A Guide to Failure Analysis for the Oil and Gas Industry

Alber Sadek, Senior Engineer
EWI

Failure analysis is a mechanical, material, physical and chemical engineering approach to determining how and why a component or system has failed. To understand exactly what is involved, two questions must be answered:

- What constitutes a failure?
- What is involved in a failure analysis?

What Constitutes a Failure?

Generally, a part or system has failed when it no longer complies with its design intent. This may include leaking hydraulic seals, decreased component stiffness, an increased rate of corrosive decay, a decreased part or system lifetime, increased operating and maintenance costs, or unacceptable aesthetics. Failures are not limited to service as they can also occur during development, production, assembly, or transportation. Failure types may include fractures, component or system malfunctions, and/or unexpected behavior resulting in customer dissatisfaction. Failure analysis can determine the root-cause or causes, the chain of events leading to the failure, fitness for service, options for repair, and recommended steps to prevent future failures.

What is Involved in a Failure Analysis?

Failure analysis and prevention is often a complex multidisciplinary activity requiring broad knowledge in areas of design, manufacturing, materials, mechanics, and testing. In the oil and gas industry, failure modes include corrosion, fracture, cracking, fretting, distortion, and thermal damage. Failure analysis activities are conducted as part of the life-cycle management of a system, structure, or component.

There are two approaches to failure analysis. A diagnostic investigation seeks to determine the root cause, while the goal of a prognostic investigation is to identify, predict, and minimize structural deterioration that could threaten safety. The latter involves damage assessments, life predictions, and simulations. This approach is heavily dependent on the cracking susceptibility of the component, the performance criteria, damage accumulation mechanisms, and the magnitude of external stressors. Understanding the nature of the external stressors allows mitigation of their effects through design, inspection, residual life assessment, maintenance, and life cycle management. The following active stressors can directly or indirectly cause a failure:

- **Mechanical**: Applied stresses, residual stresses, pressures, impacts, and fretting movement
- **Environmental**: Exposure to aggressive environments and material-compatibility issues
- **Electrochemical**: Exposure to corrosive environments
- **Thermal Exposure**: Elevated temperatures leading to material degradation
- **Radiation**: Ultraviolet light, sunlight, and ionizing radiation

The Importance of Failure Analysis

Understanding the true root-cause of a failure is essential in making well-informed choices regarding repair strategies and the mitigation of future failures. A successful failure analysis can uncover deficiencies in a component or system design, assembly errors, and fabrication defects. Issues related to improper material processing or material imperfections can be revealed, as can service abnormalities or maintenance problems. Unintended or inadvertent factors can be detected as well. Generally speaking, the benefits of a failure analysis extend well into the future as lessons learned typically lead to increased quality in subsequently designed and produced components.

Types of Major Failures in the Oil and Gas Industry

The oil and gas industry has established an impressive safety record over many decades; however, failures do occur. The most common root causes of these failures are as follows:

Corrosion Failures: Corrosion is a common cause of failure in the oil and gas industry due to the nature of the service environment. Corrosion failure is defined as the degradation of a material due to a chemical reaction with the environment leading to the deterioration of the physical, mechanical, and metallurgical properties of the material. This can result in weakening of the component due to a loss of cross-sectional area, fracture due to hydrogen embrittlement, or cracking due to the formation of nonmetallic compounds. Multiple factors should be considered during the analysis of a corrosion failure including the corrosion type, the corrosion rate, the extent of the corrosion, and the interaction between corrosion and other failure mechanisms.

The various corrosion types include:

- Uniform Corrosion
- Galvanic Corrosion
- Crevice Corrosion
- Concentration Cell Corrosion
- Pitting Corrosion
- Filiform Corrosion
- Exfoliation Corrosion
- Intergranular Corrosion
- Corrosion Fatigue
- Fretting Corrosion
- Erosion Corrosion
- Hydrogen Damage
- Microbial Corrosion
- Stress Corrosion Cracking
- Dealloying

In the case of oil and gas operation, the natural process of corrosion cannot be prevented entirely; however, it can be minimized or controlled by choosing the appropriate design, materials, and coatings, or by changing the service environment. Identification of the metal or metals used, the material surface layer, the service environment, and any foreign matter present is be beneficial in determining the source of the failure.

Corrosion Failure Case Study 1: Figure 1 shows a severe reduction in the thickness of a 20-in. diameter carbon-steel spool with an original wall thickness of 20 mm. This specimen was removed from a natural-gas production facility after 9 months of operation. The 65% reduction in wall-thickness occurred in the bottom section of the pipe as shown in Figure 1, resulting in a final wall thickness of just 7mm. All operating parameters and pertinent service information were collected and a complete metallurgical analysis was carried out.[1]

Figure 1: 65% thickness reduction of a 20-in. diameter carbon-steel pip after nine months of operation.

Test results indicated that the rapid reduction in thickness could be attributed to three simultaneously occurring mechanisms. First, erosion was caused by hard particles in the natural gas under the working flow rate and pressure. Second, corrosion contributed to the failure as a result of: (1) the presence of a large 6mm misalignment between the two pipe sections, (2) the pipe's horizontal service orientation and its location within the overall piping system, and (3) the presence of H2S in the natural gas (13 PPM), which may have been increased at the condensate, forming dilute sulfuric acid and resulting in corrosion. Third, material softening (cementite dissolving) occurred due to the applied forces during manufacturing of the spool. This can be seen in the measured hardness values. The hardness of the inner surface was 66% of the outer surface, resulting in lower wear/erosion resistance.

Corrosion Failure Case Study 2: An example of a wear failure in natural gas field equipment is provided in Figures 2 and 3. This lean-solution pump was opened to investigate a vibration issue, revealing a number of problems. An excessive clearance of 2.2 mm due to wear was measured between the balance drum and the throttling push. The required clearance in this area is specified as 0.33 mm to 0.41 mm. Further, unexpected pitting and wear was present in all impellers, intake, shrouds and blades. Erosion wear was also observed in the pump casing at the mating faces of the upper and lower halves as shown in Figures 2 and 3.

Figure 2: Erosion wear, pitting, and cracking in the pump casing of a lean-solution pump.

The failure analysis included a complete examination of the fracture surface using a stereoscope, optical and scanning electron microscopes, energy dispersive spectroscopy, chemical analyses, and microstructural evaluations.

Based on the investigation carried out on the provided pump components, gas analysis data, and

Figure 3: Evidence of the direction of flow on the eroded impeller surface.

contaminants collected from the upstream filter, the damage was attributed to three causes[2]. First, the erosion of the impeller surface was caused by hard particles in the solution, with vanadium oxide acting as the key oxide-breaching mechanism. Second, elemental mercury in contact with the stainless-steel material induced rapid corrosion. When mercury is present in its elemental form, it can cause catastrophic damage in stainless steel through an adsorption mechanism, especially if the chromium content is significantly higher than the nickel content, as was the case in this example. Third, cavitation erosion was responsible for the relatively high wastage rates and the development of pitting and craters during service (Figure 4).

Figure 4: Pitting and craters on the damaged surface.

Corrosion Failure Case Study 3: Figure 5 shows two images from a circumferential failure of a girth-welded gas pipeline, with corrosion resulting from imperfections at the weld root. This API X52 pipe was joined using the shielded metal arc welding (SMAW) process. A failure investigation concluded that undercut and excess root penetration due to high heat input were the primary causes of localized turbulent flow conditions at the weld root. These conditions led to accelerated corrosion failure at the heterogeneous grain structure, thermally stressed heat affected zone (HAZ), and fusion line.[3]

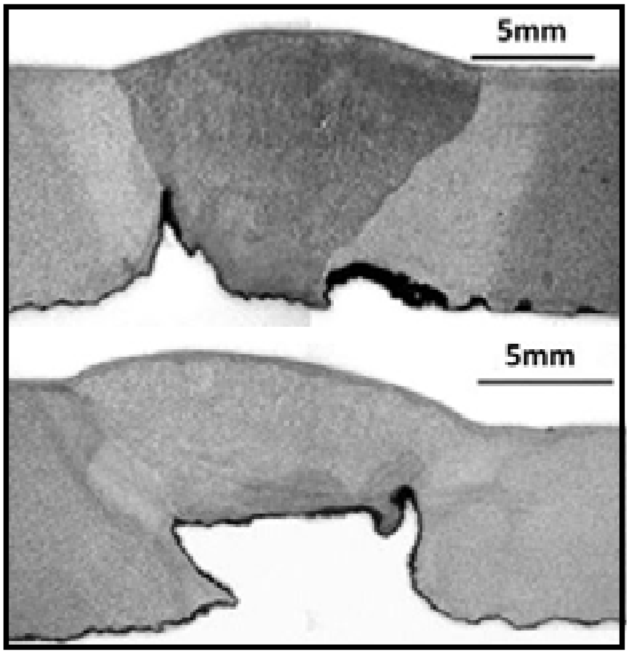

Figure 5: Corrosion of gas pipeline welds due to welding imperfections.

Fatigue Failures: Fatigue occurs when a material is subject to alternating stresses below its static yield strength over time, and cracks initiate and then propagate in regions where the strain is most severe. Such failures can be identified by the presence of two distinct regions on the fracture face: (1) a section where the surface has been smoothed or burnished by the two faces rubbing together, and (2) a section where the surface is granular in appearance due to the sudden failure of the remaining cross-section of material. A fatigue fracture surface may also feature beach-marks and striations. Striations are thought to be steps in crack propagation, where the distance between striations depends on the stress range.

Fatigue Failure Case Study: Figures 5 and 6 show a drive shaft fracture which occurred after 245,000 revolutions with the fracture surface containing typical fatigue fracture zones. Two cracking initiation zones are present, characterized by a striation pattern. A step-patterned propagation zone can be seen in Figure 5, as can the overload fracture zone. Finally, a zone with a ground and smoothed surface is present opposite to the crack initiation side, resulting from a severe friction force at the rotating fracture faying surface after failure, indicating that one end of the drive shaft had stopped rotating.

Figure 6: General view of the failed drive shaft after approximately 245,000 revolutions.

Figure 7: Step pattern fracture zones in the failed upper drive shaft.

Structural engineering materials often contain discontinuities at which fatigue cracks can initiate under cyclic stresses. The main cause of this failure was related to the presence of a large number of nonmetallic inclusions in the steel shaft, as shown in Figure 7. Potential root causes included the discontinuities themselves, the component design, or lack of proper maintenance. While the last was determined to be the root cause in this case, it was concluded that the non-metallic inclusions acted as crack-initiation sites. This behavior was particularly prevalent when the inclusions were located on the highly stressed surface.

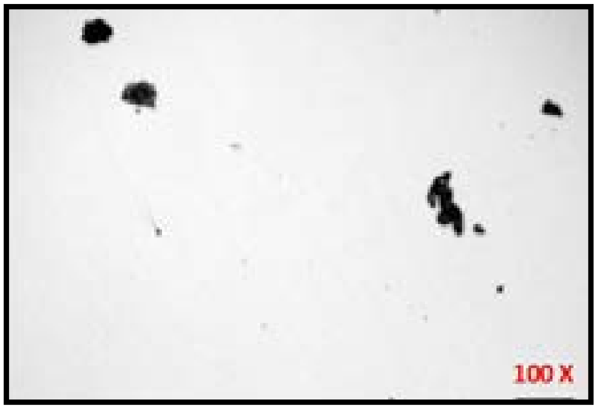

Figure 8: Observed nonmetallic inclusions.

Ductile and Brittle Metal Failures: Ductile metals experience observable plastic deformation while brittle metals experience little or no plastic deformation prior to rapid failure via fracture. Metals with a body centered cubic (BCC) structure such as low-carbon steel exhibit this behavior, becoming brittle at low temperature or at sufficiently high strain rates. Metals with a face centered cubic (FCC) structure such as aluminum and austenitic stainless steels generally remain ductile at low temperatures. Some metals experience a ductile-to-brittle transition.

The Steps of a Root-cause Analysis

A root-cause analysis determines the origin of a failure by plotting a path from the final failure back to the root cause or causes. This process begins by collecting information related to the function of the failed component or system, as well as its operational and maintenance history. Available drawings, photographs, reports, service deviations, and testimonies from operating personnel may also be valuable.

Next, the failure must be examined, as must the condition of entire region surrounding the failure, to document base material uniformity, discoloration, forms of contamination, corrosion products, and grinding marks. This examination offers the opportunity to examine the weld progression, observe other structures in the region which may have contributed to the failure, and macroscopically classify the failure.

A metallurgical examination using a scanning electron microscope (SEM), energy dispersive x-ray spectroscopy (EDX), optical microscopy, and mechanical testing may then be required. Additional steps may include chemical analysis of the base materials, contamination, and corrosion products, as well as calculation and/or measurement of residual stresses using X-Ray diffraction and strain-gauge methods. Simulation tests may also be required to understand the cause of the failure using finite element analysis (FEA) or stress analysis.

Determining the root cause, the time of failure, the best methods of detecting the failure, and the available tools of failure analysis can be complex. This requires a diverse team with expertise in material science, mechanical engineering, chemical engineering, and physics. By working together, a strong team is not only able to identify the root cause or causes of a failure, but also to establish a plan to mitigate the occurrence of similar failures in the future.

How EWI Can Help

EWI's expertise in material characterization, stress analysis, structural integrity assessment, mechanical testing, and welding engineering covers a wide range of ferrous and nonferrous alloys. With extensive in-house capabilities, EWI can perform accurate and reliable failure analyses using analytical, experimental, and simulation methods. Our full suite of software and extensive testing capabilities allow us to predict and improve weld joint performance through structural modeling, recommend welding electrodes for improved performance, select proper welding techniques, and perform microstructural analysis and characterization. EWI has significant experience performing failure analyses and developing effective mitigation strategies for the oil and gas industry. Our experts can also help manufacturers and operators in the field of oil and gas select non-destructive testing methods to ensure joint quality and monitor performance during operation.

References

1 - A. A. Sadek, "Failure Analysis Of 20 inch Carbon Steel Spool", International Conference on Failure Analysis and Repair welding, ICFARW, Cairo, Egypt, 16-19 Nov. 2009.

2 - A.A. Sadek, "Failure and Root Cause Analysis; Investigating Material and Component Failure in Petroleum and Petrochemical Industries", 1st Egyptian-Fracture seminar on Mechanical Properties and Failure Analysis of Engineering Materials,, Alexandria, 4 April, 2012

3 - H. Abdel-Aleem, K. Hafez and A. A. Sadek, "Significance of Welding Defects in Corrosion of Gas Pipelines Weld", The 27th Annual Conference, Corrosion Problems in Industry, 25-27 November 2008

***Alber Sadek** is an senior engineer in EWI's Materials group. His current work involves the selection of metals and alloys as they are applied in different industrial sectors, covering their physical properties, material characterization, weldability (similar/dissimilar alloys), corrosion, wear, fatigue, and creep properties. He investigates the effect of welding parameters, welding processes and shielding gas composition on the microstructure and mechanical properties of different alloy weldments.*