is approximately RM 2 million per day excluding the cost for manpower and spare parts. Regarding to this failure, MTBE/Polypropylene (M) Sdn. Bhd was shut down for about 2 days and the cost for this failure is approximately RM 3 million. Figure 2.3 shows the sample material is the ¾ inch 316L stainless steel tubing.

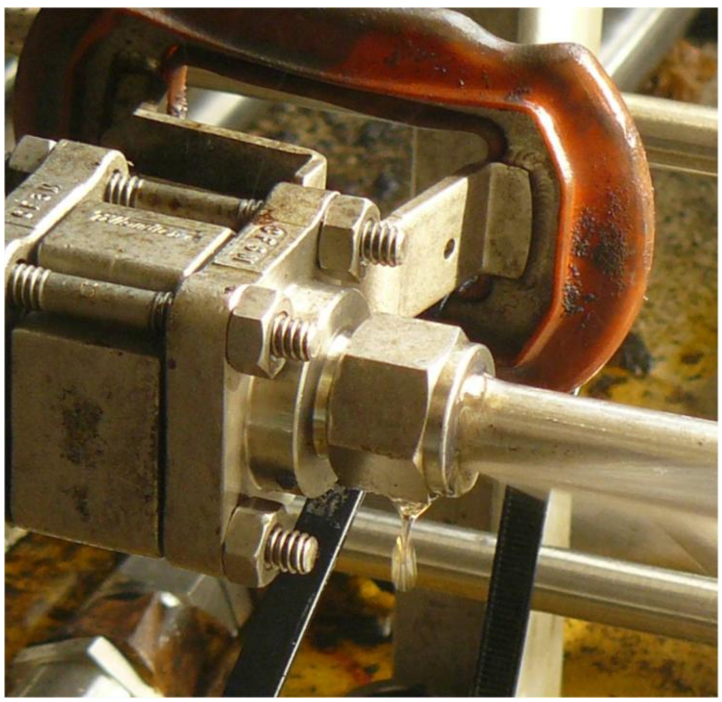


Figure 2.1: Lube oil leaking caused by tubing snap.

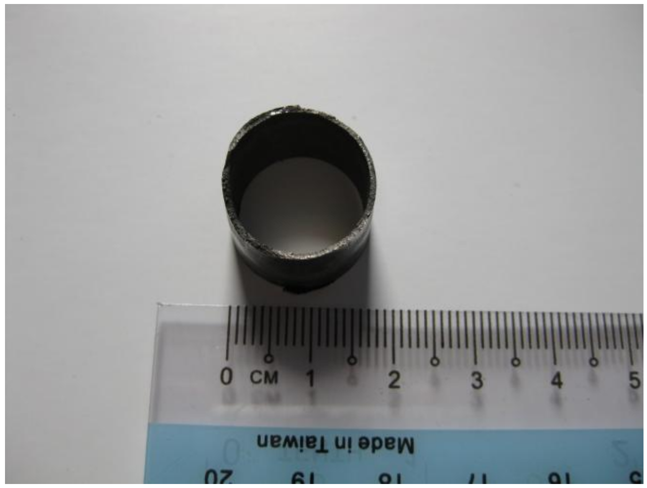


Figure 2.3: Sample material- ¾ inch 316L stainless steel tubing.

2.4 Research

Table 2.1: Journal summary.

Journal	Summary
[3]	In the ELCF regime, it was pointed out that not only surface cracking but also additional bulk damage reduces the fatigue life. In this study, the fatigue strength of stainless steel in the low-cycle and ELCF regimes and the effects of bulk damage on fatigue strength were investigated. Type 316 stainless steel was subjected to axial cyclic strain up to strain amplitude of 6%. Also, the change in fatigue life was investigated when the surface layer of the specimens was removed during the fatigue tests. It was shown that not only the surface cracking but also the bulk damage affected the fatigue life. It was also shown that the bulk damage consisted of two factors: internal cracking and local damage. Internal cracks were observed on the fractured surface when the strain amplitude was more than 1%, and in some cases the specimen was fractured by these internal cracks.
[4]	Fatigue damage requires to be expressed in terms of a crack. This will be revealed by several items of experimental evidence. First, observations on a medium carbon steel that relate to the initiation zones and the propagation of small cracks subjected to low cycle fatigue, will be presented; these

	observations being based on surface replica studies. It will be shown that the Coffin Manson high-strain, low-cycle, fatigue relationship is substantially the same as a crack growth law. Second, the effect of prior fatigue history on the growth rate of a small crack is investigated systematically using special specimens containing an artificial small hole of various diameters, i.e.40, 100 and 200 mm. Prior fatigue history is shown to have little influence on the crack growth rate in the high-strain fatigue regime. Third, it will be revealed that the loss of fracture ductility after strain cycling in high-strain fatigue tests is attributable to the existence of small surface cracks. The loss of fracture ductility depends on the crack length l. If l is larger than a critical length l(c), the fatigue crack causes macroscopic shear fracture in a tensile test following strain cycling. On the other hand, if l is smaller than l(c), the tensile fracture surfaces are of the cup-and-cone type.

CHAPTER 3

METHODOLOGY

3.1 Methodology Flow Chart

Figure 3.1 shows the methodology involves upon completing this failure analysis:

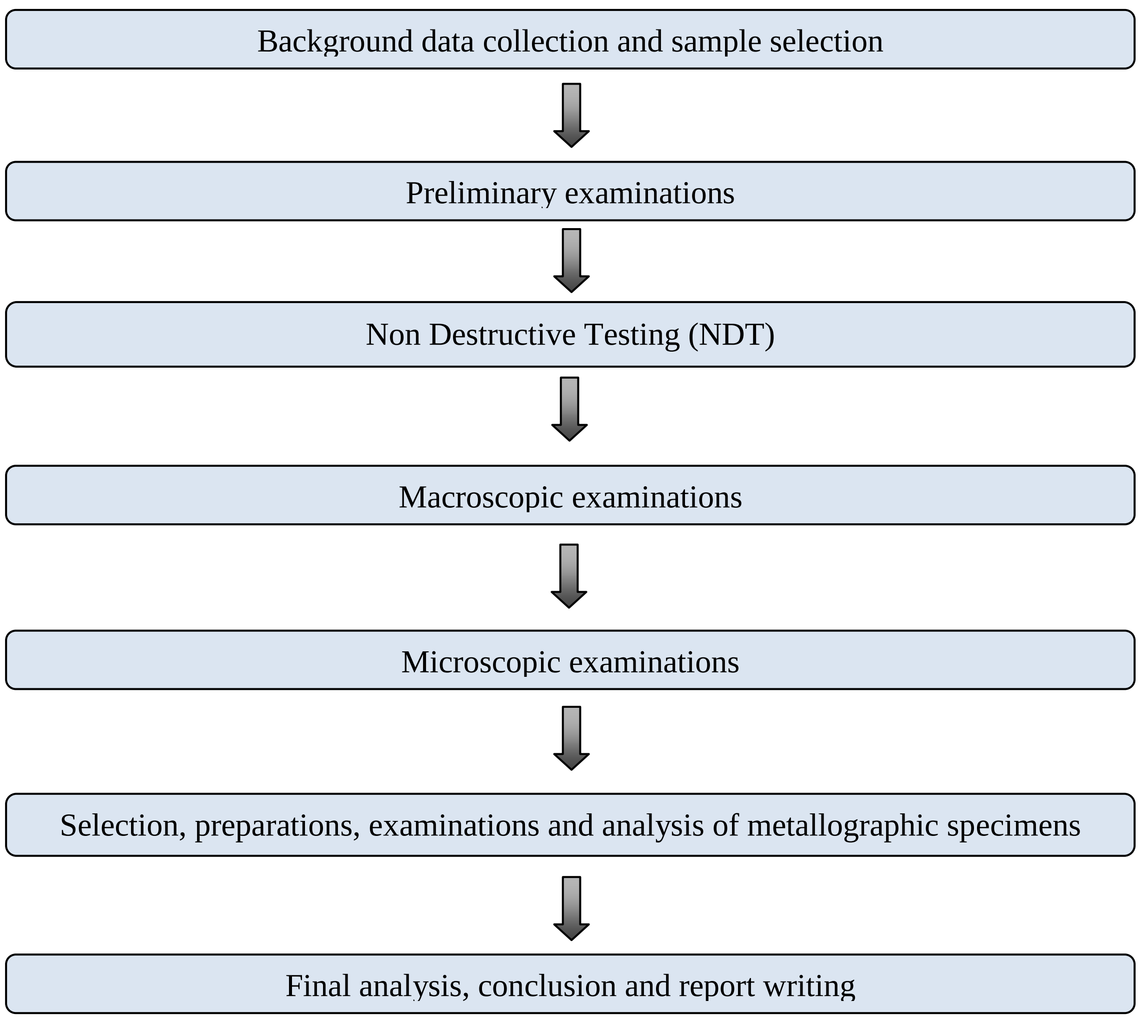


Figure 3.1: Methodology flow chart

3.2 Project activities

Taking the sample and data gathering from the industry would be the first step in this project, followed by performing RCA using Ishikawa Diagram and then various types of tests and examination to the fail material including Non Destructive Testing, mechanical testing, chemical analysis and stress analysis. Then examinations will be correlated the theoretical knowledge with the results.

The failure mode will be investigated to determine the type of failure and cause of the failure. Then, one or more suitable solution will be proposed in the final analysis as prevention to this failure that can give huge effect in the industry. Meanwhile, further research and development would be continuously practiced to ensure satisfactory results are achieved.

3.3 Preparation of Metallographic Specimens

3.3.1 Sectioning

For convenience, specimens to be polished for metallographic examination are generally not more than about 12 to 25 mm (0.5 to 1.0 in.) square. The height of the specimen should be no greater than necessary for convenient handling during polishing. In cutting the metallographic specimen from the main body of the material, care must be exercised to minimize altering the structure of the metal. Three common types of sectioning are sawing, abrasive cutter and shear cutter. In this case, abrasive cutter was used to provide good surface finish after cutting and the material alteration and deformation of the microstructure can be minimized. According to ASTM E03-01, Standard Guide for Preparation of Metallographic Specimens, the material for cutoff blade is silica carbide, SiC. [5]

3.3.2 Mounting

There are many instances where it will be advantageous to mount the specimen prior to grinding and polishing. Mounting of the specimen is usually performed on small, fragile, or oddly shaped specimens, fractures, or in instances where the specimen edges are to be examined. For this project, the specimen is the tubing which is very small and contains sharp edges as the tubing is sectioned into small part of the circle shape. Plastic compression mounting or hot mounting was chosen as the specimen will not react electrolytically with the filler material during etching and the heat and compression exerted during mounting will not affect the specimen microstructure.

3.3.3 Grinding

Grinding can be done in a number of ways, ranging from rubbing the specimen on a stationary piece of abrasive paper to the use of automatic devices. The choice of method depends on the number and type of specimens to be done, financial considerations and requirements such as flatness and uniformity. In this project, the specimen was grinded using grinder. Grinding should start with the roughest paper, platen or stone capable of flattening the specimen and removing the effects of prior operations, such as sectioning. The subsequent steps should remove the effects of previous ones in a short time. The functions of grinding are as follow:

i. Flatten an irregular or damaged cut surface
ii. Remove sectioning damage, scale and other surface conditions prior to mounting
iii. Remove substantial amounts of specimen material to reach a desired plane for polishing

In fine grinding, damage to the specimen incurred from the planar or rough grinding step must be removed. The specimen is either ground on successively finer abrasive papers (using water to wash away grinding debris and to act as a coolant) or on a rigid disc or cloth charged with a suitable abrasive. The desired surface after the grinding process before polishing is mirror surface which is about 5 µm in surface roughness.

3.3.4 Polishing

Polishing is usually distinguished from grinding by the use of loose abrasive (≤6µm) embedded in an appropriately lubricated supporting surface. The choice of abrasive, lubricant, and polishing surface support is often specific to the metal and the object of the investigation. Polishing can be divided into rough and fine (final) stages using polisher. Rough polishing is often sufficient for routine evaluations like microindentation hardness and grain size. During the final stages of polishing, the desired surface roughness is about 1 µm. For this stage, 1 µm diamond polish was used along with polishing cloth which is softer and higher in nap than rough polishing cloths. Therefore, polishing time and force must be kept to a minimum to avoid artifacts such as edge rounding and relief.

3.3.5 Etching

Etching is the final step for preparation of metallographic specimens before observation of the microstructure using Optical Microscope (OM) or Scanning Electron Microscope (SEM). The purpose of etching is to optically enhance microstructural features such as grain size and phase features. Etching selectively alters these microstructural features based on composition, stress or crystal structure. Etching involves chemical reaction between sample and etchant under controlled condition. Common type of etching is the chemical etching. [6]

For stainless steel, the etchant is the Viella's Reagent consists of 3 parts of Glycerol, 2 parts of Hydrochloric acid and 1 part of Nitric acid in ratio. During etching process, the etchant was dropped using dropper onto the polished surface of the specimen and hold for one minute. When bubbles formed and the bright metallic of polished surface disappears, the specimen was rinsed quickly with running water. Ethanol was applied to remove water and the specimen was dried off with hot blower. Now the sample is ready for OM and SEM **(refer to Appendix 6)**.

3.4 Tools/Equipment Required

3.4.1 Root Cause Analysis (RCA)

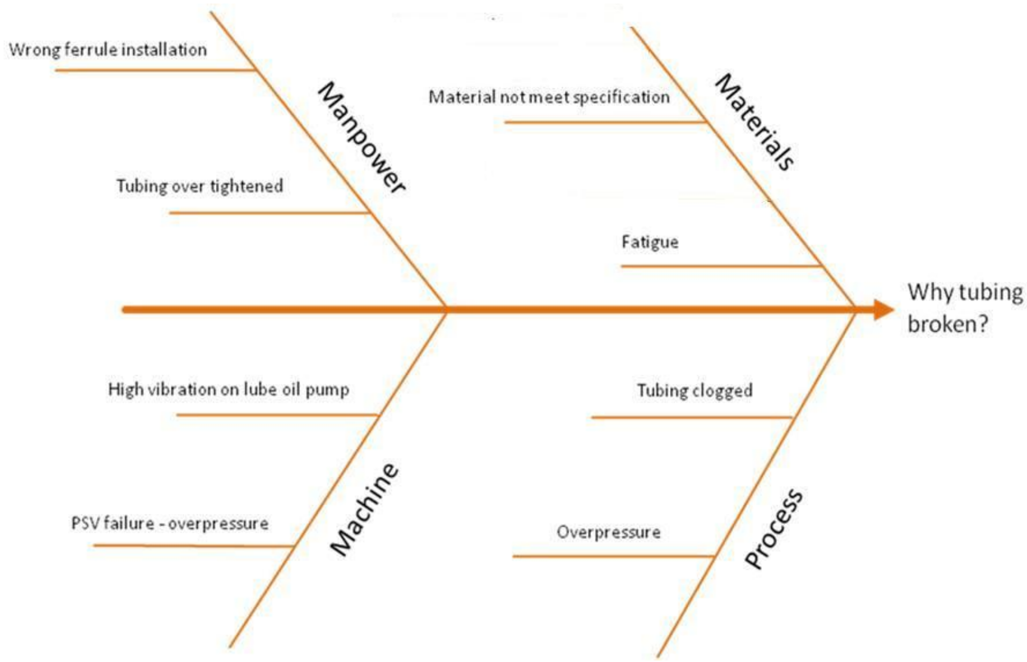


Figure 3.2: Root Cause Analysis (RCA) on stainless steel tubing failure.

Figure 2.1 shows the list of possible root causes using **Root cause analysis (RCA)**. First of all, root cause analysis was done to get the rough idea or assumption of the root cause before the failure analysis started. Root cause analysis is a class of problem solving methods aimed at identifying the root causes of problems or events. The practice of RCA is predicated on the belief that problems are best solved by attempting to correct or eliminate root causes, as opposed to merely addressing the immediately obvious symptoms. By directing corrective measures at root causes, it is hoped that the likelihood of problem recurrence will be minimized. However, it is recognized that complete prevention of recurrence by a single intervention is not always possible. Thus, RCA is often considered to be an iterative process, and is frequently viewed as a tool of continuous improvement. [8] In the RCA, based on Figure 2.1, all the possible cause was listed and branched until the factor cannot be subdivided anymore.

3.4.2 Metallographic Specimens Preparation Tools

i. Abrasive cutter (BUEHLER, Model – 102145)
ii. Mounting machine (BUEHLER, Model 20-1415)
iii. Grinder (BUEHLER, Model 95-2829)
iv. Polisher (IMPTECH 302 DVT, Model PHI 21302).

3.4.3 Optical Microscope (OM)

The optical microscope, often referred to as the "light microscope", is a type of microscope which uses visible light and a system of lenses to magnify images of small samples. Optical microscopes are the oldest and simplest of the microscopes. In this project, optical microscope manufactured by LEICA Microsystem, Model No. 251794 was used.

3.4.4 Scanning Electron Microscope (SEM)

The scanning electron microscope (SEM) is a type of electron microscope that images the sample surface by scanning it with a high-energy beam of electrons in a raster scan pattern. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography, composition and other properties such as electrical conductivity. In this case, scanning electron microscope manufactured by LEO, Model No. 1430 VP was used.

CHAPTER 4
RESULT AND DISCUSSION

4.1 Findings

4.1.1 Failure background

Further investigation has been done to seek more information about the failure. Based on the report from operation and maintenance personnel, there are 3 possible root causes for this failure to occur:

i. **Pressure Safety Valve (PSV) failure**

The tubing for the gas generator lube oil console snap on 20th February 2009 and cause the KC 201 GG Control Shutdown at 21/02/09 1810hrs due to GG Hydraulic oil tubing leak. All the PSV that functioned to release overpressure from the lube oil pump did not working correctly where all the PSV 'pop' continuously at the value of less than the preset pressure which is 500 kPa or 5 bar. This situation creates resonance effect along the tubing which is connected to the PSV. All the PSV were dismantle for rectification purpose.

ii. **High vibration of the lube oil pump.**

The shutdown of the Gas Generator has cause the plant to stop production at Area 200 at MTBE/Polypropylene (M) Sdn. Bhd. Upon the failure, the lube oil pump, KC 201 GG-PD1was found operating in high vibration approximately 2.4 mm/sec for the highest value that cause the tubing also vibrates severely. The pump was replaced with the spare from the warehouse.

iii. Wrong installation of ferrule

When the broken part of the tubing was observed, it was found that the ferrule is loosed. When installing ferrules, it must be fixed and tight to the tubing which the ferrule cannot be rotated by hand. This is maybe the sign that wrong installation of ferrules has caused the failure.

4.2 Data Gathering and Analysis

4.2.1 Visual inspection

First, visual inspection was done which is the sample fracture surface was inspected using our naked eye for the assumption of the failure mode. Visual inspection enables us to get the basic information of the failure mode and fracture type for example, brittle fracture and ductile fracture. Figure 4.1 shows the fracture surface of the stainless steel tubing. It appears to be brittle fracture where there are no sign of the ductile fracture such as reduction of cross sectional area, cup and cone shape and etc. Table 4.1 lists the comparison between brittle fracture and ductile fracture characteristics.

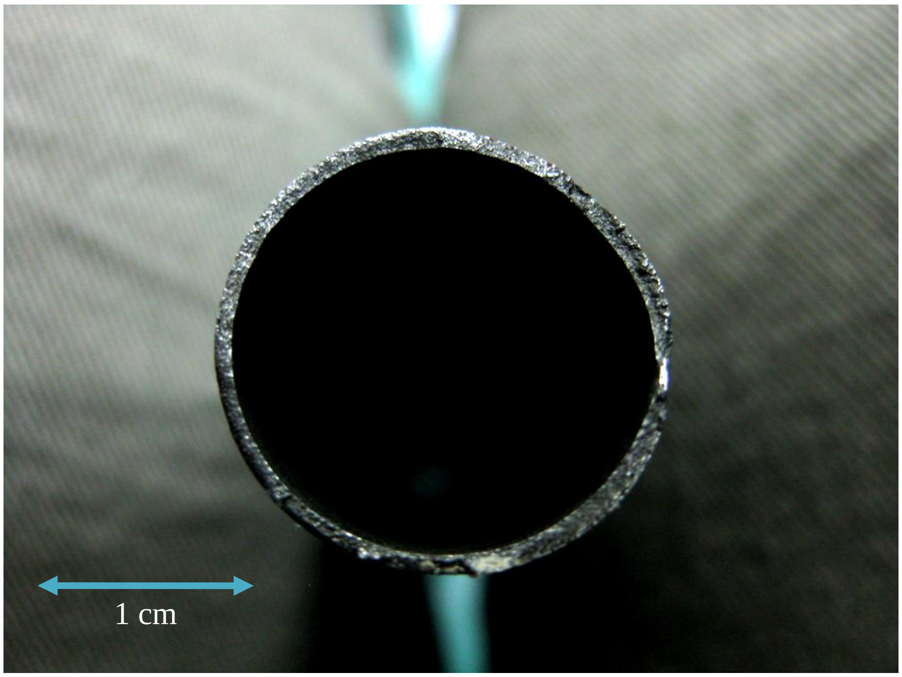


Figure 4.1: Close view on fracture surface of the stainless steel tubing.

Table 4.1: Comparison between brittle fracture and ductile fracture properties.

Brittle fracture	**Ductile fracture**
Little plastic deformation	Much plastic deformation
Flat fracture perpendicular to component surface	45 degree angles
Cross section is **not** reduced by necking	Cross section is reduced by necking
Cracks grow rapidly, often with a loud	Crack growth is slow

noise	

4.2.2 Operating condition

The gas generator uses 3 ball bearings along its shaft. The bearings were lubricated by hydraulic oil which is Aero shell 500. The gas generator has its own lube oil console which consists of lube oil pump, lube oil reservoir, Pressure Safety Valve (PSV), lube oil cooler and stainless steel tubing as the transfer medium. The lube oil pump is a gear types operated based on the positive displacement principle. The operating temperature and pressure for the lube oil is **45°C (114°F)** and **500 kPa (80 psiG).**

4.2.3 Stainless Steel

In metallurgy, **stainless steel**, also known as **inox steel** or **inox**, is defined as a steel alloy with a minimum of 11% chromium content by mass [9]. Stainless steel does not stain, corrode, or rust as easily as ordinary steel (it stains less, but it is not stain-proof) [10]. It is also called **corrosion-resistant steel** or **CRES** when the alloy type and grade are not detailed, particularly in the aviation industry. There are different grades and surface finishes of stainless steel to suit the environment to which the material will be subjected in its lifetime. Common uses of stainless steel are cutlery and watch cases and bands.

Stainless steel differs from carbon steel by the amount of chromium present. Carbon steel rusts when exposed to air and moisture. This iron oxide film (the rust) is active and accelerates corrosion by forming more iron oxide. Stainless steels have sufficient amounts of chromium present so that a passive film of chromium oxide forms which prevents further surface corrosion and blocks corrosion from spreading into the metal's internal structure [11].

4.2.4 Austenitic Stainless Steel 316L

Austenitic or 300 series stainless steels make up over 70% of total stainless steel production. They contain a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures from the cryogenic region to the melting point of the alloy. A typical composition of 18% chromium and 10% nickel, commonly known as **18/10 stainless**, is often used in flatware. Similarly, **18/0** and **18/8** are also available.

Austenitic Stainless Steel 316 contains 16% to 18% chromium and 11% to 14% nickel. It also has molybdenum added to the nickel and chrome of the 304. The molybdenum is used to control pit type attack. Type 316 is used in chemical processing, the pulp and paper industry, for food and beverage processing and dispensing and in the more corrosive environments. The molybdenum must be a minimum of 2%.

Grade 316 is the standard molybdenum-bearing grade, second in importance to 304 amongst the austenitic stainless steels. The molybdenum gives 316 better overall corrosion resistant properties than Grade 304, particularly higher resistance to pitting and crevice corrosion in chloride environments. It has excellent forming and welding characteristics. It is readily brake or roll formed into a variety of parts for applications in the industrial, architectural, and transportation fields. Grade 316 also has outstanding welding characteristics. Post-weld annealing is not required when welding thin sections.

Grade 316L, which is the material for the sample stainless steel tubing for this project is the low carbon version of 316 and is immune from sensitization (grain boundary carbide precipitation). Thus it is extensively used in heavy gauge welded components (over about 6mm). The austenitic structure also gives these grades excellent toughness, even down to cryogenic temperatures. Table 4.2, 4.3 and 4.4 show the chemical composition, mechanical properties and physical properties for the austenitic stainless steel 316L respectively while Table 4.5 shows the specifications of the sample material.

Table 4.2: Chemical composition ranges for 316L grade of stainless steels. [12][13]

Grade		**C**	**Mn**	**Si**	**P**	**S**	**Cr**	**Mo**	**Ni**	**N**
316L	Min	-	-	-	-	-	16.0	2.00	11.0	-
	Max	0.035	2.0	0.75	0.045	0.03	18.0	3.00	14.0	0.10

Table 4.3: Mechanical properties of 316L grade stainless steels. [12]

Grade	**Tensile Stress (MPa) min**	**Yield Stress 0.2% Proof**	**Elongation (% in 50mm)**	**Hardness**

		(MPa) min	min	Rockwell B (HR B) max	Brinell (HB) max
316L	485	170	40	95	217

Table 4.4: Typical physical properties for 316L grade stainless steels. [12]

Grade	Density (kg/m^3)	Elastic Modulus (GPa)	Mean Co-eff of Thermal Expansion (µm/m/°C)			Thermal Conductivity (W/m.K)		Specific Heat 0-100°C (J/kg.K)	Electrical Resistivity (nΩ.m)
			0-100°C	0-315°C	0-538°C	At 100°C	At 500°C		
316L	8000	193	15.9	16.2	17.5	16.3	21.5	500	740

Table 4.5: Specification for 316L grade stainless Swagelok steel tubing. [12][13]

Nominal OD, mm	Nominal Wall Thickness, mm	Ordering Number	Nominal Length, m	Weight Kg/m	Allowable Working Pressure, bar
18	1.0	SS-T18M-S-1,0M-6ME	6	0.425	120

4.2.5 Optical Microscope (OM) result analysis

After the sample preparation completed, the specimen can be observed under OM. Figure 4.2 shows the microstructure of the specimen in 10X magnification which is the stainless steel tubing. There are twins in the microstructure which prove that the microstructure is the austenitic type which is 316L as claimed by manufacturer.

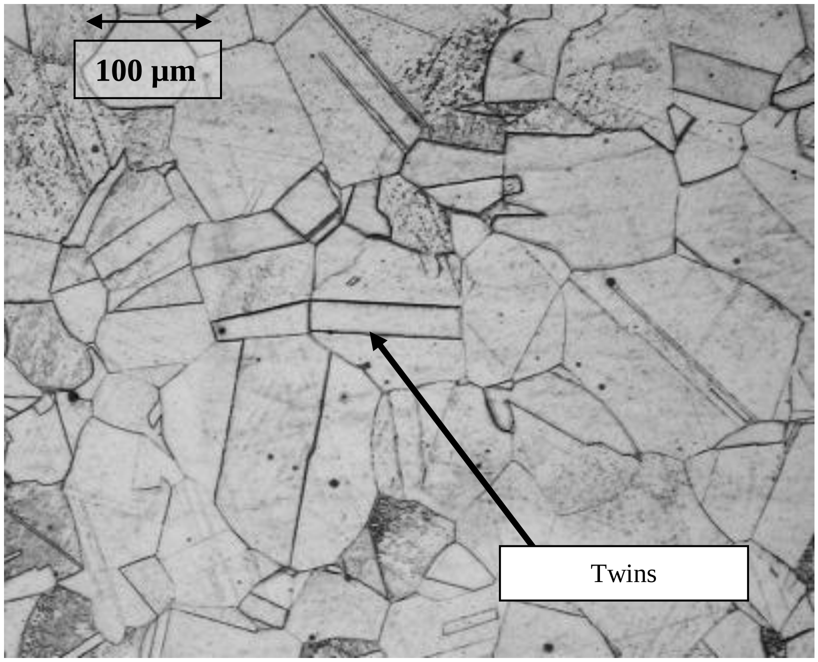


Figure 4.2: Microstructure observed under Optical Microscope (OM) for normal sample.

4.2.6 Scanning Electron Microscope (SEM) result analysis

Figure 4.3 shows the fracture surface of the stainless steel tubing under SEM observation with 50X magnification. From the figure, the fracture is a brittle fracture because the fracture surface is flat and perpendicular to component surface. The fracture can be said brittle because of the coarse texture and crystalline of the material. The crack growth rapidly and there is no sign of dimple for ductile fracture.

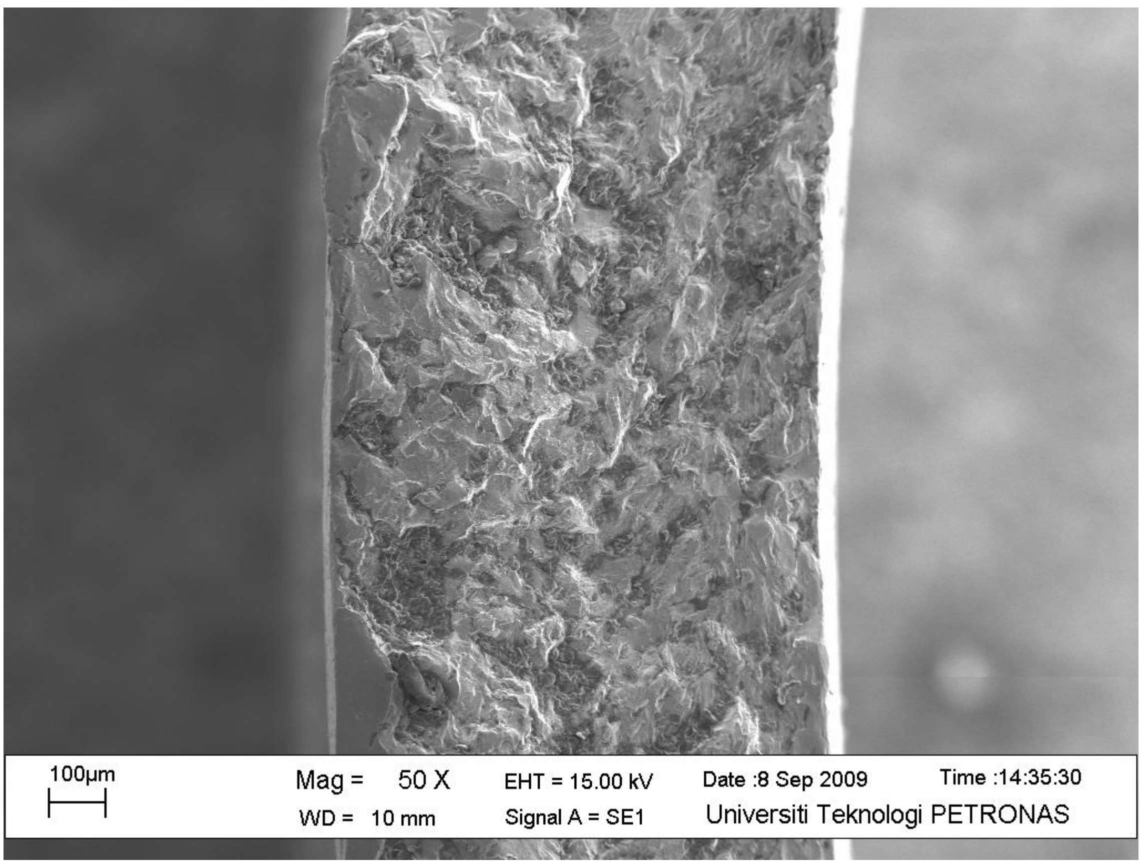


Figure 4.3: Fracture surface observed under Scanning Electron Microscope (SEM).

Figure 4.4 shows SEM observation images of a fractured surface. A relatively flat fracture surface was found near the origin of the internal cracks, while dimples due to ductile fracture were observed around them. The poor ductility may have caused the cleavage-like fracture surface inside the specimen. In the tensile test of the work hardened carbon steel, small cleavage cracks were initiated locally.

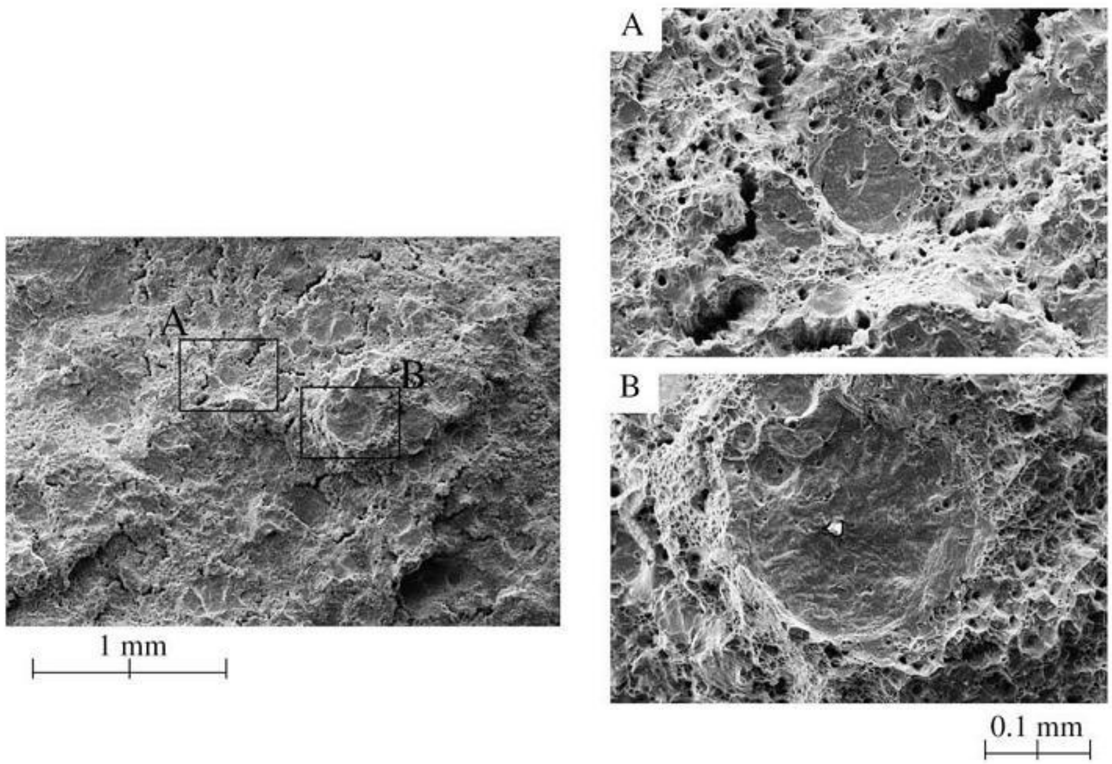


Figure 4.4: Fracture surface of sample material from journal. [3]

Compare to Figure 4.5 from the journal [3], the fracture surface from the stainless steel tubing is similar to that in the journal where the point of initiation takes place. The fracture surface around the point of initiation is brittle because of work hardening due to cyclic strain reduced the ductility of materials. Work hardening, also known as strain hardening, is the strengthening of a metal by plastic deformation. This strengthening occurs because of dislocation movements within the crystal structure of the material. [14]

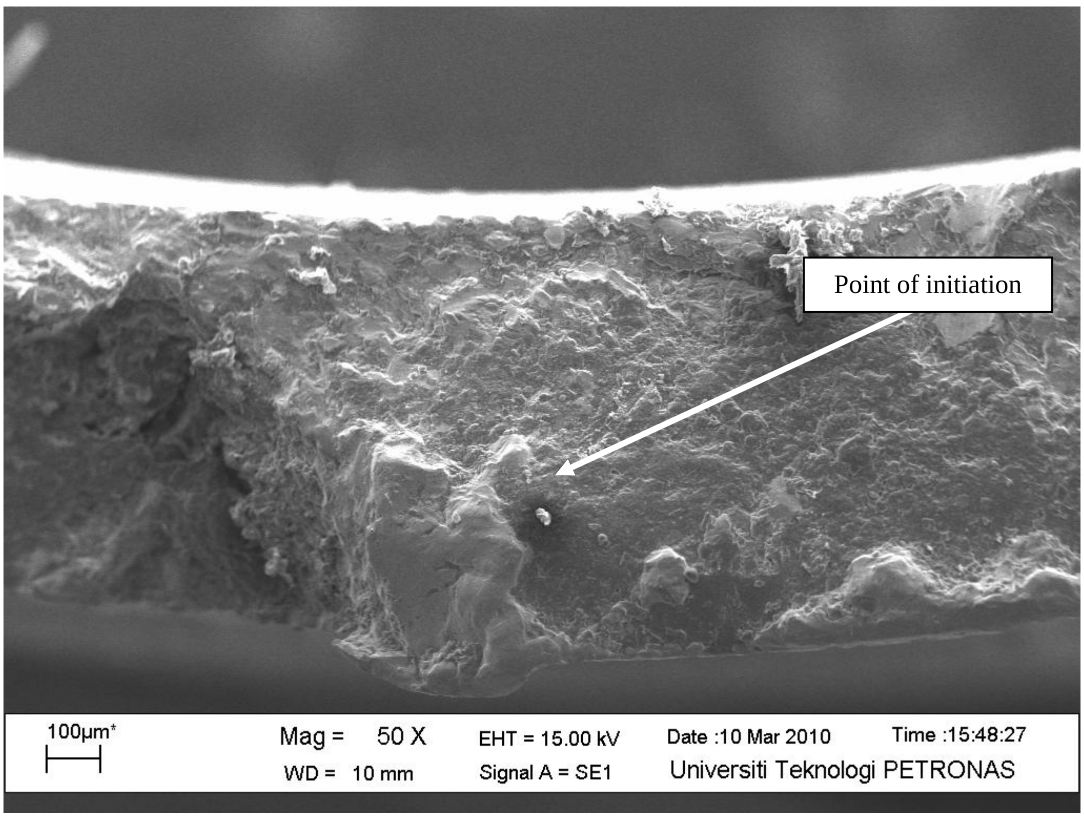


Figure 4.5: Point of initiation on the fracture surface of sample material.

The striations on the fracture surface can be visualized as in Figure 4.6 while Figure 4.7 shows close up view on the striations area. The striations were found on the fracture surface proved that the failure was caused by high cycle fatigue failure. Fatigue failure is the phenomenon leading to fracture under repeated or fluctuating stresses that are less than the tensile strength of the material. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of fluctuating stress. There are three stages of fatigue failure: initiation, propagation, and final fracture.

The location of the initiation is at a stress concentration and may be extremely small and difficult to distinguish from the succeeding stage of propagation, or crack growth. The crack initiation site is always parallel to the shear stress direction. The local stress at the tip of the crack is extremely high because of the sharp “notch,” and with each crack opening, the depth of the crack advances by one “striation” under many circumstances. Striations are very tiny, closely spaced ridges that identify the tip of the crack at some point in time. Although striations are the most characteristic microscopic evidence of fatigue fracture, they are not always present on fatigue fracture surfaces. [15]

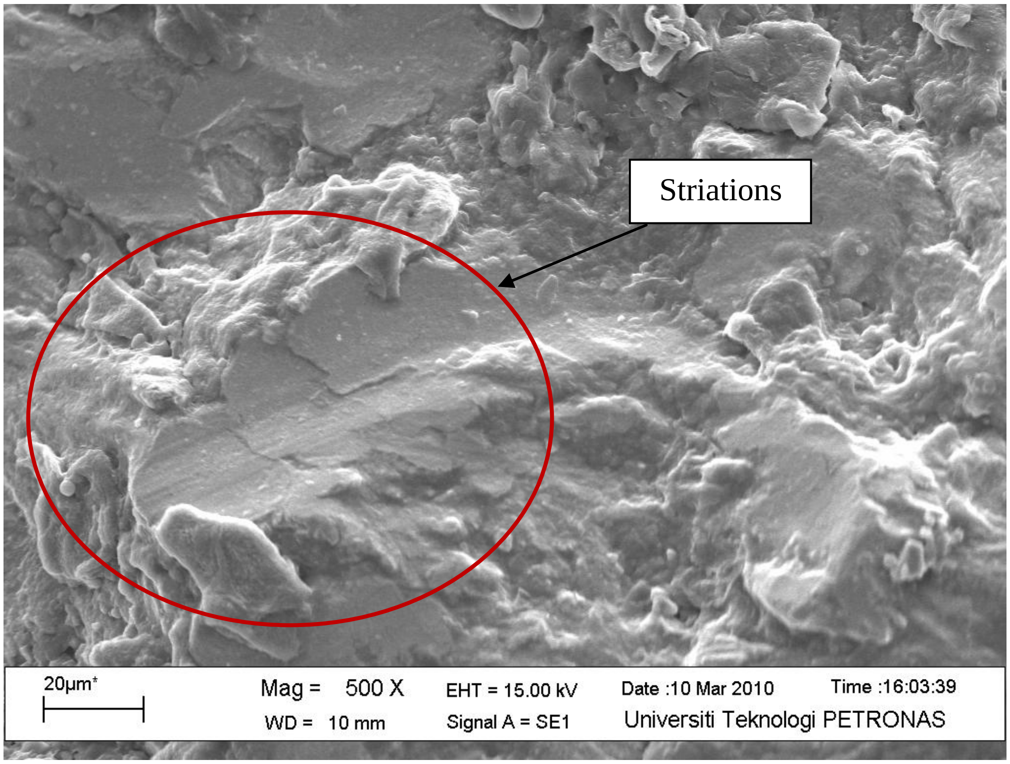


Figure 4.6: Striations on fracture surface.

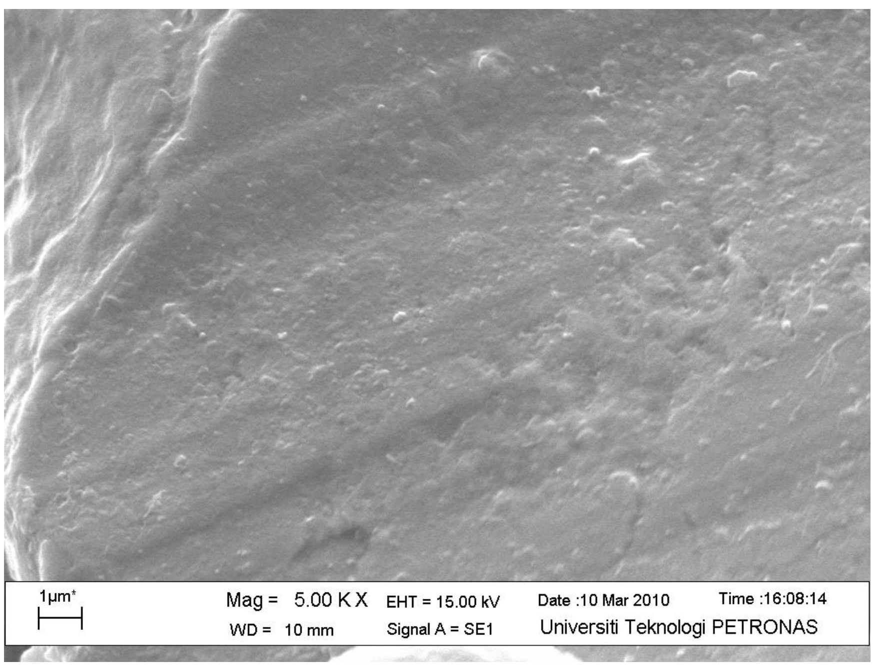


Figure 4.7: Close up view on the striations area.

Figure 4.8 shows the slip bands in the microstructure for the 316L stainless steel tubing with 10X magnification near the fracture surface. This explains why the brittle fracture occurs on the 316L stainless steel which is ductile material. During the fracture, the material deformed due to cyclic loading from the vibration called work hardening.

Work hardening, also known as strain hardening, is the strengthening of a metal by plastic deformation. This strengthening occurs because of dislocation movements within the crystal structure of the material. In brittle fracture, no apparent plastic deformation takes place before fracture. In brittle crystalline materials, fracture can occur by cleavage as the result of tensile stress acting normal to crystallographic planes with low bonding (cleavage planes). In amorphous solids, by contrast, the lack of a crystalline structure results in a conchoidal fracture, with cracks proceeding normal to the applied tension.

Work hardening reduces the ductility of the material to cause brittle fracture. The change in value of fracture ductility (ε_{FR}) with strain cycling in a fatigue regime is controlled by the following basic mechanisms; [16]

i. work hardening of the material,

ii. development of surface cracks and

iii. internal crack originating from the fracture of pearlites.

The effect of these mechanisms on the exhaustion of fracture ductility (εFR) depends on the level of plastic strain range and on the number of strain cycles involved.

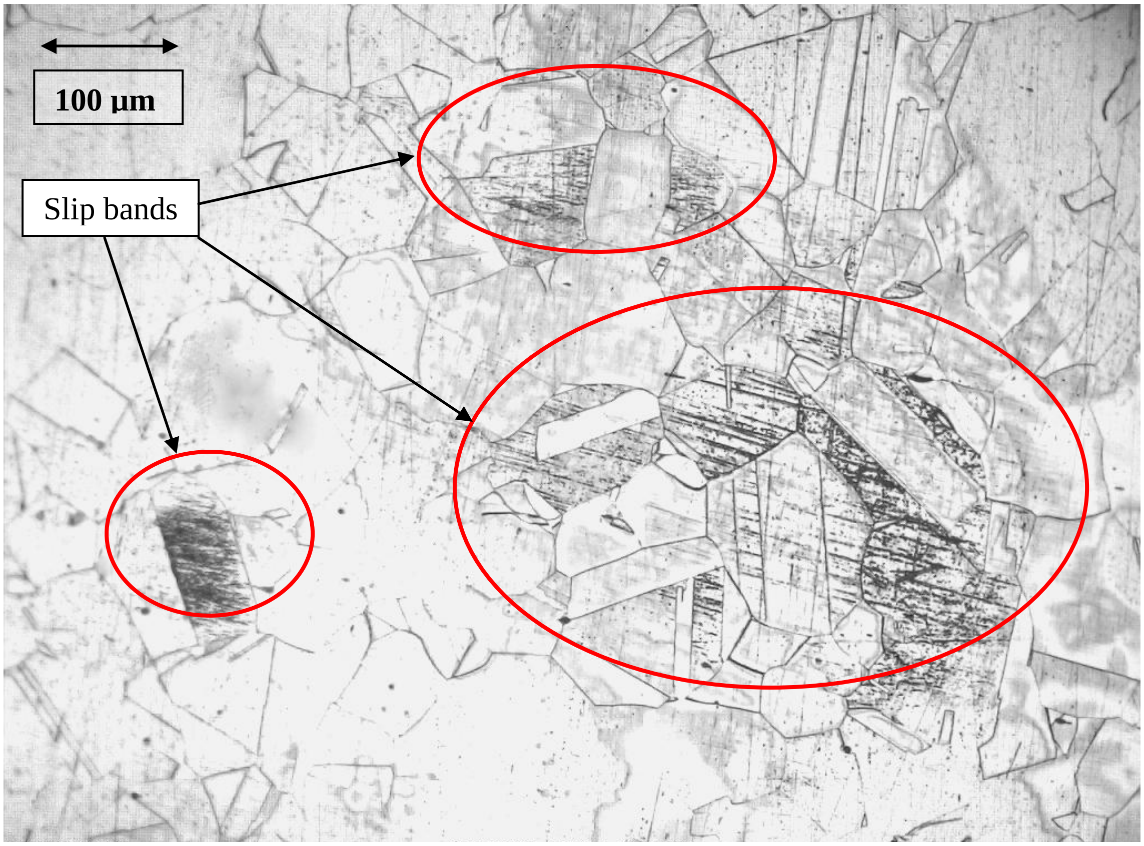


Figure 4.8: Microstructure observed under Optical Microscope (OM) near the fracture.

4.2.7 Vibration Data

Referring to Figure 4.9 and Figure 4.10, the lube oil pump for Gas Generator is operating in high vibrations which are 2.56 mm/sec for pump outboard vertical and

2.01mm/sec for pump inboard vertical. Both values are taken from Root Mean Square value. For pump outboard vertical, the early warning limit is 1.513mm/sec while for pump inboard vertical the value is 1.530mm/sec **(refer to Appendix 7 & 8)**. These mean that the pump operates at the vibration value above the early warning limit according to the pump specification. The pump is connected to the tubing and transferred the vibration through the tubing which caused failure.

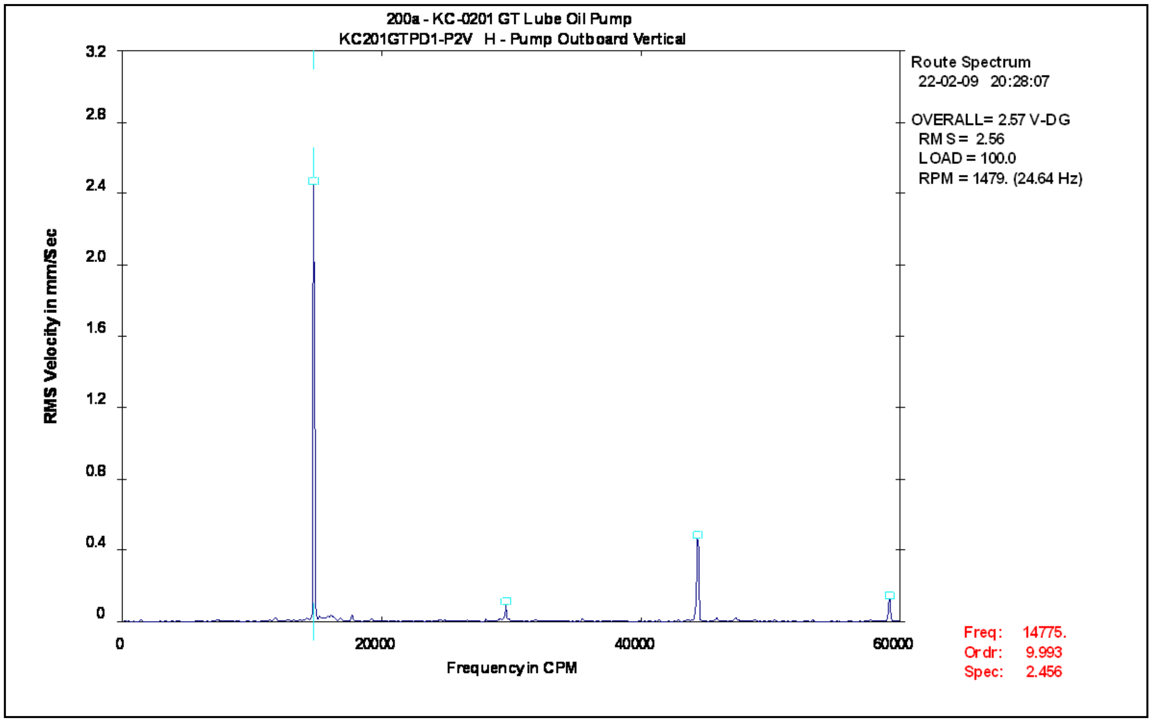


Figure 4.9: Vibration spectrums for KC 201 GT lube oil pump outboard vertical.

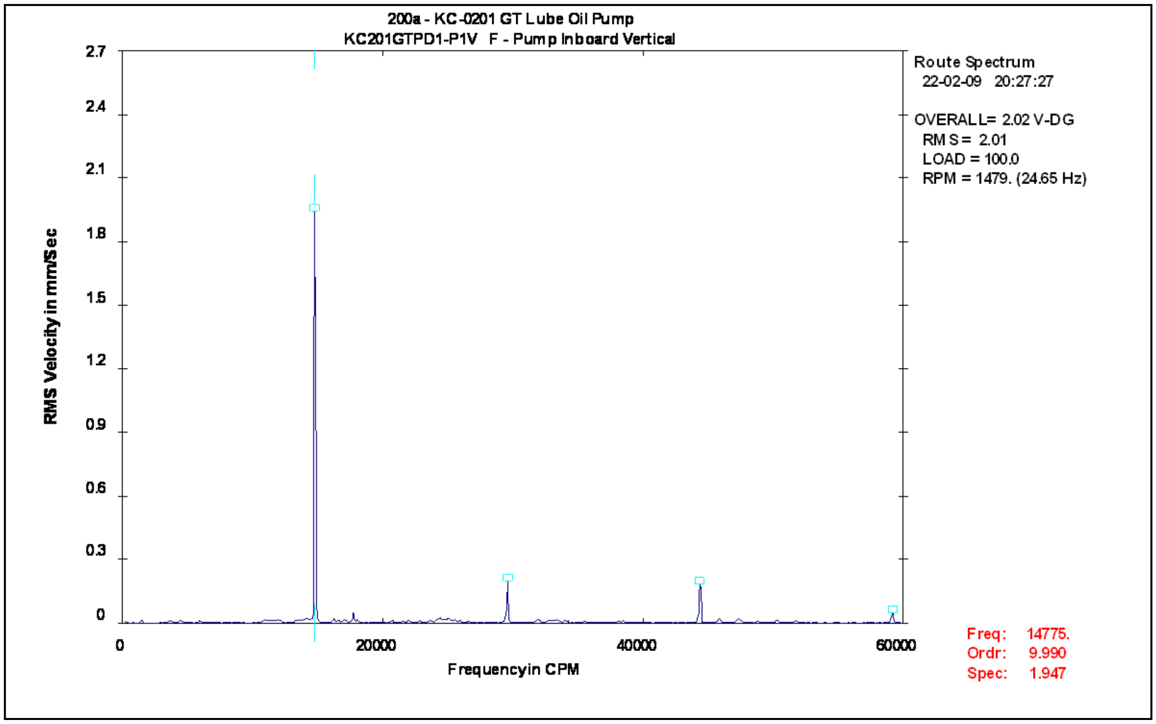


Figure 4.10: Vibration spectrums for KC 201 GT lube oil pump inboard vertical.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The methodology which is used in this project can support the objectives in the project which are to perform the failure analysis on the stainless steel tubing failure to get the type and cause of the failure that can be avoided in the future which can save a lot of money and time in the industrial field.

Based on the result and discussion part, the fracture is confirmed as brittle fracture as seen under fractography using Scanning Electron Microscope. There is also point of initiation of the failure found on the fracture surface similar to that in fatigue failure compared to the previous journal.

Although the sample material which is 316L stainless steel is a ductile material, but brittle fracture occurred. The tubing was experienced with high vibration from the lube oil pump which can cause resonance effect and fatigue failure. The slip bands in the microstructure proved that work hardening occurred at the fracture area. Work hardening is closely related to fatigue. This is the result of work or strain hardening. Work hardening reduces ductility, which increases the chances of brittle failure.

Hence, the failure of the 316L stainless steel tubing is confirmed because of fatigue. The underlying root cause of this failure is due to high vibration in the tubing resulting from the lube oil pump and also the pressure safety valves that connected to the tubing. With the source of vibration, the tubing has failed with brittle fracture. There is also supporting factor that lead to this failure which is the wrong installation of the ferrule at the tubing fitting. This incident might be providing notch at the tubing surface that can cause high stress concentration area which is the starting point of this failure. There is no sign of overpressure because the pressure in the tubing is relatively low.

This project is relevant enough as the sample material is collected and selected from the real industrial equipment and the failure occur based on the flaw and faulty of the equipment. Thus, the failure analysis that was carried out crucial that will be beneficial to both company’s performance and also for the educational purposes.

5.2 Recommendation

Based on the root cause, the failure occurred because of the high vibration from the lube oil pump and pressure safety valves. So, the author had suggested that the tubing can be replaced with flexible hose with the same size and specification. With the use of flexible hose, even if the system operates in high vibrations, the flexible hose will absorbed some of the vibrations that can avoid failure that can lead to plant shutdown and production loss.

Instead of monthly monitoring and vibration data collection, it is recommended that vibration transmitter should be installed at the lube oil pump and any other equipment that can cause vibration so that the monitoring can be done 24 hours and there is warning if the vibration exceeds the early warning limit value. Apart from that, the condition of the pressure safety valves also important that should be monitored more frequently. The lube oil console is a critical system because the failure of this system can cause major problem in the plant operation.

Upon completing this project, there is some recommendation can be applied in order to improve this analysis. During sample preparation for the metallurgy, there are scratches at the sample surface that can affect the result in the microstructure observation. It is recommended that the appropriate polishing process can be done in the future to remove the scratches. Besides, the usage of colour etching is recommended in the future to make the microstructure can be seen more clearly.

REFERENCES

[1] Failure Analysis Methods, Tools and Services, Advanced Logistics Development.

[2] <http://mot.vuse.vanderbilt.edu/mt322/Ishikawa.htm> retrieved 25th October 2009.

[3] Masayuki Kamaya, "*Fatigue properties of 316 stainless steel and its failure due to internal cracks in low-cycle and extremely low-cycle fatigue regimes*", 2009, International Journal of Fatigue 32 (2010) 1081–1089.

[4] Y. Murakami , K.J. Miller, *"What is fatigue damage? A view point from the observation of low cycle fatigue process"*, Department of Mechanical Engineering Science, Kyushu University, University of Sheffield, Sheffield, UK.

[5] ASTM E03-01, Standard Guide for Preparation of Metallographic Specimens.

[6] 27th February 2009, "Short course on Introduction to Metallographic Sample Preparation notes", Material Laboratory, Universiti Teknologi Petronas.

[7] <http://www.siliconfareast.com/ishikawa.htm> retrieved 25th October 2009.

[8] <http://en.wikipedia.org/wiki/Root_cause_analysis> retrieved 25th October 2009.

[9] "Steel Glossary". American Iron and Steel Institute (AISI).

[10] "Why is Stainless Steel Stainless?"<http://www.stainless-online.com/why-stainless-steel-stainless.htm> Retrieved 2nd September 2009.

[11] Ashby, Michael F.; & David R. H. Jones (1992) [1986]. "Chapter 12". Engineering Materials 2 (with corrections Ed.). Oxford: Pergamon Press. pp. 119.

[12] <http://www.azom.com/Details.asp?ArticleID=863> retrieved 24th October 2009.

[13] TM Swagelok Company catalogue, Printed in U.S.A MI, May 2003, MS-01-157-SCS.

[14] Degarmo, Black & Kohser, 2003 <http://en.wikipedia.org/wiki/Work_hardening#CITEREF> p. 60, retrieved 25th March 2010.

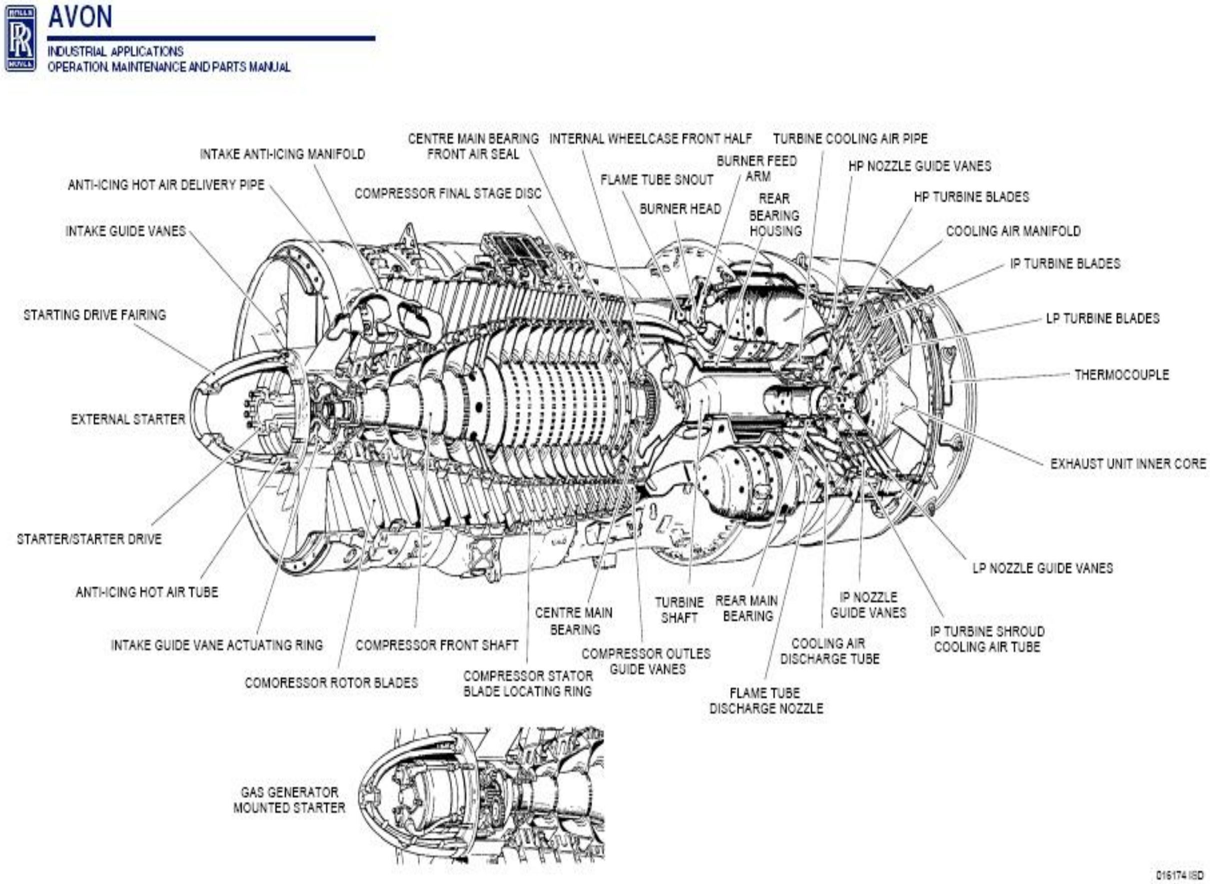
[15] <http://www.corrosionlab.com/papers/techincal-brief-fatigue-failure.htm> retrieved 20th May 2010.

[16] J. Komotori and M. Shimizu, *"Microstructural effect controlling exhaustion of ductility in extremely low-cycle fatigue"*, Trans Jpn Soc Mech Eng A **57** (1991), pp. 2879–2883.\

[17] William D. Callister Jr (2007) *"Material Science and Engineering: An Introduction"* 7th Edition, Wiley Asia Student Edition, The University of Utah

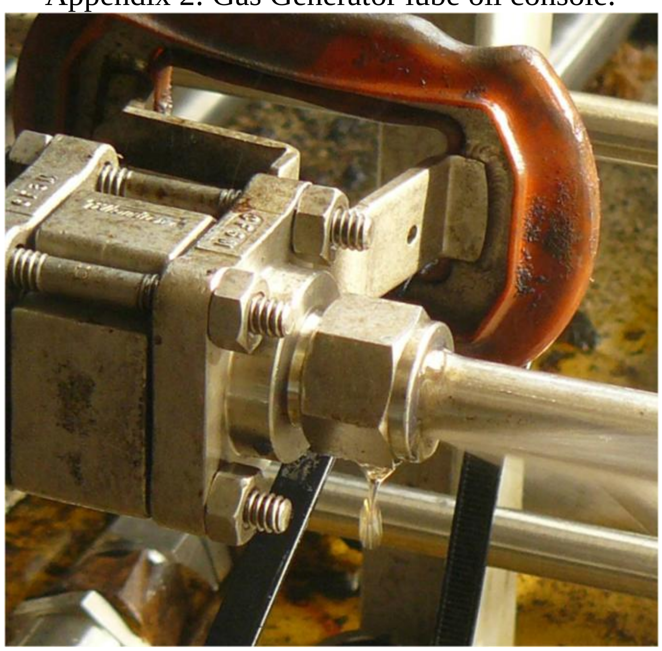
[18] Mars G. Fontana "Corrosion Engineering" Third Edition, McGraw-Hill International Edition, Materials Science and Engineering Series.

APPENDICES



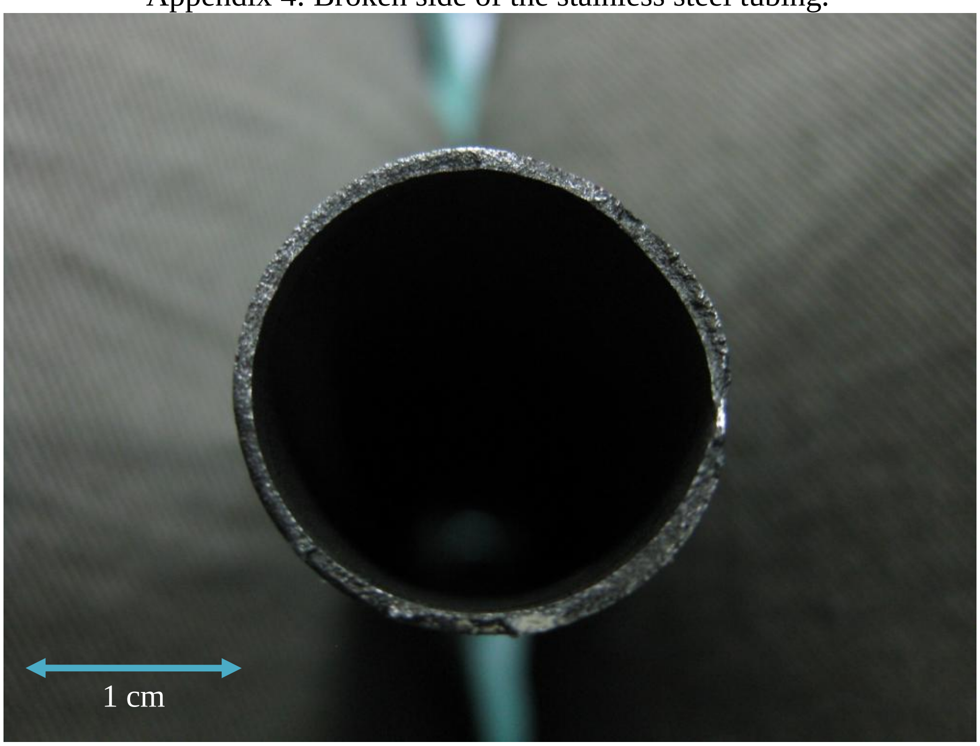
Appendix 1: Gas Generator drawing.

Appendix 2: Gas Generator lube oil console.



Appendix 3: Close view on the leaking tubing.

Appendix 4: Broken side of the stainless steel tubing.



Appendix 5: Fracture surface.

Appendix 6: Sample metallographic for OM and SEM .

KC201GTPD1 - P1V-F - Pump Inboard Vertical

		mm/Sec
13-06-08	11:09	1.553
10-07-08	10:28	3.948
08-08-08	10:39	4.593
04-09-08	10:17	2.381

	15-10-08	09:35	3.516
	23-12-08	15:15	4.292
	15-01-09	11:00	3.436
	22-02-09	20:27	2.861
	21-05-09	15:11	3.604
	17-06-09	11:20	3.669
	25-06-09	10:24	2.397
	08-07-09	09:49	2.314
	29-07-09	11:12	2.227
	13-08-09	10:27	2.848
	10-09-09	14:55	3.284
	30-10-09	10:56	4.030
	11-11-09	10:30	3.608
Baseline Value	-----------------		1.199
Calc. Mean Value	-----------------		3.210
Standard Deviation	-----------------		.833
Early Warning Limit	-----------------		1.530
Alert Limit Value	-----------------		6.363
Fault Limit Value	-----------------		9.898

Appendix 7: Vibration reading for pump inboard vertical.

KC201GTPD1 - P2V-H - Pump Outboard Vertical

			mm/Sec
	13-06-08	11:10	1.080
	10-07-08	10:29	7.274
	08-08-08	10:38	9.153
	04-09-08	10:17	8.548
	15-10-08	09:36	8.529
	23-12-08	15:15	6.664
	15-01-09	11:02	6.044
	22-02-09	20:28	3.637
	21-05-09	15:13	3.320
	17-06-09	11:22	4.695
	25-06-09	10:26	5.051
	08-07-09	09:49	4.428
	29-07-09	11:14	3.260
	13-08-09	10:28	5.441
	10-09-09	14:56	5.159
	30-10-09	10:57	4.823
	11-11-09	10:30	4.592
Baseline Value	-----------------		1.066
Calc. Mean Value	-----------------		5.394
Standard Deviation	-----------------		2.130
Early Warning Limit	-----------------		1.513
Alert Limit Value	-----------------		6.363
Fault Limit Value	-----------------		9.898

Appendix 8: Vibration reading for pump outboard vertical.