M3-003 Fatigue Life Analysis of Liquid Ring Compressor Shaft CO-4301-1

Gatot Prayogo*, Sugeng Supriadi*

*Mechanical Engineering Department
University of Indonesia, Depok 16424
Tel. 021-7270032, Fax. 0217270033
e-mail: gatot@eng.ui.ac.id

ABSTRACT

A fatigue life analysis for liquid ring compressor shaft has been performed. A series of attempt i.e. visual and microscopic examination for fracture surface, corrosion test, and fracture mechanics approach have also been conducted. Fatigue life evaluation for undamaged shaft in normal condition was also conducted using S-N diagram to check its fatigue design. Based on fracture surface examination, it can be shown that the crack propagation began after pitting deep of 0.4 mm was reached. Therefore, estimation can be made on the time required for pitting corrosion from the initial corrosion until the critical dimension to initiate crack propagation. Corrosion test was examined on potensiodynamic and corrosion cells and under acid condition using dissolution of HCl and distilled water (pH 5.1) at 25 °C. The result of corrosion test for SUS 420 under set up condition is 0.6311 mpy (0.0160 mm/y) which is equivalent to about 25 years operation time. From fracture mechanics analysis, the number of cycles to propagate the crack is about, N = 2.25 x 10^8 cycles which is equal to 128 days operation time. Based on S-N diagram analysis, the compressor shaft has unlimited life when its operating condition is normal and there is no any damage occur on shaft. Considering the above results, theoretically it can be concluded that the fatigue life of Liquid-Ring Compressor Shaft CO-4301-1 is very dominantly controlled by corrosion process which is more than 95 % of its fatigue life, however, the time to propagate crack from critical pitting size to final fracture is not a dominant process.

***Keywords** : Fatigue life, S-N diagram, Corrosion test, Fracture Mechanics,Compressor Shaft.*

1. Introduction

Metal fatigue has a problem since at least 1840 when failure in railway axles and mill machinery were discussed. Basically there are three steps of fracture process for rotating shaft under cyclic loading, i.e. crack initiation, crack propagation, final fracture. The surface and the influences from the environment (roughness, corrosion, temperature) have a strong effect to fatigue life of shaft. A lot of other influence from load, material, fabrication, and other parameters with all their multiple combinations have also controlled fracture process. Fatigue crack may sometimes be produced even when the stress amplitude is lower than the static tensile strength or yield strength. Although this will be understood in the case where the amplitude of repeated stress is equivalent to the static tensile stress. It may be difficult to understand the reason why the fracture occurs when the amplitude of repeated stress is lower than the yield strength.

In the real condition, there are numerous machine components fractured prematurely, or in other word its fatigue life prior to its design life. This things can generate serious problem in industry since it can disturb production capacity. Therefore, the objective of this research work is to evaluate fatigue life of liquid ring compressor shaft CO-4301-1. The detailed construction of liquid ring compressor shaft CO-4301-1 can be shown in Figure 1, below.

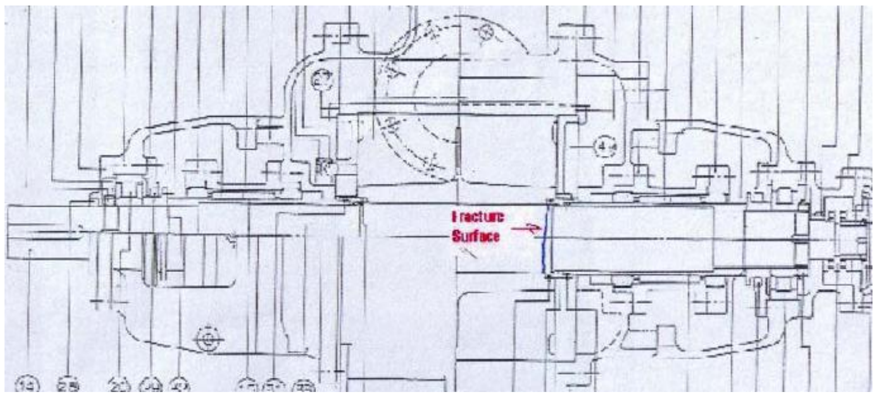


Fig. 1. Construction of liquid ring compressor shaft CO-4301-1 showing fractured region.

2. Method

In order to evaluate fractured shaft of liquid ring compressor above, there were some technique have been conducted like fracture surface examination, corrosion testing, design life evaluation for undamaged shaft, fracture mechanics evaluation. Fracture surface examination was conducted to get failure mechanism and some important information related to fracture processes. Corrosion testing conducted at similar condition with shaft operating condition was also performed to get critical pitting dimension. Design life evaluation was performed to clarify its fatigue life when the compressor shaft without any damage. Fracture mechanics was also used to predict number of cycle to propagate crack from critical condition to final fracture.

3. Result and Discussion

3.1. Corrosion Test

Corrosion is the dis-integration of a material into its constituent atoms due to chemical reactions with its surroundings or environment. This type of damage or corrosion product typically produces oxide(s) and/or salt(s) of the original metal. Reaction between metal and environment is electrochemical process. Because electrochemical reactions occur in an electrochemical cell with oxidation reactions occurring at one electrode and reduction reactions occurring at the other electrode, they are often further defined as either cathodic reactions or anodic reactions.

Corrosion test was examined on potensiodynamic and corrosion cells. potensiodynamic measures the electric current produced by voltage changes. Corrosion test was conducted under acid condition using dissolution of HCl and distilled water (pH 5.1) at 25 °C. The result of the experiment is depicted in Fig. 2, named the Tafel curve. It was found that corrosion rate of SUS 420 under set up condition is 0.6311 mpy ~ 0.0160 mm/y. Based on fractograph from previous Failure Analysis data, it can be concluded that the crack propagation began after pitting deep 0.4 mm was reached. Based on the above analysis, estimation can be made on the time required for pitting corrosion from the initial corrosion until the critical dimension when the crack propagation begin.

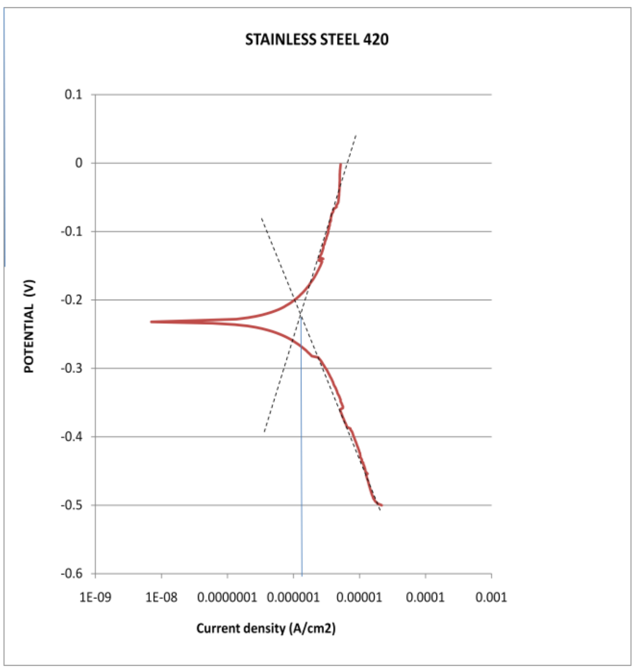


Fig. 2, Tafel corrosion test

Corrosion rate can be calculated from tafel corosion test with following equation:

Corrosion rate, $CR = K_i \frac{i_{corr}}{\rho} EW$ = 0.6311 mpy ~ 0.0160 mm/y

Where :

K_i : Constanta of mpy : 0.129
I_{corr} : Current ($\mu A/cm^2$) : 1.38
EW : Equivalent Weight : 27.92
ρ : Density (gr/cm^3) : 7.87

Estimation time of the shaft failure under pitting condition :
Time to produce critical pitting dimension (0.4 mm)

= pitting deep / corrosion rate
= 0.4 mm / 0.0160 mm/y
= 25 years

This result is longer than actual due to corrosion test is running under room temperature. If the test set up on 50°C , corrosion rate will increase since passive layer will dissolve on this condition.

The total service life of the shaft failure under pitting condition is equal to the time needed to produce critical pitting dimension above and the time needed for crack propagation until failure. Fracture mechanics approach is applied to estimate the number of cycles to failure.

3.2. Fatigue life evaluation of undamaged compressor shaft

In order to evaluate the fatigue life of compressor shaft in normal or standard condition i.e. normal load and without occurrence of damage like crack, corrosion pitting, etc., It can used S-N diagram for compressor shaft material (SUS 420 J2). Mechanical properties of SUS 420 J2 are follow : Tensile strength ($\boldsymbol{\sigma_u}$) is 55 kgf/mm^2 or 539 N/mm^2, Yield strength ($\boldsymbol{\sigma_y}$) is 23 kgf/mm2, and Hardness is 235 HB.

The value of fatigue limit ($\boldsymbol{\sigma_n}$) for compressor shaft can be calculate based on formula below :

$$\sigma_n = C_L\, C_D\, C_S\, \sigma'_n$$

Where $\sigma'_n = 0.5\ \sigma_u$

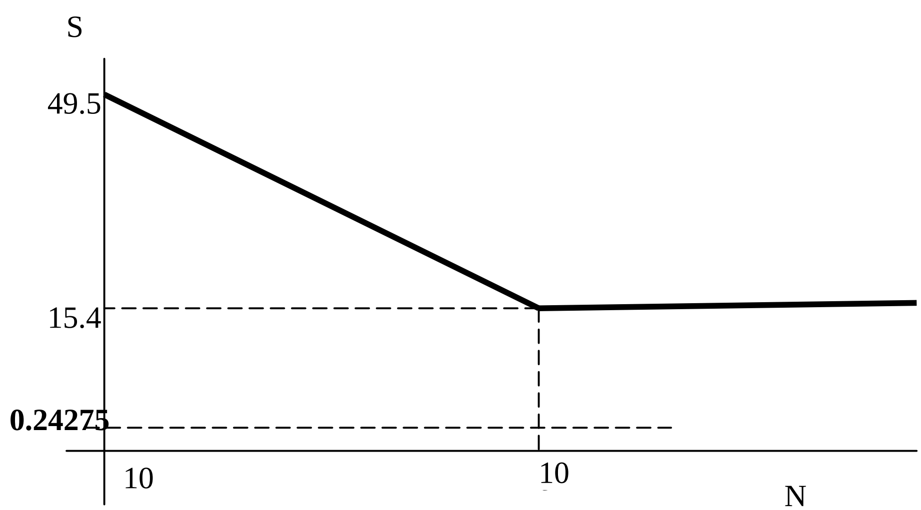
C_L = 1 , for completely reverse bending load (ref 3)

C_D = 0.8 for diameter of shaft greater than 2 inch (ref 3)

C_S = 0.7 for machined surface finished and σ_u = 55 kgf/mm2 (74 ksi), see figure below.

$$\sigma_n = 1 \times 0.8 \times 0.7 \times (0.5 \times 55)$$
$$= 15.4 \text{ kgf/mm}^2$$

Finite life for N = 10^3 cycles is 0.9 σ_u (49.5 kgf/mm^2), therefore S-N diagram for compressor shaft can be shown in Figure 3 below.



Based on S-N diagram above, it can be concluded that working stress at critical point for compressor shaft is about 0.24275 kgf/mm^2, which is much less then its fatigue life strength i.e 15.4 kgf/mm^2. Therefore, compressor shaft has unlimited life or will not fail when its operating condition is normal and there is no any damage occur on shaft.

3.3. Fracture mechanics approach to estimate crack propagation

Crack growth rate behavior in a cyclic loading can be expressed as :

$$\frac{da}{dN} = C(\Delta K_1)^m \quad (1)$$

Where : $\frac{da}{dN}$ = crack growth rate

ΔK_I = stress intensity factor for mode I

m = constant

Crack propagation rate for SUS420J2 can be calculated approximately by equation (Ref. 5.) :

$$\frac{da}{dN} = C(\Delta K_1)^m = 8.04 \times 10^{-11} (\Delta K_1)^{3.18} \quad (2)$$

According to the results of observation on fracture surface as shown in Fig. 4, the crack initiated at point A shown as scattered corrosion pitting, then subsequent propagation to point B as final fracture region. The depth of scattered corrosion pitting was measured at about 0.4 mm, therefore a_i = 0.4 mm. The final fracture which is located at point B, and the distance from A to B is about 84.7 mm, therefore a_c is about 84.7 mm.

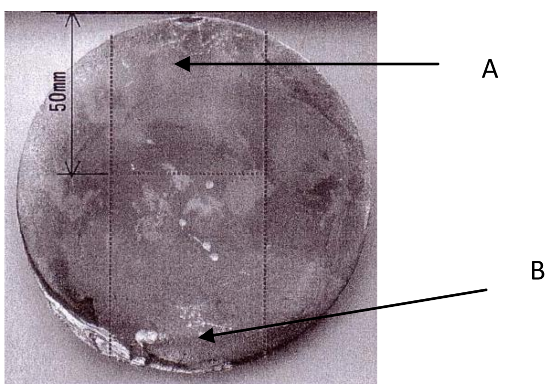


Fig.4,Fracture surface of shaft

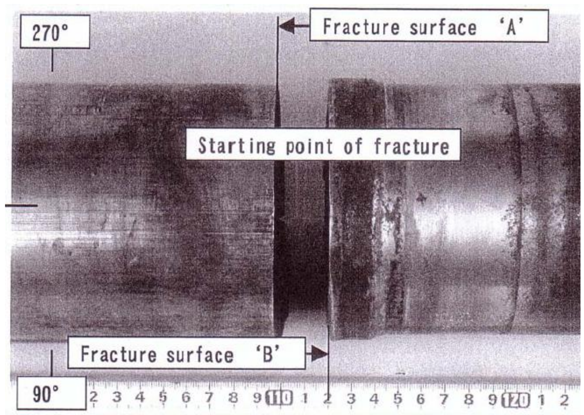


Figure 5. Fractured shaft showing that crack propagated perpendicular to shaft axis.

During operation the shaft suffered bending moment (bending stress) and torsion moment (shear stress). Since crack path is perpendicular to the shaft axis, therefore it can be concluded that the crack propagation is controlled predominantly by bending moment (bending stress). The role of torsion moment (shear stress) to control crack propagation can be neglected.

A model for estimation of stress intensity (K1) is shown in figure 6 below :

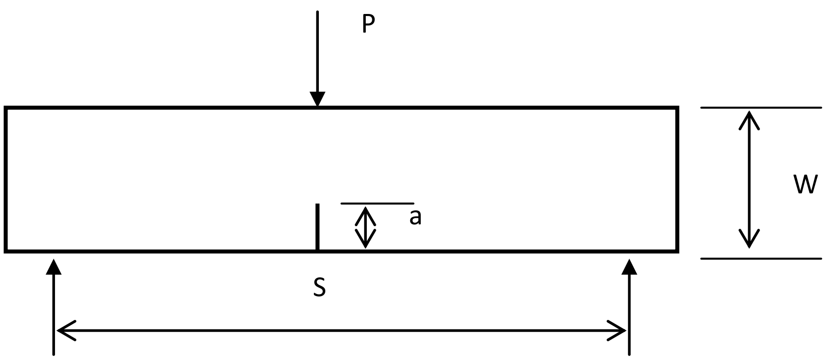


Fig. 6, idealization of loading condition for shaft

The stress intensity factor K_1 can be calculated as :

$$K_1=\sigma_o(\pi a)^{0.5}.F(a/W) \qquad (3)$$

Where nominal bending stress :

$\sigma_o= 3PS/2W^3$, $\xi = a/W$

$F(\xi) = A_o+A_1\xi+A_2\xi^2$

S is the span and W is the with of the test specimen (mm)

Since S ≥ W, the following assumption can be made:

$F(\xi) = A_o = 1.12$
$K_1 = \sigma_o (\pi a)^{0.5}. A_o$; where $A_o = 1.12$

Integrating equation:

$$dN = \frac{da}{C(\Delta K_1)^m}$$

$$N = \int_{a_i}^{a_c} \frac{da}{C(\Delta K_1)^m}$$

$$N = \int_{a_i}^{a_c} \frac{da}{C(\sigma_o A_o)^m (\pi a)^{m/2}}$$

$$N = \frac{1}{C(\sigma_o A_o)^m \pi^{m/2}} \int_{a_i}^{a_c} a^{-m/2} da$$

Equation above has solution as follows :

$$N = \frac{1}{C'} \frac{1}{(m/2)-1} \left[\frac{1}{a_1^{(m/2)-1}} - \frac{1}{a_c^{(m/2)-1}} \right] \; ; \qquad (4)$$

Where : $C' = C(\sigma_o A_o)^m \pi^{m/2}$;

Substituting C = 8.04 x 10^{-11}, m=3.18, A_o=1.12, a_i=0.4mm, a_c=84.7mm, and σ_o = 2.454 kgf/mm^2. The number of cycles to propagate the crack from point A to point B (see Figure 4 above) is about 2.25 x 10^8 cycles.

Compressor was working in revolution of 975 rpm intermittently for 1 hour and 35 minutes (95 minutes) running and 15 minutes stopping cycles, hence for 24 hours operation time, the number of intermittens = (24 x 60) / (95+15) = 13.09 intermittens which is equal to 1243.6 minutes each day or equivalent to 1,212,546 cycles per day. For the number of cycles N= 2.25 x 10^8 cycles, the time of crack propagation can be calculated as 186 days. Total service life of the shaft under pitting condition is 25 years and 186 days.

4. Conclusion

Considering the result of above analysis i.e. corrosion test, fatigue life analysis, and fracture mechanics analysis, it can be concluded as follows :

1. Fatigue life of Liquid-Ring Compressor Shaft CO-4301-1 is very dominantly controlled by corrosion process which is more than 95 % of its fatigue life, theoretically. However, the time to propagate crack from critical pitting size to final fracture is not a dominant process.
2. Compressor shaft has unlimited life or will not fail when its operating condition is normal and there is no any damage occur on shaft.

References

[1]. Wulpi Donald, Understanding How Components Fails, American Society for Metal, 1995.
[2]. Liquid Ring Compressor Shaft-CO-4301-1 Failure Analysis, Internal Report of ___Group, 2009
[3]. Juvinal R.C., Engineering Consideration of Stress, Strain and Strength, McGraw-Hill, Inc., 1967
[4]. Roberge, P.R., Handbook of Corrosion Engineering, McGraw-Hill, USA, 1999
[5]. Shin-Ichi Nishida, Failure Analysis in Engineering Applications 1st Ed., Butterwort-Heinemann, 199.