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An Important and Simple Roadmap to Analyze Failures and Avoid Poor Conclusions When Evaluating Failures of Metallic Products

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Abstract: Fracture analysis is considered an anomaly that can either result in minor problems for product functionality or disastrous consequences when there are lives at stake. Also, it is an area of knowledge in which a narrow analysis or superficial evaluation allows problems to reoccur, which is basically time consuming because of machine downtime which leads to higher costs. Therefore, this paper presents an easy roadmap, to follow that allows engineers and technologists to analyse, with confidence, the root cause of failed parts. Additionally, it gives inputs on how to obtain important data leading to a precise and correct conclusion. Furthermore, it shows the main equipment to use in each step, in order to analyse the failed product, and it also demonstrates the capabilities of the equipment used and the output of this equipment. An accurate failure analysis passes through a detailed evaluation of all the possibilities, compiles them, collects data from the samples and consequently reaches a conclusion based on tangible evidence.

Keywords: Failure analysis, Metallic products, Roadmap

Introduction

Engineers have been designing machines and equipment using manual calculations and numeric simulations that help them to develop products that perform in the field and, as a consequence, they do not fail [1]. For this purpose, sophisticated software is utilized by engineers to replicate the application of their engineered products, with relative precision and within a well-defined boundary condition. It should be noted, that most of the time the software users (engineers) simulate the most important parts of the machines or equipment. However, when the machine is simple, they can simulate a complete machine. In this regard, the professionals strive to replicate reality adding several inputs like: product material, material mechanical properties, part geometry, constraints on the part, type of load, load localization, load intensity and distribution. However, even though engineers try to replicate the application as much as possible, there are uncertainties that can negatively impact product performance and lead it to product failure.

According to [2] mechanical failure may be defined as any change in the size, shape, or material properties of a structure, machine, or machine part that renders it incapable of satisfactorily performing its intended function. This means that sometimes failure is not critical because it can be contained if it is identified early enough. On the other hand, as indicated by [3], failure can be catastrophic, as is the case, when an aircraft’s structural component fails and there are lives at stake. At its broadest level, failure evaluation encompasses fracture analysis which involves a wide range of investigation including the end product, the process, and the product application. These investigations are necessary to reach the root cause of the failure.

In fact, failure and fracture analysis require a multi-disciplinary approach to determine how and why a material or product fails. Several research papers using different techniques to analyze the failure of metallic parts have been published. In [4] for example, analyzed a 321 Stainless Steel heater tube using a Scanning Electron Microscope (SEM) to evaluate the fractured surface, a durometer to measure the hardness Vickers, and an X-Ray Diffraction (XRD) to determine the residual stress in the material. [5] analyzed a stainless steel pipe by using a durometer to measure the micro hardness Vickers, observed the fractured surface using macro-fractographic and optical microscopic analyses, and further evaluated the fractured surface using EDS and SEM analyses. Using a slightly different approach, [6] evaluated failure of a turbine disc of an aero engine, to determine the starting point of the fatigue phenomenon, using a microscope in conjunction with finite element analysis.

In [7] on the other hand, it has a different approach and proposes cost effective preventive monitoring by optimizing inspection intervals, because failures have a critical role in maintenance costs and in the operation of the system. This paper proposes an easy roadmap for engineers and technologists to enable them to perform analyses of failed parts. It covers the main procedure to analyze a failed product as well as describing the importance of getting as much information as possible to reach a precise and accurate conclusion.

Methodology

The initial stage of any investigation involves an in-depth discovery phase of the circumstances surrounding the failure and any relevant background information, including environmental factors, type of application, service life and pertinent design information (Element, 2019). Two very well-known and effective tools can be utilized for this purpose, the 5 Whys and Ishikawa.

Collect Data in the Field

Step 1 – Talk to user and check main data input in the field

Talk to user

Initiate an interview with the user of the equipment to find out how failure happened. Get the user's description and then develop a more elaborate, detailed technical description of the occurrence. Also, look for material evidence supporting the description and include these in your investigation data book.

a. Adopt either 5 Whys or Ishikawa tools and proceed with them throughout all the analyses (Figure 1).

b. Write the most precise question or problem statement possible, for example:

i. For Ishikawa describe the problem precisely, then evaluate each variable on the fish bone.

ii. For 5 Whys – get as much data as possible and elaborate the most appropriate Why. Also think about the best way to describe the problem. For example,

1. Why did the bolt fail after only 03 hours of installation? Elaborate on the question based on the precise details of the failure, paying attention to describing the problem using accurate data. Keep going with Whys.
2. Why does the equipment always fail in the winter?
3. Why do two identical pieces of equipment behave differently; one is stable while the other fails? Using comparison is a good strategy.

Treat the description of the problem as a treasure, [8] in this way you will not blame an individual or infuse the situation with emotion. Most of time the problem is a systemic issue and can be fixed by adopting effective procedures and good practices.

Figure 1. 5 Whys Analysis and Ishikawa Chart [9-10]

Prepare a draft indicating the possible causes of failure do to your own or another user's actions

Brain Storming is another powerful tool (Brown, 2016). The draft is simply a list of possibilities at this point.

Application

How the user applies the product when following the procedure manual. Check whether operational manuals for the machine or equipment, or their technical drawings, are available, and obtain copies of them all. This is a crucial first step to understanding the problem as a whole. Evaluate whether the load applied is static or dynamic; this information can help you analyse the fractured surface to determine whether to consider fatigue.

Environment

How the atmosphere contributes to failure - is it corrosive, dirty, muddy, etc.? Was the product exposed to a different condition, for example, chemicals? Does the operating manual specify where to use the product? Is the failure associated with a particular season? Collect as much information as possible about the environment in which the machine or equipment was used.

Materials

Collect samples of fractured product and also functional ones. Don’t forget to protect samples from corrosion, e.g., by using a VCI bag for storage. Obtain as much information as possible about the specification of the material used to produce the part. Make a visual inspection, such as magnifying the image in the field, if possible.

Collect as much data as possible in the field, avoid premature conclusions or biases. Don’t ignore or discount any data at first glance. Figure 2 shows the initial steps for collecting data.

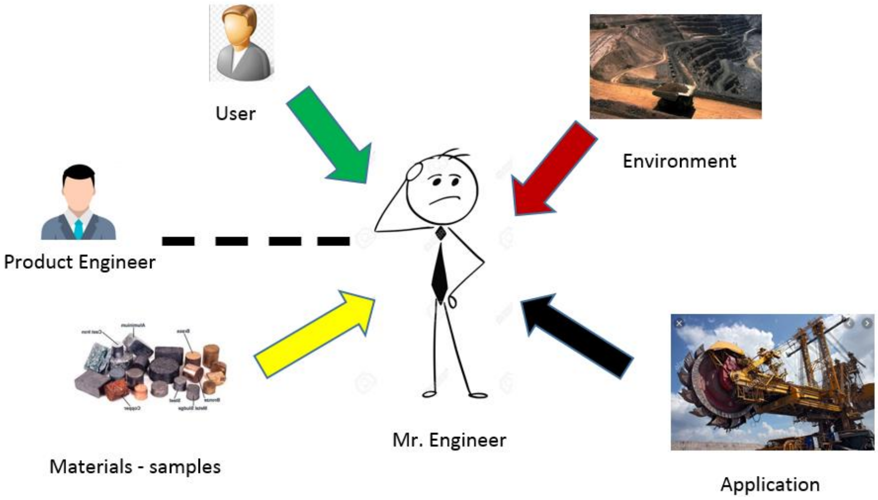

Figure 2. First Step in Field - Collect Data (Google Images)

Talk to the Product Engineer

If possible, talk to either the engineer who designed the product. Interview him to get as much data as possible; such as, the product material, the material mechanical properties, the part geometry, constraints that the part is subjected to, the type of load, the load localization, and the load intensity and distribution. This information will also help you to match this data with the fracture surface. Question the design engineer about the product traceability and get his opinion about the failure.

Make Your First Analysis of the Initial Data and Then Draft Your Plan for Fracture Analysis

After this first step, it is important to have an initial evaluation of the problem and summarize the data collected. At this stage, it is important to come back to 5 Whys analysis or Ishikawa to feed it with selected information which you have filtered. Evaluate how deeply you should go in order to determine which equipment to use for further analysis, keeping in mind equipment capability and availability.

Visit Metallurgical Laboratory to Make Your Analysis

Collect specifications or standards of the material used to make the part (i.e., chemical composition and mechanical properties).

- a. Make a plan to evaluate the part, following these steps:
  - i. Analyze the basic chemical composition using an Optical Emission Spectrometer (Figure 3), and analyze the mechanical properties using a Universal tensile test machine (Figure 4). Compare the data obtained with the technical specifications.

Figure 3. Optical Emission Spectrometer [12] (left) and Chemical Analysis [13] (right)

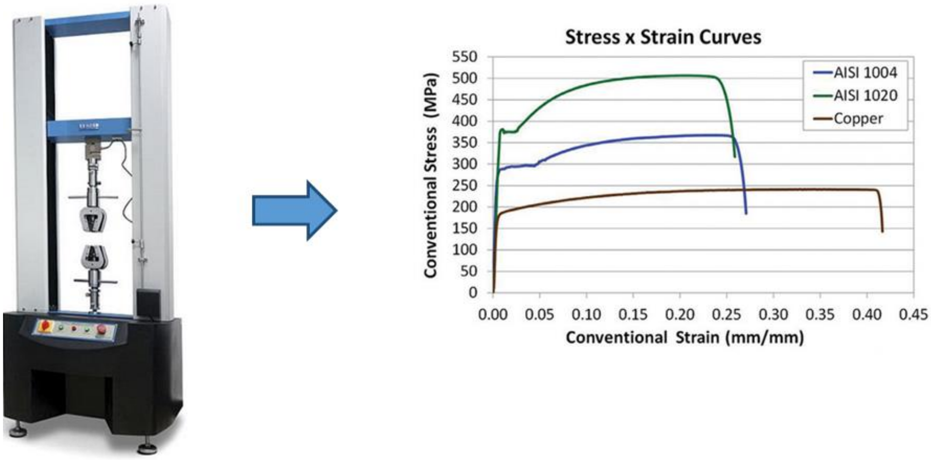

Figure 4. Universal Tensile Machine [14] (left) and Stress x Strain Curve [15] (right).

Revisit your objective, in other words, check whether deviation in chemical composition exists and obtain information about the influence of faulty elements on the mechanical behavior of the product (Figure 4). Do not forget, always compare the results with a specification or standard.

Use Microscopes for Metallographic Analysis

Metallography is the study of the physical structure and components of metals using microscopy (Figure 5). The first evaluation is the analysis of fracture surface in order to identify brittle fractures or fatigue fractures. Look for a coarse surface with beach marks to identify fatigue phenomena or corrosion. Normally, a magnification of 400x gives a good image for evaluation. High magnification examination of a fracture surface is critical for the metallurgist during the course of a failure investigation in order to determine the cause of the fracture. Close examination of the topography and fracture features can help determine the fracture mode, as well as the fracture origin and crack direction.

Visualize the grain contours. For this analysis, it is important to have a good sample preparation [16-17]. Also evaluate microstructure; check whether the microstructure is compatible with the application of the material, the raw material used to produce the part, and its hardening process. Evaluate whether there are one or more microstructures, and whether the microstructures are distributed throughout the cross section of the part.

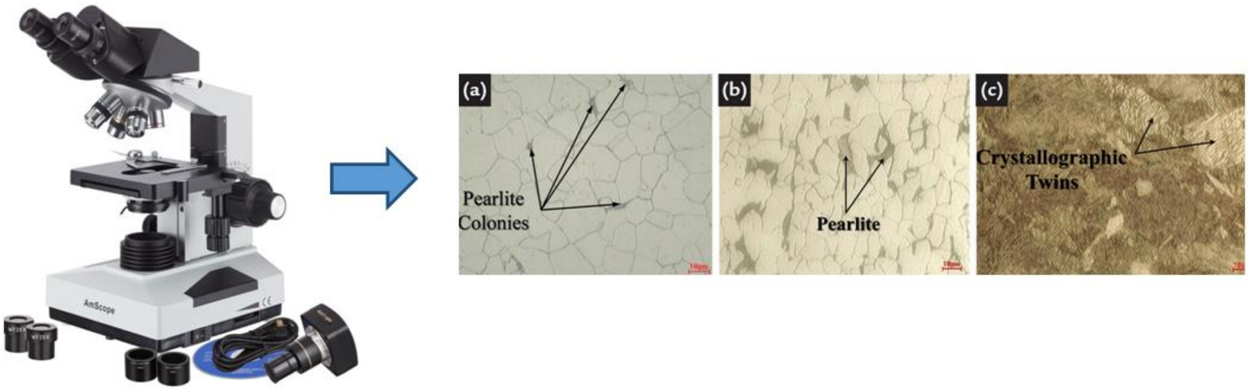

Figure 5. Metallurgical microscope [18] (left) and Metallography [15] (right)

Deeper in the Analysis Using Scanning Electron Microscope (SEM)

When a deeper analysis is necessary, a Scanning Electron Microscope with Energy Dispersive X-Ray Spectroscopy (EDS), Figure 6, is used [19]. With this equipment, it is possible to magnify the image from 20 times to 30,000 times, in order to obtain a clear picture of the fractured surface. Additionally, some important analyses are possible, for example:

a) Failure analysis
b) Corrosion Analysis
c) Identification of contamination debris
d) Phase analysis
e) Analysis of coatings
f) Tungsten carbide and PDC diamond
g) Non-metallic materials
h) Tungsten carbide and PDC diamond
i) Non-metallic materials

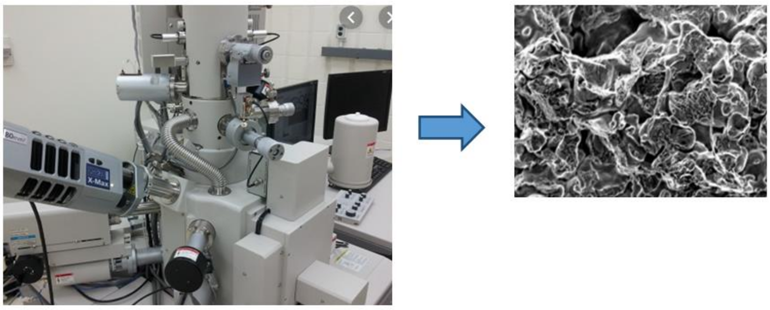

Figure 6. SEM/EDS (left) and Fractured Surface (right) [20]

Profound Analysis Using X-Ray Diffraction

The determination of plastic deformations and their residual stress is a much more advanced step which can be performed by using an X-Ray diffractometer (Figure 7). However, it should only be considered if the cause of the fracture was not found by any of the steps already taken. Also for fatigue analyses, the knowledge of the stress state is important in determining the root cause, for example, the presence of tensile stress. If the fatigue phenomenon is found, it is useful to produce a finite element analysis in order to determine stresses and compare them with the sample. It is important to reinforce, that the residual stress determination requires a very sophisticated technique to measure atomic planes. This test is very expensive, nevertheless, it can be performed in order to reinforce data which has been obtained using a microscope, and to evaluate the fractured surface with more accuracy.

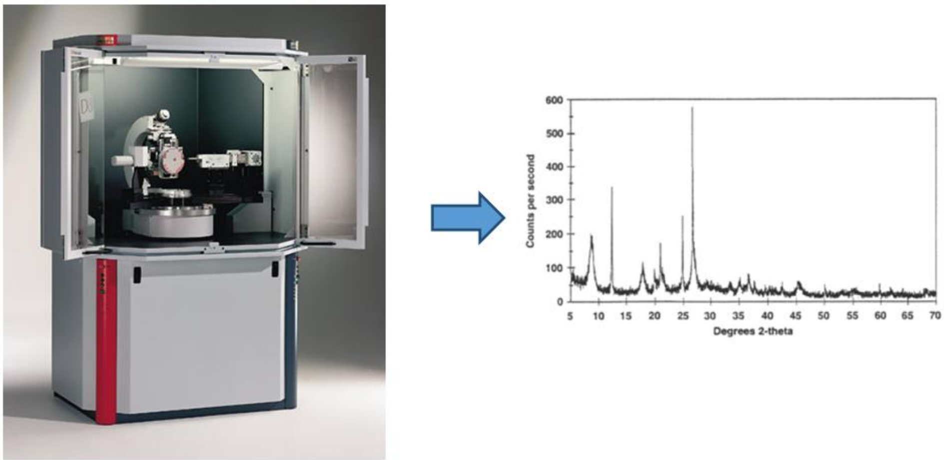

Figure 7. X-ray Power Diffraction (XRD) (left) and Diffraction Angles (right) [21]

Conclusion

Most of the fracture analysis papers have a very detailed characterization of the problem and can determine the root cause of the failure. However, there isn’t a clear roadmap to use as a guide. The actual cause of a fracture is only reached with accuracy if application of the part is known. A short cut in the analysis or a superficial analysis can be detrimental for the user. The steps to consider during the analysis, the types of equipment to use and their capabilities are crucial in determining a precise cause for the failure. This paper has attempted to describe more accurately, the steps and equipment needed, as well as provide a robust way to avoid short cuts and furnish a precise diagnostic of the failure.

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