Metallurgical Viability, Inc.
100 WEDGEMONT DRIVE
ELKTON, MD 21921
443-616-4339

Lemonade from a Materials Failure

By

Robert R. Odle, Ph.D.

Metallurgical Viability, Inc.

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Background

You just had a major piece of equipment go down because of the failure of a metal component. How do you get the most value out of what may otherwise be a disaster? In short, can you make "lemonade" out of lemons. Should you conduct a failure analysis, or perhaps, a Root Cause Investigation? What do you have to gain by doing so? And, if you proceed, how do you do it right?

Introduction

Over $300 billion a year is lost by the process industries due to corrosion-induced equipment failures and the downtime, system re-engineering, equipment replacement, personal injury liability, and other costly circumstances that may result. Additional failures result from mechanical causes. When a failure occurs, process liquids may be released from the system violating the Clean Water Act, among others. There can be civil and criminal charges.

When the failure of a small metal component causes your plant to shut down, short term, you have to get your plant back up and running. What you may not realize is that you have been given a golden opportunity to improve the reliability of your plant. If you learn from this failure, you have a chance to improve the reliability of your process, your internal procedures, and even your management abilities.

Criticality of Metal Failures

Our examples will be primarily about metal failures caused by corrosion, but much of what is discussed here will be valid for any type of metal or material failure. Metal failures of sophisticated parts, such as impeller blades, can be debilitating, as delivery times of metal parts from foundries, fabrication shops, welding shops, etc. can take months, sometimes years in today's market. In the time it takes to get your plant back on line, a profitable use of your time is to understand why this metal part failed and address the root cause of the failure; otherwise, your plant will face similar situations in the future.

Failure Analysis, as the first Step in a Root Cause Investigation

Services to understand metal failures and to prevent their recurrence is a specialized and growing field. However, bridging the gap between a specialized failure analysis from a metallurgist and identifying and correcting the root cause of the failure are two related, but different activities.

Every metal failure represents a unique opportunity to improve the technical, production and management systems in your company. Although each response must be tailored to the circumstances, some general steps that must be taken to insure that your failure analysis is the first step in your root-cause investigation include:

1. Protect the evidence, Table 1.

2. Conduct a failure analysis to identify the physical cause of the failure and to characterize the type of failure.

3. Develop an action plan to address replacing the present part, by necessity, usually before all the facts are gathered.

4. Review the process conditions, especially deviations in the process, and make a determination of their role in the failure.

5. Review how management policies, company procedures, and quality control, or the lack thereof, contributed to the failure. Use the failed part as an example of how your company works. How was the metal chosen, for what conditions, and how did this compare to actual process conditions. If you could do it over, how would prevent this failure from happening. Now apply this to knowledge to the future.

6. If appropriate, review the economic trade-offs between process changes and material changes to prevent a future failure of the same system.

7. Based on the insights gained from this failure, develop an initiative to address: (1) preventing a future failure in the same system, (2) modification of management policies, systems, and procedures to reduce the probability of failures in similar locations in the rest of the plant, and (3) early warning systems (corrosion monitoring, non-destructive testing, inspections) to determine the progress of corrosion in high risk areas. If possible, employ an independent consultant to play a devil's advocate throughout the entire reformation.

Table 1.

Protecting the "Crime Scene"

Consider these steps at your next metal failure:

- With an indelible marker, start labeling failed items and associated items that are to be removed from the system.
- Items, such as pipes, that have no clear orientation after removal should be labeled in a way that their orientation is clear after removal, i.e., top, bottom, horizontal, vertical, etc.
- If there are several parts, label each one of them, with a simple system such as "A", "B", "C", etc.; keep a logbook and write down what each represents.
- Use a digital camera to take area shots of the equipment with the failed component and the surrounding areas and gradually work toward the failed part.
- Finally take close-ups of the actual failure at every angle possible.
- After taking the above pictures, remove the failed component without disturbing any of its surroundings. Take pictures as the equipment is disassembled. Do not clean off any contamination, unless a safety risk is involved.
- After removing the parts, do not attempt to put the faces of the failed components back to together. This can dislodge the real evidence and create damage on the surface that will have to be explained during the investigation.
- Wrap the parts in plastic bags, tape them shut and label them using the same convention you used to label the parts ("A", "B", "C", etc.). Gather them all together and take several overall pictures to show what is being transported to the laboratory.
- Make a copy of your notes and your digital pictures and give them to the lab along with your pictures.

Protecting the Physical Evidence

When your plant goes down because of component failure, what you do in the first few days, and even hours after the failure can protect evidence that may be crucial in understanding why the component failed. Imagine your next metal failure as a crime scene. Whether the failed part is a leaking pipe, a shaft on a motor, a leaking heat exchanger, a discolored stainless steel fixture, or, any other failures, it contains evidence on what caused the failure.

If possible, get the metallurgist performing the failure analysis involved in collecting this data. Let him know up front that he is be involved in a root cause investigation, not just a characterization of a failure.

Collecting Supporting Data

Next, set up a box, either physical or electronic to collect data on the operating conditions, Table 2. It is important to understand how the process or equipment was working compared to how it was designed to work.

The laboratory receiving this information and samples should review the documents furnished and be advised on what the expectations are for the investigation . Any safety or potential legal issues with the samples should be understood. There are ASTM guidelines regarding the handling of evidence if a legal case is involved, ASTM E 860 and ASTM E 1188. Once this discussion occurs, the laboratory receiving the documents and samples should log each sample and document received from the client into a log, again physical or electronic. The laboratory should take their own pictures and label each sample as it is removed from its container. It is now possible to start the failure analysis and/or root cause investigation with as much of the evidence intact as possible and all the background information necessary to understand the failure, not only of the component, but possibly of the system. The above is an ideal scenario. In most cases, the investigator gets a broken piece of metal and a three line email. It is not hard to imagine which approach has the potential of improving future performance of your plant.

Table 2.

Examples of Other Supporting Data

- Recent process logs, physical or electronic.
- Data sheets with original equipment specifications
- Interviews with anyone present during the failure.
- Incident Reports of the failure or previous failures of the same equipment or process.
- From Quality Control, Control Limits, Control Reports, and Excursions for the Last Three Months.
- Get process to explain the QC excursions and their cause.
- If a mechanical component has failed, such as a shaft, get operating speeds, motor amps, noise and vibration data if available, and again compare it to the "normal".
- From engineering, Design or Equipment Specifications and or Data Sheets for the failed part.
- Related Vendor data.

Laboratory Characterization of the Failure, the Classic "Failure Analysis"

There are literally hundreds of failure modes and an infinite combination of failure modes than cause a piece of metal to fail. Fortunately, metals have been used and studied for thousands of years and the greater majority of failure analysis can be performed by simply collecting evidence from the sample, using the background information and some common sense to match the evidence with what is described in the literature. (It is the exception that makes the failure analyst's job interesting.) Although each failure analysis has to be tailored to the job, some typical steps in collecting the laboratory evidence include:

- Detailed photography at the site of the failure, before, during, and after any cutting or actions that may potential destroy some of the evidence on the samples. Many failure analysis is solved by going back to pictures taken at a earlier stage in the investigation.
- Stereoscopic Examination and Photography, before, during and after cleaning the failure site. It is important in many corrosion failures to understand where a corrosion product is originating and its composition. Also, the origin of the failure on the part can usually be assessed at this stage. For example, beach marks on a fatigue failure can often be followed on the fracture surface back to the point of origin.
- The sample is cross-sectioned in the area of the failure and polished to a mirror finish to look at the microstructure of the sample. Many corrosion modes, such as stress corrosion cracking, will progress far below the surface similar to a tree, and are best studied under a metallograph.
- Chemical analysis of deposits and residues, taken from the failure site often provides evidence on the corrodent involved in the failure. Normally anion analysis are the most useful since the cations in the corrosion products typically come from the metal being corroded. Halides, chlorides especially, sulfates, and oxides are the most common corrodents. The electrochemical corrosion process can often concentrate anions, especially chlorides, inside of cracks and provide evident about the bulk environment that may not be known.
- Metallographic examination of key cross sections near the failure site can be used to characterize the failure and the microstructure near the failure site.
- Scanning electron microscope can be used to characterize the failure site/fracture site and characterize the failure mode. For instance, intergranular attack, metal cleavage and ductile fractures could be characterized by looking at the fracture surface on the SEM. An SEM equipped with EDX (energy dispersive spectroscopy) can be used to identify corrosion products in the cracks, on fracture faces, or to identify segregation of alloying agents or the concentration of various elements between the grains and the grain boundaries.

All of these tools enable the metallurgist to characterize the alloy and failure and to identify any irregularities. Evaluation of the evidence allows the investigator to begin answering some questions, Table 3. If a Root Cause Investigation is to take place, the questions broaden to include questions about the process, your engineering, your company's quality control department, etc., Table 4. After the Root Cause Investigation identifies the probable cause of the failure, and possibly contributing factors, there is still the question of what actions should be taken immediately, Table 3, and what longer term improvements need to be made in the way your business is conducted, Table 4.

Table 3.

Typical Questions To Ask During the Laboratory Investigation.

What is the mechanism of failure, some examples include:

- A Mechanical Failure (tensile, shear, fatigue, etc.)
- A Corrosion Failure (under-deposit, stress corrosion cracking, etc.)
- A Fatigue Failure

Are there defects in the metal? Its assembly or fabrication?

If it is a fatigue failure, are stress concentrators present?

Did the part fail because of corrosion?

What type of corrosion?

What was the mechanism?

What is the quality of welds (if present)?

Table 4.

Typical Questions Asked in a Root Cause Investigation of the Failure?

- What is the purpose of this investigation?
- Identifying who caused the problem?
- Correcting the problem?
- Reducing downtime? expense?
- Are their legal ramifications?
- Are their secondary damages?
- Was someone hurt or killed?
- Are their other parties with standing in the case?
- What is the most appropriate report format?
- Who is the Report For?
- Is the process being operated outside of design conditions?
- Are their inadequate controls in place to assure quality?
- Is the part under-designed? poorly designed?
- Is the part being exposed to loads/conditions it was not designed for?
- Was the correct material specified? Supplied? Used?
- Was the process properly defined? Was a Process and/or a Material Design Criteria Developed?
- Was the process running within design specifications?
- Did the process change?
- Did process upsets contribute to the corrosion?
- Are more parts in the system subject to the same conditions?

As a tool during a Root Cause Investigation, a decision tree can be developed for your company. The decision tree can be organized around the type of failure or it can be organized around your functional departments and management groups. Whatever the route, focus must be centered on improving the quality and functionality of your organization, not on placing blame. A simplified Root Cause Diagram is given in Figure 1 illustrating the elements that go into a Root Cause Decision Tree.

Table 5.

Typical Questions That Should Be Addressed Immediately

What is the most economical way to resolve the problem?

- Upgrade the alloy?
- Control the process better?
- Are there secondary benefits of controlling the process better?

What is the most expeditious option?

What materials are available today?

Will changing alloys lead to galvanic problems?

What Design Life is Reasonable?

What are the Life Cycle Costs of the Options Under Consideration?

Are spare parts available?

Can the Part Be Purchased or Made Quickly? What material options exist?

What is the strategy? Get back on line now and deal with long-term issues later?

If the same material is put back in service, how much time do we have to affect needed changes in the process?

Table 6.

Typical Questions That Should Be Asked to Learn From the Failure

Is the organization capable of dealing with the Material Challenges Facing It?

Does some organizational changes need to be made to deal with Material Challenges?

Do some departments need to be strengthened?

Is this our core competency? Do we need outside help on an ongoing or part-time basis?

What is best long-term solution?

Is this a repetitive problem? A typical problem?

Should Corrective Action could include:

- Reducing the Corrosivity of the Process Through Improved Process Control or Process Modification
- Alternative Materials of Construction
- Improved Use of Inhibitors
- Monitoring of Corrosive Conditions with Electrochemical Probes or Corrosion Coupons
- Field Measurement of the Rate of Corrosion with Electrochemical Probes
- Using corrosion probes as an indicator of a process upsets?

Figure 1.
A Simplified Root Cause Diagram