Analysis for Failure, Damage, and Fracture

Table of Contents

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1 Introduction

The field of metallurgical failure analysis encompasses all of metallurgy and materials science and engineering, from raw material production to end product use. There is an extremely wide variety of factors that contribute to damage accumulation and failure in components and systems, including part geometries, alloys, manufacturing techniques, post-manufacture treatments, assembly methods, service conditions, types of loading, environments, and a myriad of combinations of all of these. Evaluation of metallurgical characteristics and deformation distribution can help identify the key contributing factors and circumstances of failed mechanisms.

2 Scope

This document applies to case working personnel using the associated instrument(s) and supporting equipment in support of metallurgy examinations. It supplements METAL-210 by detailing how inspection and analysis techniques can be applied to damage evaluation.

3 Equipment

A list of items commonly used in these examinations is provided in the METAL-210 Equipment section. Not every item is used for all failure and damage investigations. The instrumentation and equipment used will depend on the nature of the evidence to be examined and compared.

4 Standards and Controls

The standards and control materials used in this procedure will depend on the specific analytic methods employed and the nature of the item under analysis. Any instrument used in this procedure will employ such standards as required under its specific technical procedure. If available, exemplars for evidentiary items (i.e., known materials) may be obtained and examined to establish the expected variability of manufactured characteristics.

5 Sampling

Visual examinations are performed on every item examined under this protocol. Further testing is based on the suitability of individual items, or portions of items, for relevant examination techniques. Case notes will describe which examinations were performed on which items. If initial examinations reveal that an analyzed characteristic varies on a single item, the means of selecting a location to test the characteristic will be noted in the case file.

Specimens or sections may be taken from the items for analyses of coating(s), substrate material(s), corrosion product(s), deposits, contaminants, or any other material relevant to the determination(s) requested. Destructive specimen removal should be approved by the contributor prior to modification of the evidence.

For failure analysis, sample selection is typically based on observable damage, and thus is usually non-statistical in nature. The manner of specimen selection will be recorded in the case notes.

6 PROCEDURE

The following analysis sequence was derived from guidelines established by ASM International and augmented for forensic metallurgical applications. Data gathered during examinations will be included in the case notes.

6.1 Required

A. Perform a preliminary visual inspection of the item(s) to evaluate the condition of the item(s) and characteristics relevant to material, stress condition, and environment. Stereomicroscopy can aid preliminary evaluations. Inspect features such as:
   - configuration of components in an assembly
   - joining methods
   - individual component fabrication method(s),
   - presence and integrity of coating(s)
   - marks from service use/abuse
   - type(s) of failure and damage,
   - exogenous materials/possible contamination

B. Protect fracture surfaces from contact with other components to avoid possible destruction of valuable surface information. Presumed mating fracture surfaces should not be brought into contact with each other to “see if they fit”.

C. Photograph submitted or in situ items in the “as-received condition” (ARC) to record characteristics to be considered during the failure/damage analysis, such as:
   - in situ orientation and environmental exposure of components
   - in situ fracture and failure orientation relative to its environment and to other components
   - positions of individual components in an assembly
   - service conditions
   - service abuse

D. Additional photography should be conducted during the metallurgical examinations to record any features or characteristics upon which a conclusion is likely to be based. Whenever practicable, include a scale in the photograph or apply a verified micron marker to the photograph.

E. Prior to any specimen cleaning or specimen removal, perform visual and low power magnification examinations of fracture surfaces, secondary cracks, relevant surface phenomena, gross deformation, thermal damage, and any other metallurgical or environmental characteristics deemed appropriate.

6.2 Optional

A. Any of the analysis techniques presented in the METAL-210 Procedures section can be used to elicit relevant information for evaluation of failure, damage, and fracture. The additional considerations below are not required in every situation and their use and sequence will vary depending on circumstances and the evidence.

B. Acquire and analyze documentary information to assist in the reconstruction of the sequence of events leading to the damage and/or failure. Such information can include fabrication, manufacturing and processing information; service history; interviews of eyewitness individuals; interviews with individuals whose duties, behavior, or failure to act could have induced, or could have affected, the material behavior in question; as received item photos; site/in situ photographs; repair history; environmental details (e.g., temperatures, loading conditions, load magnitude(s), environment chemistry); and similar component history.

C. Evaluate the physical properties of the items by measuring appropriate features, such as dimensions, mass, and magnetic response.

D. Collect specimens from the items for chemical analyses of coating(s), substrate material(s), corrosion product(s), deposits, contaminants, or any other material relevant to the determination(s) requested.
   1. Remove test specimens in a manner that minimizes alteration to the remainder of the evidence.
   2. Record with notes and photographs any information derived from the preliminary examinations which may potentially be needed to reach a conclusion but could be otherwise lost due to specimen removal.
   3. Provide adequate protection of all fracture surfaces and damaged regions to prevent contact with each other, with other portions of the same component, or with other objects or items during transport and examination. If appropriate and feasible, package with desiccant to reduce degradation by corrosion.
   4. It may be necessary to collect specimens prior to, or between stages of, cleaning.
   5. Analyses such as EDXRF and SEM/EDS can often be helpful in identifying the chemical compounds present on a failed component.

E. Clean specimen(s) using methods that progress from least to most aggressive (see Table 1 for examples) until contaminant is removed. Preserve any replica(s) or contaminant/debris for appropriate analysis.

Table 1. Specimen Cleaning Procedures

Aggressiveness	Activity
Less aggressive	Dry air blast
↓	Soft artist’s brush
	Stiff non-metallic brush
	Aqueous rinse
	Organic solvent (e.g., isopropanol, hexane)
	Chelating Agent (e.g., EvapoRust™)
	Ultrasonic cleaning
More aggressive	Plastic replication

F. After cleaning, perform additional examinations of relevant metallurgical characteristics. A variety of microscopes and lighting techniques can be used to further characterize fracture surface features and any exogenous material present.
G. Perform qualitative or quantitative compositional analysis of any materials which assist in evaluating damage characteristics or determining cause(s) of failure.
H. Perform X-ray inspection to examine for internal defects such as unopened cracks or large inclusions. Other means of nondestructive testing (i.e., magnetic particle, liquid dye penetrant [LDP], ultrasonic, and other electromagnetic evaluations) can be performed, provided the appropriate validations are developed.
I. If destructive testing is permitted by the contributor, perform mechanical testing (i.e., hardness, microhardness, or uniaxial testing) to characterize material properties.
J. Perform metallographic examinations to evaluate microstructural features of interest. Note the presence of features such as:
    - inclusions
    - microstructural segregation or inhomogeneities
    - decarburization; carbon pick-up; improper heat treatment
    - corrosion
    - grain size
    - type, distribution, and morphology of microstructural constituent(s)
K. Evaluate the data and facts accumulated to determine the fracture mode or cause(s) of the damage exhibited.
L. Perform a mathematical analysis of mechanical factors leading to fracture. Such analyses can be used to:
    - predict flaw size which caused catastrophic fracture at a load below that expected to cause failure
    - evaluate manufacturing flaws
    - establish a quantitative framework for evaluating structural reliability
    - assist in the design and prediction of service life
M. When the history and service conditions of the evidentiary specimen are known, test exemplar specimens under similar conditions to simulate expected damage.
N. Report findings after evaluation of all gathered data.
O. Although it is not typical for criminal cases, it may be prudent to suggest corrective measures to prevent future failures.

7 CALCULATIONS

- Calculations associated with the use of a particular instrument will be found in the appropriate technical procedure.
- Calculations used to characterize mechanical factors leading to fracture will clearly be attributed to appropriate citations.

8 ACCEPTANCE CRITERIA – INSTRUMENT PERFORMANCE

For instruments that require verification, standardization, or energy adjustment, a copy of the appropriate record(s) will be included in the case notes.

9 Measurement Uncertainty

See METAL-210 for measurement uncertainty considerations for comparative analysis or reporting quantitative results.

10 Limitations

The limitations of a particular failure analysis are determined by the type, amount, and condition of objects(s) being analyzed, the available background information, the specific examinations required, and subsequent determinations made, thus cannot be predicted within this protocol. Limitations encountered during the examinations will be recorded in the case notes.

11 Failure Analysis Conclusions

The conclusions derived from this procedure are based on careful interpretation of all factual information gathered from completed testing and investigation. If a unique scenario does not explain the failure, all reasonable possibilities will be reported in the conclusion.

12 Reporting Results

Report the results of metallurgy analysis for failure, damage, and fracture in accordance with METAL-210 Metallurgy Laboratory Reports section. Metallurgy Laboratory Reports will also comply with the language limitations detailed in METAL-904 FBI Approved Standards for Scientific Testimony and Report Language for Metallurgy (the Metallurgy ASSTR) and the Department of Justice Uniform Language for Testimony and Reports for the Forensic Metallurgy Discipline (the Metallurgy ULTR).

13 Safety

- Wear an X-ray film badge or dosimeter when operating instruments that generate X-rays.
- Never bypass or disable safety interlocks on instruments.
- Wear personal protective gear and use engineering controls that are appropriate for the task being performed (e.g., safety glasses when cutting and chemical fume hood when etching).
- Electrical or mechanical hazards may require special precautions (e.g., grounding to prevent electric shock or wearing a face guard to prevent impact from flying debris.)
- Review instrument technical procedures and pertinent Safety Data Sheets (SDS) prior to conducting examinations.

14 References

- METAL-210, Examinations for Association and Origin, Chemistry Unit, latest revision
- METAL-904, FBI Approved Standards for Scientific Testimony and Report Language for Metallurgy (the Metallurgy ASSTR), latest revision
- Department of Justice Uniform Language for Testimony and Reports for the Forensic Metallurgy Discipline (the Metallurgy ULTR), latest revision

15 Revision History

Revision	Issued	Changes
09	09/30/2022	Revised to comply with new formatting requirements. Removed expository information to retain as training material. Relocated information among Introduction, Scope, and Principle sections. Added compositional analysis details. Added Reporting Results section. Removed informational references. Added references to technical procedures.
10	08/15/2024	Revised to incorporate Department of Justice Uniform Language for Testimony and Reports for the Forensic Metallurgy Discipline, latest revision effective 5/8/2024. Removed expository information from Introduction, Scope, and Principle sections to retain as training materials. Relocated other material from Principle section to Introduction and Acceptance Criteria sections, and removed Principle section. Made METAL-220 dependent on METAL-210 and removed redundant content throughout. Relocated exemplar information from Specimens section to Standards and Controls. Added requirement to cite source of mechanics equations. Clarified the use of non-destructive inspection methods. Added references to the metallurgy ASSTR and ULTR. Reformatted lists.