Introduction to Metallurgical Failure Analysis with Case Studies

An Online Continuing Education Course for Engineers

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Introduction

The failure analysis process can be a complex but necessary tool available to engineers to determine the causes of a failure. The failure analysis process draws upon many different technical disciplines and uses a variety of observation, inspection, and laboratory techniques. Additionally, the ability to evaluate evidence and put this evidence in context is a crucial skill for the engineer to develop. This evidence will likely include, but not be limited to component background, service history, service conditions, design and manufacturing specifications, and a quantitative understanding of the mechanical stresses, to name a few. In order to perform a proper failure analysis, the engineer must be able to remain unbiased and access and contextualize evidence as it is made available or discovered. This is even more critical when collaborating with subject-matter experts who may, whether intentionally or not, introduce their own biases during the analysis. However, information and experience provided by subject matter experts need to be integrated into the analysis appropriately.

An important aspect of failure analysis is material testing. When the scope of the failure analysis is restricted to a material/metallurgical perspective, the nomenclature needs to reflect the limited scope. Therefore, a specialized failure analysis is referred to as metallurgical failure analysis. The data collected from the material testing will help the engineer determine the metallurgical mode of the failure, otherwise known as the metallurgical failure mode (MFM). This MFM coupled with additional background information is critical to determining the overall root cause of a failure; however, in some instances, clients are satisfied with the knowledge of the mode of failure. Additionally, the MFM will provide contributing factors that lead to the failure. The MFM is defined in simple terms that engineers are familiar with and define the manner in which the failure occurs from a local, metallurgical perspective. Commonly used terms such as overload, fatigue, stress corrosion cracking, hydrogen damage, etc. to name a few. The MFM adds a lot of context to a failure analysis and, in fact, maybe the most critical component of an overall failure analysis.

Typical Tests Performed During a Metallurgical Failure Analysis

There is a myriad of tests that can be implemented to determine MFM. A typical metallurgical failure analysis will include visual and low power magnification examinations, fractography, metallography, scanning electron microscopy, chemical analysis, mechanical testing, and non-destructive testing. Mechanical testing typically includes hardness, tensile, impact tests. Examples of pertinent evidence that can be gleaned from each test are outlined below.

1. Visual and low power magnification examination – The engineer should look for deformation, especially near fractures, that may indicate the nature and direction of the applied load, coating holidays, corrosion, wear, cracking (follow the crack path to origin), etc. This information can be used to develop working theories when little background information is known, to direct further testing, and/or corroborate background information.

2. Fractography – Fractography, or fractographic examination, is one of the most useful activities to perform during a failure analysis, especially if the fracture surfaces can be examined under high magnification. Characterization of the fracture surface (flat, sloped, dull, shiny, local plastic deformation, etc.) will determine the mode and/or nature of the fracture (tensile, shear, fatigue, etc.).

3. Metallography – Metallography is performed in the polished and etched conditions. The polished condition makes identifying the presence and location of cracking, pitting, non-metallic inclusions, and/ other defects easier. However, metallographic examination in the etched condition generally provides more information, particularly in regard to heat treatment of the material. Large libraries of etchants exist for various metals that are catered to highlight the pertinent aspects of the microstructure being examined. It would be wise to memorize the common etchants used for at least carbon steel, stainless steel, and aluminum. Examples of what metallography can help determine include:
    a. The nature of the heat treatment (quenched, tempered, annealed, case hardened, etc.).

    b. Is the cracking or fracture path intergranular or transgranular? For example, intergranular corrosion in austenitic stainless steels is indicative of sensitization, whereas, transgranular cracking is indicative of stress corrosion cracking.

    c. Is there grain distortion in the microstructure? This is indicative of plastic deformation (ductile material), where a lack of grain distortion can indicate a brittle material and/or fatigue.

    d. The morphology of pitting can help identify the corrosion mechanism. For example, subsurface or undercutting pits in carbon steels can be indicative of microbially induced corrosion where round, subsurface pitting can be indicative of a chloride-containing environment in stainless steels.

    e. In the case of welds, lack of fusion and/or improper heat input can be identified by examining the microstructure in the vicinity of the weld.

4. Scanning electron microscopy (SEM) – SEM provides the magnification required to resolve micro-scale features on samples, particularly fracture surfaces. For example, shear ruptures that occur as a result of a ductile

overload failure can be equiaxed or directional in nature. The ability to determine the directionality of the shear dimples can reveal the direction of the predominant load on the sample and assist in locating the fracture origin. Additionally, the fine striations that are clear evidence fatigue, and will indicate the direction of crack propagation, are almost solely documented via SEM.

5. Chemical analysis - Comparing the composition of the sample to the material specification is a quick method to determine if the sample chemistry is a contributing factor to the failure. Experience has shown that, in general, sample compositions are within specification, but may approach the maximum or minimum allowable values for a given element.

   Chemical analysis of corrosion products and deposits on sample surfaces can provide insight as to the agent responsible for the corrosion. One must be sure to examine the region between the base metal and corrosion product in order to determine the driving mechanism (metallographic samples). For example, analyzing the base of pits and the crack tips of incipient cracks are more valuable that corrosion products on the surface of the material. A popular tool for analyzing corrosion products and deposits on sample surfaces is Electromagnetic X-ray Spectroscopy (EDS) used in conjunction with SEM examinations. The engineer must take caution during sample machining, sectioning, and cleaning processes as dissolved minerals, detergents, acids, salts, etc. used will alter the measured EDS values.

6. Mechanical testing – As with chemical analysis, comparing the mechanical properties of the sample to the material specification is an obvious technique to determine a contributing cause of a failure. Off specification mechanical properties are typically a reflection of improper processing and/or chemistry. For example, low ductility (reduced elongation and particularly reduced reduction in area) are possible indications of improper heat treatment and/or inclusions in the material. Hardness testing is one of

the most valuable tests that can be performed because it is not only simple to execute but are also capable of indicating heat treatment issues and/or residual stresses well before the variations in the microstructure become apparent. Additionally, hardness can be used, particularly in carbon steels, to estimate the tensile strength of the material. Measuring hardness distribution across weld cross-sections is particularly fruitful. Mechanical testing, in conjunction with metallography, is invaluable during a metallurgical examination.

Non-destructive testing (NDT) – The engineer or the engineer's client performing NDT on a sample may often be the reason a more extensive analysis is requested. In other words, performing NDT may result in the client requesting a more in-depth analysis. NDT has the benefit of providing information that will support and expedite the analysis. Penetrant and/or magnetic particle testing will locate surface cracks (and incipient cracks that may be difficult to resolve with a visual examination). Magnetic particle testing is generally preferred over penetrant testing, and magnetic particle testing also has the advantage of locating some subsurface defects. Ultrasonic testing can identify wall thickness and subsurface defects. Positive Material Identification (PMI) will provide initial material compositions when material specifications are not available. If NDT is performed by a third party, the engineer would be wise to make attempts to collect the data prior to beginning the analysis.

Value and Purpose of Case Studies

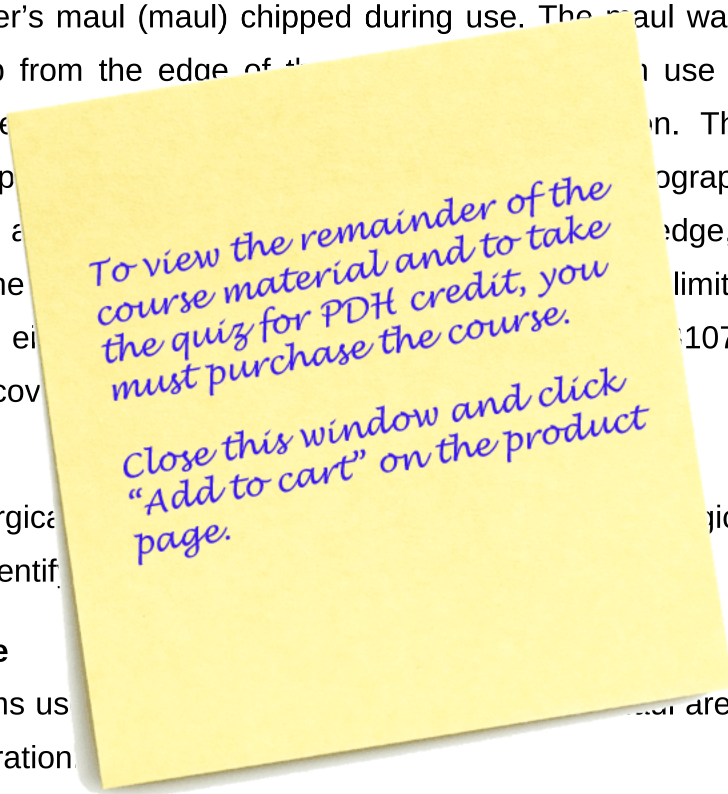
Reading case studies are an invaluable learning experience for the engineer. The activity can be an effective measure to bridge the gap between traditional, academic knowledge and applied engineering experience. The following case studies are to provide insight into the activities and reasoning a typical metallurgical failure analysis. Reading the case studies will highlight how the various test data and examinations accumulate to deliver not only the failure mechanism but additional evidence which grants a level of comfort to the engineer. Hopefully, the selection of case studies below will provide a reasonable representation of some of the various circumstances that can arise during metallurgical failure analysis.

Case Study I: Failure of a Woodchopper's Maul

Background

A woodchopper's maul (maul) chipped during use. The maul was reported to have ejected a chip from the edge of ... use which entered the user's abdome... n. This resulted in an extended hosp... ographs illustrating the condition and a... edge, as received, are illustrated in the ... limited, and identifying decals were ei... 107.54 has specific requirements cov...

Metallurgica... gical condition of the maul and to identif...



Nomenclature

The terms us... are noted in the following illustration...