Failure Investigation of Repetitive Crack on MW-701D Gas Turbine Exhaust Manifold

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Abstract. A gas turbine power plant is the best choice for peak load conditions in power generation. As we know using gas turbine need less time to start and stop operation than a coal-fired power plant. In East Java, Indonesia has 9 unit Gas Turbine Power Plant, which usually operates in peak load conditions. In this paper, a study will carry out an investigation based on maintenance data history which since 2010 founded repeatedly crack in exhaust manifold. Failure Investigation in the exhaust manifold has been carried so that repetitive crack can be handled in the future. The crack location was mapped to find the root cause of failure. Fuel consumption and operation condition was analyzed to find the cause of the crack. Analysis with Fluent software found that streamline of flue gas makes a turbulency in the spotted area. Material selection and design no free expansion in the exhaust manifold increase possibility of failure.

1. Introduction
Gas turbine power plant has good reliability, so it relies on high demand in peak load. Start and stop operate gas turbines need less time than a coal-fired power plant. This is one of the reasons, gas turbine power plant always used until now. In East Java, Indonesia has 3 blocks of combined cycle gas turbine power plant where 3 gas turbines combine with 3 HRSG (Heat Recovery Steam Generation) and 1 Steam Turbine. Table 1 showing the amount and combination of gas turbines in East Java. Hot gases from combustion which have a temperature of about 550°C be used to heat-up HRSG to produce steam and turn the steam turbine. The exhaust manifold is part of a gas turbine used to direct the flow of hot gases from combustion to HRSG. If it has a failure in the exhaust manifold, it can reduce the productivity of steam because the efficiency of HRSG reduced. Figure 1 shown the scheme of the exhaust manifold in gas turbine power generation. From 2010 until 2016 always founded crack in the exhaust manifold area. This paper will investigate the cause of crack in the exhaust manifold that repetitive crack will be handled in the future.
Table 1. Number of Gas Turbine Power Plant in East Java Indonesia

|                      | HRSG  | Steam Turbine |
|----------------------|-------|---------------|
| GT Block 1 (1.1 to 1.3) | 1.1 to 1.3 | 1.0           |
| GT Block 2 (2.1 to 2.3) | 2.1 to 2.3 | 2.0           |
| GT Block 3 (3.1 to 3.3) | 3.1 to 3.3 | 3.0           |

Figure 1. Exhaust Manifold in System Gas Turbine Power Generation.
Figure 2. Exhaust Manifold in Gas Turbine Power Generation

Figure 3. Repetitive Crack in Exhaust Manifold Area

2. Investigation Method
Investigation based visual inspection and collecting data from historical data maintenance from 2010 until 2016. All unit gas turbine always operate in ready state condition, it means if high demand electricity so gas turbine must be ready to start as soon as possible. Start-stop operates conditions may be affected by thermal fatigue of the exhaust manifold. Fuel used in gas turbines also influenced the tendency to fail in the material. Some gas turbines using mixing fuel HSD and gas to operate. Sulfur content increases the corrosion rate and reduces the strength of a material. The composition of the material can be known using XRF (X-ray Fluorescence). The compatibility of material used to determine the endurance of part to applied thermal stress or static load. Using ANSYS software flow analysis, to found the design effect of fin exhaust manifold and stiffener with spotted turbulence of flow hot gases.

3. Observation and Result

3.1. Crack Location based on Visual Inspection
Figures 4 and 5 show the shape of the exhaust manifold which in area D3 founded more crack than another area.

**Table 2.** Total Founded Crack in Gas Turbine Exhaust Manifold.

|        | D1 | D2 | D3 | D4 |
|--------|----|----|----|----|
| GT 1.1 | -  | -  | 3  | 2  |
| GT 1.2 | -  | -  | 1  | 3  |
| GT 1.3 | -  | -  | 3  | 4  |
| GT 2.1 | -  | -  | 1  | -  |
Table 2 shows all unit gas turbine founded crack in the exhaust manifold. Area D3 are dominated the total number of crack 20 times. The total number concentration of crack in area D3 can be analyzed to find the cause of failure.

### 3.2. Fuel Consumption used in Gas Turbine
Fuel consumption may be affected cause of crack in the exhaust manifold. HSD fuel has more sulfur content than fuel gas. High sulfur content increases the corrosion rate and reduce the strength of a material. Fuel consumption in GT Block 1, Block 2, and Block 3 shown table bellows.

#### Table 3. Fuel Consumption GT Block 1

| Years | GT 1.1 | GT 1.2 | GT 1.3 |
|-------|--------|--------|--------|
|       | HSD | GAS | HSD | GAS | HSD | GAS |
| 2010  | 0  | 252  | 0  | 349  | 34  | 324  |
| 2011  | 2  | 290  | 95 | 264  | 1  | 345  |
| 2012  | 0  | 181  | 26 | 132  | 0  | 151  |
| 2013  | 0  | 166  | 0  | 162  | 0  | 149  |
| Total | 0.024 | 99.78 | 11.77 | 88.23 | 3.486 | 96.51 |

#### Table 4. Fuel Consumption GT Block 2

| Years | GT 2.1 | GT 2.2 | GT 2.3 |
|-------|--------|--------|--------|
|       | HSD | GAS | HSD | GAS | HSD | GAS |
| 2010  | 130  | 122  | 107  | 152  | 132  | 126  |
| 2011  | 2215 | 103  | 271  | 63   | 184  | 114  |
| 2012  | 042  | 82   | 17   | 47   | 22   | 45   |
| 2013  | 0    | 119  | 0    | 89   | 0    | 39   |
| Total | 47.6 | 52.4 | 52.95 | 47.05 | 44.36 | 55.64 |

#### Table 5. Fuel Consumption GT Block 3

| Years | GT 3.1 | GT 3.2 | GT 3.3 |
|-------|--------|--------|--------|
|       | HSD | GAS | HSD | GAS | HSD | GAS |
| 2010  | -  | 317  | -  | 340  | -  | 336  |
| 2011  | -  | 353  | -  | 356  | -  | 334  |
| 2012  | -  | 139  | -  | 117  | -  | 94   |
| 2013  | -  | 169  | -  | 182  | -  | 117  |
| Total | 0  | 100  | 0  | 100  | 0  | 100  |
Fuel Consumption in GT Block 1 more than 80% using fuel gas. Block 2 using mixed fuel HSD and fuel gas in the range 47% HSD and 53% gas. Allover Block 3 using 100% fuel gas. The maximum temperature combustion gases in the exhaust manifold are 550°C so the deposit of sulfur can’t be formed because of the dew point of sulfur about 130°C-150°C. Fuel consumption hasn’t significant effect cause of crack in the exhaust manifold it is confirmed that all Block (Block 1, Block 2, and Block 3) also has founded crack.

3.3. Operation Condition
Combine Cycle Gas Turbine Power Plant in East Java, Indonesia used for supplied all demand in Java and Bali Island. Allover Industries in Java Island, it makes a demand of electricity increase in rush hour. Start and stop in gas turbine power plants can’t be avoided depending on the needs. Table 6 shows the cycle off the start and stop operating from 2010 until 2016.

**Table 6. Frequency Start and Stop the Operation of Gas Turbine Power Plant**

| Frequency Start – Stop Operation | Cycle Times |
|---------------------------------|-------------|
| GT 1.1 | GT 1.2 | GT 1.3 | GT 2.1 | GT 2.2 | GT 2.3 | GT 3.1 | GT 3.2 | GT 3.3 |
| 7 | 182 | 22 | 319 | 297 | 247 | 71 | 58 | 123 |

Table 6 shown that block 2 operate in peak load condition. Total cycle times of start and stop gas turbine block 2 more than another block, it means block 2 more often start and stop operation than the other. From this data can be analyzed that condition operation hasn’t significant effect cause of crack in the exhaust manifold. This confirmed that all block founded crack in the exhaust manifold.

3.4. Material Selection
Temperature gas combustion in the exhaust manifold about 550°C. Material selection is important to improve reliability. Testing has been carried out in material exhaust manifold. Table 7 shown tested XRF in the material exhaust manifold.

**Table 7. Chemical Composition of Exhaust Manifold**

| Percentage of Content | Cr | Mn | Fe | Ni | Cu | Mo |
|-----------------------|----|----|----|----|----|----|
| Exhaust Cylinder      | 11.95 | 0.54 | 87.13 | 0.18 | 0.05 | 0.04 |
| Exhaust Manifold      | 2.22 | 0.41 | 96.25 | 0.08 | - | 1.04 |

Based on the chemical composition material used in the exhaust manifold is ASTM A387 gr 22 class 2. The maximum requirement temperature this material is 1250 F or 675°C. The yield strength (σy) of this material is 310 MPa. Based on operation data, the maximum working temperature of the exhaust manifold is 551°C. Tw < Ts is safe to operate. Where Tw is working temperature and Ts is the
specification of range temperature material. To calculate the strength of material with thermal stress used formula bellows.

\[ \Delta L = \alpha \times \Delta T \times L \]

Then

\[ \sigma_{therm} = \alpha \times \Delta T \times E \]

Where:
- \( \sigma_{therm} \): Thermal stress (Mpa)
- \( \alpha \): Coefficient of thermal expansion (m/m.°C)
- \( \Delta T \): Temperature change (°C)
- \( E \): Elastic Modulus (Pa)
- \( \Delta L \): Change of length (m)
- \( L \): Original length (m)

Because design stiffness has no free expansion or fixed joint, it can increase the possibility of failure in material because the length of material will increase and expansion is blocked.

3.5. Microstructure Examination

![Figure 6. Microstructure Examination of Exhaust Manifold](image)

The microstructure in the exhaust manifold is ferrite-pearlite. The microstructure is under normal condition. No found defect indication micro void. Grain size no enlarge and no found defect corrosion. There is no increase or decrease in hardness value in this area. it means this material doesn't indicate to reduce strength because of stress corrosion and no indication of fatigue failure.

3.6. Stress Distribution

The design of the exhaust manifold has flowed simulation with ANSYS Fluent software. Figure 7 shown flow simulation. The range on blue and red color in the legend is a variation of velocity. The
blue color is means low velocity and the red color means high velocity. Temperature, specification of material, hot gas velocity, and the dimension of exhaust manifold used to analyzed flow in this area.

![Figure 7. D-D Cross Section Exhaust Manifold Fluent Simulation](image1)

![Figure 8. Exhaust Manifold Fluent Simulation](image2)

Form Figure 7 shown that area D3 applied high velocity and sees spot turbulency. It means high-stress concentration in area D3 will reduce the lifetime of the exhaust manifold. Design stiffness of exhaust has no free expansion or fixed joint, it can increase the possibility of failure in material because deformation in the material which the length of material increase.

4. Analysis of Failure Cause

Crack in exhaust manifold founded in all unit gas turbine power generation in East Java. Operation condition and fuel consumption have no significant effect cause of crack in the exhaust manifold. The material used in the exhaust manifold has a minimal requirement to applied in load condition gas turbines. This material applied compression stress because of fixed joint and no free expansion. Based
on fluent simulation area D3 shown high velocity and turbulency it reduces the lifetime of the exhaust manifold.

5. Conclusion

1. Based on history maintenance, all unit gas turbine founded crack in the area exhaust manifold.
2. Area D3 has more total number of crack.
3. Fuel consumption in gas turbines has no significant effect on the cause of failure.
4. Frequency starts and stops operation has no significant effect to cause a crack in the exhaust manifold. It confirmed that all unit gas turbines in East Java founded crack in the exhaust manifold.
5. The material used in the exhaust manifold ASTM 387 gr 22 has a minimum requirement to apply for exhaust manifold with stress thermal.
6. Design no free expansion in the exhaust manifold possible to make deformation in metal and tendency to failure crack.
7. Based on fluent simulation area D3 shown high velocity and turbulency, it makes reduce the lifetime of the exhaust manifold because of high-stress concentration.
8. Further engineering studies are needed to improve the performance of the exhaust manifold.

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