Systematic Analysis of Technical Failures

Edited by
Günter A. Lange

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ISBN 3-88355-091-4

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Edited by Prof. Dr.-Ing. G. A. Lange

Course of advanced instruction organized
by Deutsche Gesellschaft für Metallkunde in
cooperation with Schweizerischer Verband
für die Materialprüfung der Technik and
Deutscher Verband für Materialprüfung

Printed in Germany (FRG)

Preface

A large proportion of the failures in metallic materials is due to the fact that the basic principles for their application have been ignored. Components fail less frequently due to the complex interaction of unforeseen effects. Contrary to common belief material defects cause breakdown in machines, plant or constructional components only in isolated cases .

The material processes which take place on overloading and during destruction must be known before the limitations in the use of metals and alloys can be understood and, possibly, modifications suggested. This knowledge is important both for the designers and for investigators of failures. On the one hand, the number of possible failures can be reduced to a minimum and on the other, a complete understanding of the causes of a failure and the feedback in design, material choice, manufacture, testing and loading conditions can largely prevent a recurrence of similar failures.

The emphasis in this book is on the material aspects. After an introduction into the working procedure of failure analysis and the various methods of investigation, the mechanisms of development of the various modes of fracture and failure processes in corrosion and wear are discussed in relation to material condition and state of loading. The macroscopic and microscopic features are explained in terms of the mechanisms. Separate chapters are devoted to fracture mechanics and damage of welds. Examples are chosen to illustrate the fundamental concepts and forge the link to practice.

I am particularly indebted to all coauthors for their commitment and for the care in the preparation of the manuscripts.

Braunschweig, March 1986

G.A. Lange

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Working Procedures for the Analysis of Technical Failures

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1. Purpose and aims of failure analysis

Primarily, an analysis of a failure should provide the reasons for the failure of a component. In addition, it serves to prevent further cases by influencing design, material choice, manufacture, testing techniques or operating conditions. Inspection may be introduced and suspect parts in operating machines, apparatus, instruments and plant replaced before actual failure occurs.

There are very many causes of failure and, equally, many ways in which failure manifests itself. Therefore, in this paper only the basic methods of approach and criteria of evaluation are discussed. Suitably adapted to a specific case they should enable the majority of service failures to be solved.

2. Failure documentation

As a first step the remains of the damaged component must be secured. Parallel to this, information should be collected. The following points should be borne in mind:

Evidence

- Both or all fracture surfaces must be saved; one fracture surface can exhibit features which are not visible or have been destroyed on the opposite face.

- Parts liable to corrosion must be protected: dessicator, lacquer spray. Care must be taken if corrosion products are to be investigated. Fracture surfaces must not be handled!

- Photographs should be taken if possible (in colour of corrosion products), otherwise sketches made. Dimensions should be noted.

(Photographs are not merely for documentation purposes. They enable a renewed assessment of the original state, if necessary, if the original part has been sectioned in the course of the examination.

If the failure is examined on site or in situ (as opposed to a component which has been submitted) then the following should also be undertaken:

- Macroscopic examination of the original state of the fracture.

- Recording of the general impression and surrounding circumstances. Statements from witnesses.

- Instructions for dismantling or cutting of parts for investigation so that subsequent changes are avoided (e.g. cutting by torch or cutting wheel at a sufficient distance from the fracture surface, possible cooling).

- Coding of sections to be removed for material examination (punching to prevent mixing of the specimens). Marking in the drawing of the component that region from which the test specimen was removed.

Information regarding the failure

Extensive, reliable information simplifies the investigation considerably and largely prevents a wrong assessment. Depending on the type of failure the following details should be established (erroneous information must be anticipiated):

- Material (possible test certificates)

- Heat treatment of the material or component

- Production, manufacture, acceptance test of component

- Design of component: constructional drawing, mode of function, type and degree of loading, dimensioning, constructional changes, one-off or mass produced component.

- Function and position of component in machine, apparatus or plant (bear in mind distant effects of failure sources).

- Operational details: age, time in operation, previous damage, repairs, overhauls, inspection intervals, changes in operation, overload, stoppages.

- Environment: temperature, pressure, corrosive or erosive media.

- Operating conditions at time of failure: starting up, part load, full load or overload, heating up or cooling down.

- Course of failure - particular observations, point in time and sequence of events.

- Occurrences after failure: subsequent damage, improper treatment or storage, previous examination.

In practice only a small fraction of this information is available to the investigator. Often therefore, some of these aspects are the object of the investigation. (Two significant cases are discussed at the end of this article).

3. Execution

The procedure and scope of the investigation should be agreed with the customer. Often a quick and cheap solution is required without a detailed explanation of all the aspects of the failure. The limitations of the experimental methods must be emphasised, particularly when special techniques have been requested. Enquiries show often that the requested technique is in no way appropriate. Isolated tests required by the customer without providing the background information are normally useless (e.g. a chemical analysis is requested whereas the cause of a fatigue failure is in fact required).

The programme should be planned in detail so that no evidence is lost which may be required at a later date. This applies particularly to the removal of specimens. A specimen must be representative for the property under investigation and it should not be affected by the specimen removal (microstructural change by heating, loss of graphite on preparation of cast iron specimens for analysis, etc.). The position of removal should be marked on a photograph or sketch.

The determination of the type of fracture is in most cases the prime object of the investigation. Not infrequently it is sufficient to solve the problem. The type and appearance of fracture provide information on the stress state and partly also on the material condition and thus on the cause of failure. It may also be possible in addition to distinguish between primary fracture and resultant damage.

In each case it is necessary first to carry out a macroscopic assessment of the fracture - naked eye, magnifying glass or stereoscopic microscope. Often pronounced macroscopic features are sufficient to enable the type of fracture to be identified. In the event of a large number of damaged components (e.g. in aircraft crashes, explosions) the fractures possibly responsible for the accident can only be presorted by a macroscopic examination.

If a macroscopic examination is insufficient to determine unequivocally the cause of failure microscopic examination becomes necessary - usually by scanning electron microscopy. This is particularly the case for thin walled parts or small sections as well as for subsequently damaged fracture surfaces. In addition to determining the fracture type useful information can be obtained by scanning electron microscopy e.g. peculiarities at the source of fracture, propagation of cracks, microstructure. (A statistical evaluation of 180 failures in civil aviation resulted in the following distribution: in the case of 24% of all fragments the fracture type could be determined unequivocally from macroscopic examination; in 43% of the cases an indication was possible but could only be confirmed by scanning electron microscopy. In 30% of the cases no definite prognosis was possible by macroscopic examination so that scanning electron microscopy was indispensible. Additional information was obtained in 35% of the cases.)

Ideally the result of the microscopic examination confirms that of the macroscopic examination. If the results are not satisfactory simulation tests may help. Specimens are taken from the failed component (if necessary, with reservation, from a replacement component) and tested to destruction under conditions similar to those in operation. The fracture surfaces are then compared with those of the component. If the operating conditions are not known various fracture types are produced using several specimens.

Depending on the type of failure various material investigations may be necessary. They provide information on the type and state of the material, in particular deficiences and deviations from guaranteed values. The most important techniques are metallography, mechanical testing, chemical analysis and non destructive testing. If information is not available on the specified or desirable state, then parallel investigations on similar parts in other plant or machines or on spare parts are helpful. The criticism can then be met that the material is suspect but of sufficient quality for the application in question.

The procedure, investigation results and conclusions are usually included in a failure report. The report should contain suggestions as to possible remedies.

Instruction sheets on the analysis of failures can be found in Refs (1-3). Standard forms were developed by Schmitt-Thomas (4). Reports on material causes of failures as well as numerous examples were listed by Allianz (5-7), the American Society of Metals (3), Naumann (8) and Colangelo (9).

The following two examples should demonstrate the influence of failure initiation of apparently unimportant effects. The constructional features of axial compressor stages of established helicopter turbines had been apparently insignificantly changed - near the edge of the disc a circumferential ridge had been machined. This enabled surplus material to be removed easily during balancing. After about 1000 hours operation at 44,000 revs/min two turbine discs broke as a result of intergranular stress corrosion (Fig. 1 + 2). The corresponding discs from other helicopters showed pronounced attack and were exchanged. The steel employed X15Cr13 (0.15%C, 13%Cr) had been heat treated after hardening only to 540°C (instead of 700-750°C) to maintain the high strength and hence was particularly susceptible to corrosion due to the intergranular precipitation of chromium carbide and resultant chromium deficiency. The condensation from the air was no longer thrown off by centrifugal forces. The water was retained on the inside of the ridge and destroyed the sensitized steel in this region (10).

During shooting with a repeating rifle some bath hardened parts of the gun-lock broke, seriously injuring the marksman. About 50 shots had been fired with the rifle, the first with about 30% overload. The accident, ununderstandable for the participants, was explained as follows: all gun-lock parts were destroyed by cleavage fracture. The material was extremely brittle as a result of incorrect heat treatment. The rifle had been acquired in June; the accident occurred in November of the same year at a temperature of +1°C. The decrease in temperature had reduced further the initially low ductility and thus created the prerequisite for brittle fracture. The result of the investigation was confirmed by metallography as well as a notched-bar impact test at 20°C and 1°C on fracture parts and comparison specimens from a similar weapon (11).

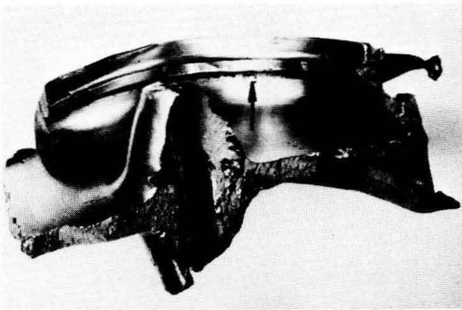

Fig. 1: Fragment of an axial compressor. Corrosion attack on the inside of the ridge (arrow). Disc diameter 130mm.

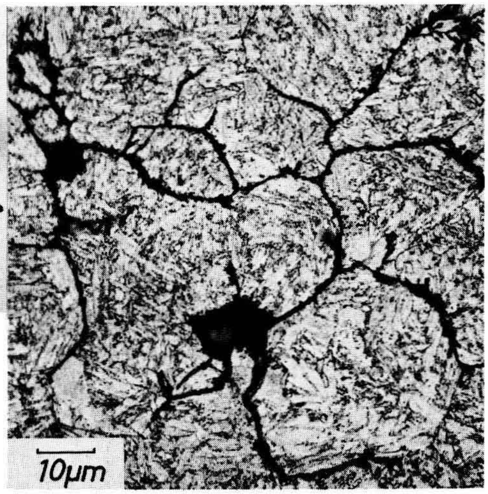

Fig. 2: Intergranular corrosion in the region of the ridge. Vilella.

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Classification, Causes and Characteristics of Fractures

Günter Lange

1. Types of fracture

There is a whole series of different proposals for classifying fractures. In addition, there are different names for the same type of fracture, partly with imprecise or incorrect designations. This book uses terms developed by a VDEh-DVM-Subcommittee in cooperation with the editor (1). Depending on the type of loading fractures can be classified as in Table I. Additional fracture types not discussed in this chapter will be treated in the corresponding chapters.

2. Definitions of types of fracture

Independently of the detailed description of the various types of fracture in sections of this book the definitions of the concepts in Table I are collated below.

Fracture caused by mechanical loading

Overload fracture occurs under moderately rapid to sudden unidirectional loading. The microscopically ductile or dimple fracture occurs by slip on the planes of maximum shear stress. The microscopically brittle fracture occurs perpendicularly to the plane of largest tensile stress, almost without plastic deformation, by overcoming the material cohesive strength. Uniaxial stress, tough material, low loading rates and high temperatures favour ductile fracture. Opposite conditions favour brittle fracture. Based on the microscopic appearance there is a further subdivision into trans- and intergranular dimple fracture, on the one hand, and transgranular cleavage and intergranular brittle fractures on the other. Mixed fractures are combinations of these various types.

1.	Fracture by mechanical loading
1.1.	Overload fracture
1.1.1.	(Microscopically) Ductile fracture = dimple fracture
1.1.1.1.	Transgranular dimple fracture
1.1.1.2.	Intergranular dimple fracture
1.1.2.	(Microscopically) Brittle fracture
1.1.2.1.	Transgranular brittle fracture = cleavage
1.1.2.2.	Intergranular brittle fracture.
1.1.3.	Mixed fracture
1.2.	Fatigue failure
2.	Corrosion induced cracks and fractures
2.1.	Intergranular corrosion
2.2.	Intergranular stress corrosion cracking
2.3.	Anodic stress corrosion cracking
2.4.	Hydrogen induced cracking and fracture
2.5.	Hydrogen induced stress corrosion cracking
2.6.	Corrosion fatigue
2.7.	Metal embrittlement
3.	Thermally induced cracks and fracture
3.1.	Creep failure
3.2.	Weld cracking
3.3.	Hot cracking
3.4.	Hardening cracks
3.5.	Grinding cracks
3.6.	Thermal shock cracks

TABLE I: Classification of fracture types.

Fatigue failures develop under fluctuating stress conditions. A fatigue crack develops from one or several nucleating sites and propagates into the interior of the component until the residual