Identifying Inconel 718 Fasteners Failure Using Structured Problem Solving Method

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Abstract: This paper is about the development of problem solving method to identify failures in inconel 718 mainly applied in the subsea environment. A3 analysis with support from fishbone diagram and 5 whys analysis techniques were introduced to identify the actual cause of failures. Upon identification of the actual cause of failure, improvement actions were taken to eliminate the actual cause. In this research, the identification of the actual cause of failure related with the Inconel 718 fasteners that were used for Methanol Injection Tree Valve (MITV) was performed. Lab analysis on fresh and failure fasteners was performed by comparing the mechanical properties, chemical composition and microstructure analysis. The data was then compared to understand the characteristics of the failure. Future state and target in A3 stage required a mitigation action to eliminate the cause of failure. This was performed by conducting new material analysis i.e. L7M fasteners for future reference. Standard template for subsea's problem solving method was established upon completion the analysis for future use.

1. Introduction

Many organizations nowadays consider quality as the first and foremost priority in their products and services within their management systems [1]. Fasteners used for critical applications in subsea industry provide a challenge in terms of material selection, quality control, traceability and documentation for manufacture and delivery. Criticality of subsea fasteners are defined as both pressure containing and primary load bearing members that may affect the functionality of valves, equipment and instruments for safe and reliability [2]. As reported on Wall Street Journal in July 2016, the bolt issue could affect more than 2,400 platforms and oil rigs in the Gulf of Mexico, as well as of 23 off the coast of California, and one active rig on the outer continental shelf in Alaska.

Hydrogen induced stress cracking (HISC) or hydrogen embrittlement (HE) was identified as the major failure mechanism experienced during the last decades that was resulting from the hydrogen charging conditions of the cathodic protection (CP) system. The main bulk of fasteners used subsea is of low alloyed steel grade type which relies on electrical continuity to the cathodic protection system to avoid sea water corrosion such as ASTM 320 Grade L7, L7M, L43 bolts with ASTM 194 Grade 4, 7M, 7 nuts, that will have a possibility prone to HISC/HE if the fastener hardness and strength level exceed the specified and established limits [1].

A leak was detected on the Production Wing Block (PWB) of Subsea Tree (XMT #2) which has been installed on P201 Well for three years since 2014. Further investigation reveals that a stud
mounting of the Methanol Injection Tree Valve (MITV) has broken off. A portion of the broken stud from XMT#2 was retrieved from subsea and was sent out for lab analysis. Figure 1 shows the actual condition on what were happened in subsea during this incident. Fluid was observed came out from the MITV due to one out four stud bolts were broken off.

![Image](image_url)

Figure 1. Fluid observed coming out from this point

2. Methodology

2.1 Problem Solving and A3 Technique

T.C Lin et al. [3] mentioned that problem solving competence is largely determined whether the members can effectively utilize knowledge resources located within the team. Based on the trans active memory concept and following traditional wisdom, that knowing the location of knowledge allow better problem-solving competency. There was a quality approach refers as Total Quality Management (TQM) introduced to the organization aims to guarantee organization’s success. Powel [4] defines this approach as a systematic framework which enhances operational activities of an organization to fulfill customers’ expectations. There are eight steps in the A3 tool that needs to be completed prior to identify the actual cause of the issues or problems. The steps are designed to ensure systematic approached is applied to understand the situation correctly. Deming [5] was highlighted that the top management has the responsibility to assign the employees a clear work standard. This will provide us with the correct improvement actions i.e. short and long-term solutions. M.S. D Caro et al. [6] mentioned on his research that the successfulness of the problem solving methods were based on (a) the demands of the task being performed, (b) the characteristics of the individual performing the task and (c) the constraints of the skill execution environment. Anderson [7] mentioned the importance of Deming theory on the organizational system creation that encourages on learning and cooperation in enhancing the management practices implementation. Below are the eight steps that will be applied in A3 tool approach described in Figure 2.

Please take note that, the A3 implementation technique is only a problem solving tool that requires full support from respective functional area namely Engineering, Manufacturing and Quality to work hand on hand to ensure actual cause of failure is identified. The main objective of performing this activity to the team is to identify the underlying root cause and not only focusing on the primary root cause.

Below description describe each column expectation in order to complete the analysis.

1. Observed Problem
   Describe the problem so that it is understandable for the reader
   The problem should be based upon a (performance) gap between the goals or customer needs

2. Current State
   What do we know about the problem to be resolved
   What characteristics the system that the problem is a part of (the process, the product, the organisation etc.)
Which facts and data can we gather to understand the problem better, and what do these facts tell us about the problem?
Facts or outcome of analysis shall be visually illustrated

3. Problem Description
Based on what we have learned about the system and our observations of the current state, which actual problem should we take forward in the A3?
The description should be written in the present tense or visually illustrated.
The description must visualise why it is important to solve this problem, for instance by relating it to the company’s vision/goals.

4. Root Cause Analysis
Find the cause(s) of the problem using 5 Why’s.
If there are several causes of the problem, an analysis must be conducted in order to find out which effects of the possible causes that are related to the problem. Analysis may be used for this process – eventually hypotheses generation and testing of potential causes.
In the A3, the results of these analyses should be visualized graphically in order to illustrate which effects the potential causes have.

5. Future State and Target
Create hypotheses for how can we solve the root cause.
Map how the ideal future state should look after the problem is solved.
Draw/sketch how the solution should be.
Set a target for the improvement initiative – How can we measure that we have achieved the desired improvement?

6. Actions and responsibility
Define and prioritise actions to analyse, as well as to implement and test that solutions that are established in the future state.
Implement one action at a time to be able to accurately measure cause and effect.
Define a clear responsibility and deadline for the actions and follow up status.

7. Results
Visualize the results from the implementation of the results.

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Figure 2. A3 tool process flow descriptions

1. Describe the problem so that it is understandable for the reader.
2. What characteristics of the system make it a problem in a part of the process, the product, the organization, etc?
3. What are the facts that tell us about the problem better, and how do we visually illustrate the description?
4. How do we verify that the observed problem is related to the problem?
5. What are the potential causes of the observed problem?
6. What are the effects the potential causes have?
7. What are the actions that are required to implement the results?
8. How can we measure that we have achieved the desired improvement?
The results shall be directly comparable to the chosen standard/measure stated in the future state and target section. The results shall also visualize the relationship between individual initiatives and their effect on the result. If the results do not compare to the target, return to the Observed Problem or the Current State sections.

8. Continued Actions
   - To evaluate whether the results require the establishment of a new standard or whether A3 may be relevant to others.
   - Are there similar processes in our or other business units?
   - Shall the information gathered and the lessons learned be shared with other support units.

2.2 Root Cause Analysis
For Root Cause Analysis column, two (2) existing and famous methods will be used to identify the possible causes for a problem especially when a team’s thinking tend to fall into ruts. These two methods are:

1. The Cause and effect diagram/Fishbone diagram
2. 5 Whys analysis technique

The fishbone diagram is identifies many possible causes for an effect or problem. It will be used to structure a brainstorming session and immediately sorts ideas into useful categories. Below principles will be followed through during the brainstorming session to ensure team members are fully contributed to the process:

1. Agree on a problem statement (effect)
2. Brainstorm the major categories of causes of the problem. This will be performed by referring to generic headings:
   - Methods
   - Machines (equipment)
   - People (manpower)
   - Materials
   - Measurement
   - Environment
3. List down the categories of causes as branches from the main arrow.
4. Brainstorm all the possible causes of the problem. 5 Whys Analysis techniques will be applied during this stage. As each idea is given, the facilitator/team leader needs to list down it as a branch from the appropriate category. Causes can be written in several places if they relate to several categories.
5. Again ask “why does this happen?” about each cause. Write sub–causes branching off the causes. Continue to ask “Why?” and generate deeper levels of causes. Layers of branches indicate causal relationships.
6. When the group runs out of ideas, focus attention to places on the chart where ideas are few. This fishbone diagram was drawn by a manufacturing team to try to understand the source of periodic iron contamination. The team used the five generic headings to prompt ideas. Figure 3 illustrates the fishbone diagram example.

The root cause analysis will be supported by another quality tool called the 5 Whys Analysis technique. The 5 Whys technique is true to this tradition, and it is most effective when the answers come from people who have hands-on experience of the process being examined. It is remarkably simple: when a problem occurs, you uncover its nature and source by asking "why" no fewer than five times.
Here it is in action:

Problem: Customer is refusing to pay for the leaflets that were printed out for them.
   i. Why? The delivery was late, so leaflets couldn’t be used
   ii. Why? The job took longer than planned
   iii. Why? Printer’s ink shortage
   iv. Why? Sudden additional quantity ordered
   v. Why? Not enough printer’s ink in stock

As a countermeasure from the above analysis, team has to identify and appoint a supplier who can deliver the printer’s ink at very short notice so that will help the team to reduce inventory, waste and response to customer demand in a timely manner. Figure 4 shows the 5 Whys analysis technique templates that will be used to complete this research.

![Image of Cause and Effect Diagram]

**Figure 3.** Cause and effect diagram example

**Figure 4.** 5 Whys analysis technique template

The A3 tool is team work effort and requires full support and commitment from each team member. Therefore, team work is very crucial to ensure the fruitful of the brainstorming and analysis conducted. It is very important to have hands-on team members that were experiencing the issue. There will be a lot of questions and answers session during the brainstorming stage until there is no answer to explain on why the issue happened. Time frame to complete the analysis will be different.
for each issue depending on the criticality and severity of the issue. Follow-up meeting is always requiring after the initial start-up. This is to ensure updated and recent findings especially on the validation of the improvement actions are captured and reviewed again. Therefore, this approach can be considered as a continuous improvement effort.

3. Results and Discussion

3.1 Current State
A portion of the broken stud from XMT#2 was retrieved from subsea and was sent to material laboratory for further material analysis where the analysis was conducted previously following a similar failure that occurred on XMT #1 (10127822; SN: 190131-001). As there were some studs of the same heat no. in current stock, one of the stud was sent to material laboratory so that it can be compared against. Due to the similarity in many aspect of the material analysed, it can be concluded that the two failed studs and the fresh stud from stock are indeed from the same batch of material.

The fact that the fresh stud has never been torqued exposed to seawater and cathodic protection reflects the condition of the stud material in the as supplied condition. Work hardening or exposure to sea water and cathodic protection has not contributed to the increase in hardness of the failed studs. Reference made to mill certificate supplied by the supplier in the Manufacturing Record Book (MRB), confirms that the material has been treated to ASME SB-637-93a which will result in a high tensile strength material. Due to the condition of the material, the material is considered highly susceptible to Hydrogen Induced Stress Cracking (HISC).

HISC is very likely to be the possible cause of failure due to the following reasons:

1. Strength and hardness of material that is significantly more than the requirement of MS-607 as well as API Standard 6A718
2. The studs are under a constant tensile stress as due to the preload
3. Presence of cathodic protection means that hydrogen is abundant
4. Intergranular brittle failure was observed as the crack initiation and propagation
5. Crack path is sharp and singular profile without any significant branching indicates the unlikeliness of Stress Corrosion Cracking (SCC)
6. No corrosion product was observed on the fracture surface.

In this section, the implementation of another quality tools namely Fishbone Diagram/ Cause and Effect Diagram and 5Whys Analysis template are used to identify the actual cause of the failure. The decision has been made to send out the broken stud bolt that was failed subsea operation to the material lab for further analysis. Another fresh stud bolt from the current stock with the same heat no was sent out together to be compared with. Scope of Works of this analysis is defined in the next section of the analysis. Figure 5 shows the Cause and Effect Diagram established to analyze the potential cause of the failure.

Figure 5. Cause and effect diagram performed for the failure analysis
There are four criteria’s of the potential causes of the failures that required being focus on. There are
1. Method
2. Man
3. Machine
4. Material
Those criteria’s also required the definition whether the identified potential cause will/maybe contributed to the actual failure or not. Therefore, the definition of below categories is defined clearly into the template.
   i. Not contributing to root cause (label in orange)
   ii. Potential contributor to root cause (label in red)
Incorrect method applied during the stud replacement activity was identified as not contributing factor to root cause in the method category. This is due to proper monitoring/witnessing and record was performed earlier during the execution of the activity. Figure 6 shows on the actual record – Serial/Batch no of new stud was recorded into section 3.2 CITV1 Stud Replacement while performing this activity earlier.

### 3.2. CITV1 Stud Replacement

| Step | Description | Date/Sign/Remarks |
|------|-------------|------------------|
| 1    | Record Serial/Batch no. of new stud (P/N: 10060080) and nut (P/N: BB17-MX0407-13) to be installed onto CITV1. Stud Serial/Batch No: | 1/12/11 |
|      | Nut Serial/Batch No |                   |
| 2    | Apply grease on stud prior to installation. Use ALCO-EP-73 PLUS or equivalent. | 1/12/11 |

**Figure 6.** Serial/batch no recorded during the studs replacement

Over-torqueing activity during the assembly process was identified as not a contributing factor to the root cause in the Man category. The decision was made after review the actual torque application value record performed earlier. Figure 7 shows the actual torque value application on the replacement of four studs to 305ft-lbf.

**Figure 7.** Torque value application during the studs replacement
Torque Wrench that was used during the torquing application was ensured to be calibrated prior to use. This has eliminated the potential of having incorrect machine/equipment usage into Machine criteria. The analysis was continued by focusing into material criteria. There are three potential causes identified into the Material criteria as below:

i. Inconel 718 Alloy hardness material was not meeting the specified requirement

ii. Inconel 718 Alloy was under a constant tensile stress as due to the preload

iii. Presence of cathodic protection

Further analysis is required for Item i and ii above by using the 5 Whys analysis technique to understand the actual cause of the failure or underlying cause. Please take note that, by completing the cause and effect diagram analysis only the primary cause of failure is identified. Therefore, the analysis is continued further by implementing the 5 Whys analysis technique. The objective of performing further evaluation is to dig out the details actual cause of failure that has contributed to the issue. By identifying the actual cause then only the correct countermeasure i.e. containment and corrective actions can be suggested and implemented to ensure no re-occurrence for future. Presence of cathodic protection was set aside as the Subsea Tree was designed to be applied with the cathodic protection criterion. Thus, necessary actions are required to ensure those requirement are fulfilled for the Subsea Tree deployment. 5 Whys analysis was performed to identify the potential cause related with the Inconel 718 Alloy hardness material issue that not meeting to the specified requirement. This is shown in Figure 8. This action was performed upon received the lab test analysis report that focus on below scope of works.

i. Visual/Macro Examination

ii. Cross-sectional Metallographic Examination

iii. Chemical Composition Analysis

iv. Hardness Measurement

Figure 8. 5 why analysis on the Inconel 718 alloy hardness material was not meeting specified requirement

One broken stud bolt with 17mm Outer Diameter (OD) and 35mm length (L) of MITV connection was analyzed to understand the characteristics and behavior of the material consists of mechanical and chemical composition analysis. The objective of the analysis was to establish the possible cause (s) of the failure of stud bolt:

1. The stud bolt had been broken in brittle mode with intergranular profile in association with torsional loading in addition to the normal tensional loading
2. The crack initiated from circumferential areas of the thread root where higher stress had exerted
3. Intergranular fracture was likely attributed to hydrogen induced stress cracking (HISC) in the exposure of cathodic protection
4. The chemical compositions of the broken stud bolt met the requirements of MS-607 specification of material Inconel 718 as well as API standard 6A 718-2009
5. Microstructure of stud base material reveal fine grain austenite matrix with large carbides/nitrides particles.

3.2 Visual/Macro Examination
The broken stud bolt was undergone the visual inspection upon received at the material laboratory. Figure 9 showed the visual appearance of the broken stud bolt as at received condition. The remaining length of the stud was measured and estimated around 30mm.

![Figure 9. As-received condition of broken stud bolt](image)

The result from the visual inspection activity was recorded. Figure 10 showed the visual appearance of the broken stud bolt. It was observed that the stud bolt had broken at the thread root, which was the high stress region. Fracture surface revealed flat and little plastic deformation with rough surface appearance, indicative of brittle fracture. It also revealed multiple initiation planes distributed around the bolt circumference. There was a location, which displayed fibrous and shear lip features suggesting final consequential fracture area. This fracture appearance indicated that the bolt had experienced torsional loading in addition to the normal tensional loading.

![Figure 10. Fracture surface of broken stud bolt](image)

3.3 Cross-sectional Metallographic Examination
Cross sectional metallurgical examination was conducted across the fracture surface of the broken stud bolt. Metallographic sections were prepared and etched according to ASTM E3-11 and ASTM E407-07. The Kalling’s No.2 reagent was used for etching the Inconel alloy 718 of bolt material. Figure 11 shows a cross section macrograph which revealed nearly straight fracture profile with little macro plastic deformation observed, evident of brittle fracture path [8].
The cross-sectional activity was continued to inspect the rolled thread profile of broken stud. Figure 12 displayed the rolled thread profile of broken stud bolt.

Incipient crack was identified upon performed a cross section micrograph at initiation area. Figure 13 was shown a cross section micrograph at initiation area.

A cross section of SEM micrographs was performed along the threads next to broken area. This is shown in Figure 14 and it was revealed that the grain deformation along the threads resulting from work hardening processing i.e. thread rolling operation.

**Figure 11.** Cross section macrograph of the broken stud bolt

**Figure 12.** Rolled-thread profile of broken stud bolt

**Figure 13.** Grain deformation at the thread root of initiation area intergranular fracture path

**Figure 14.** Cross section SEM micrographs revealed grain deformation at the thread roots.
3.4 Chemical Composition Analysis
Chemical analysis was conducted on the base material of broken stud bolt sample using an Optical Emission Spectroscopy (OES) Analyzer. The results were tabulated in Table 1 as below. It was shown that the chemical compositions of the broken stud bolt met the requirements of MS-607 specification of material Inconel 718 as well as API standard 6A718-2009.

| Element     | Weight % | MS-607 Spec | API Standard |
|-------------|----------|-------------|--------------|
| Carbon, C   | 0.02     | 0.045 max   | 0.045 max    |
| Silicon, Si | 0.1      | 0.35 max    | 0.35 max     |
| Manganese, Mn | 0.06  | 0.35 max    | 0.35 max     |
| Phosphorus, P | 0.01 | 0.01 max    | 0.01 max     |
| Sulphur, S  | <0.001   | 0.01 max    | 0.01 max     |
| Chromium, Cr | 17.63 | 17-21       | 17-21        |
| Molybdenum, M3 | 2.8 - 3.3 | 2.8 - 3.3 | 2.8 - 3.3 |
| Nickel, Ni  | 54.03    | 50-55       | 50-55        |

3.5 Hardness Measurement
Rockwell hardness measurement (HRC) was performed on the base material of broken stud bolt sample by using a Zwick/Rowell ZHR machine. The results were indicated in figure 15 as below:

![Figure 15. Rockwell hardness measurement performed on the base material of broken stud bolt](image)

The hardness values are slightly 18% higher than maximum value (40 HRC) specified in MS-607 specification of material Inconel 718 as well as API standard 6A718-2009. Visual appearance of flat fracture surface with little plastic deformation and intergranular surface morphology under SEM examination proved that the stud bolt had broken in brittle mode. Fracture surface showed multiple initiation planes distributed along the circumferential areas of the thread root with the final fibrous shear lip area. This observation suggested that the stud bolt had experienced certain torsional loading in addition to the normal tensional loading. Cross section examination revealed straight and intergranular fracture path which was consistent with brittle fracture mode. It was plausible that intergranular fracture path was contributed by either grain boundary precipitation or hydrogen induced stress cracking (HISC). Magnified microstructure of the base material of the broken stud bolt clearly revealed austenite grain boundary with twin structure suggesting that intergranular fracture due to grain boundary precipitation was of less possibility.

It was reported that the broken stud bolt was installed in Subsea Tree#2 (XMT#2) which was exposed to cathodic protection (CP). CP is one of the sources rendering to hydrogen charging to the respective component in the offshore equipment and to subsequent HISC. From the analysis, it was found that the broken stud bolt material was high strength and high hardness material. It is well known that the higher the strength and the hardness, the higher the susceptibility to HISC. Besides, cross section examination displayed the grain deformation along the threads indicating that the threads had
been undergone rolled threading process. This might possibly cause inherent residual stress at the threaded areas.

4. Conclusion
It was concluded that the objective of this research was successful by achieving below objectives.

1. To develop a problem solving method for identifying the actual cause of failure of the Alloy 718 studs on the MITV connection. The development of A3 problem solving technique with implementation of the fishbone diagram and 5 Whys analysis technique was successfully identified the actual cause of failure was due to high hardness material value (more than 35 HRC) than the specification.
2. To validate the effectiveness of using the A3 problem solving method to be used in subsea's industry for future issue. The A3 template with fishbone diagram and 5Whys analysis technique was used successfully.
3. Validation was done through the establishment of the containment and corrective actions as below.
   a. Containment actions
      i. Concession to de-rated the Subsea Tree#2 (XMT #2) to 5,000psi and change out the studs material from Alloy 718 to L7M
      ii. Clamping down MITV valve to allow additional 4 unit of stud bolts to be added during the refurbishment stage
   b. Corrective actions
      i. Change out stud bolt material to from Alloy 718 to L7M during the refurbishment stage
      ii. To consider the use of L7M stud bolt for future design Subsea Tree for the same application. This has been added up into Global Subsea Lessons Learned database

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