General Procedure of Failure Analysis

This chapter present basic approach of proceedings with failure analysis and care need to have useful findings about few most potential causes of the failure. Step by step approach of failure analysis of the mechanical components has been described. It is important to note that these steps need not to be followed strictly in sequence (given below) as findings of any stage of investigation will dictate further direction of failure analysis.

40.1 Introduction

In the field of engineering, mechanical components are made using variety of materials processed by different manufacturing processes and are used in extremely wide range of the service conditions. Potential causes of the failure of the components and their mechanism are also numerous. Therefore, procedure of the failure analysis of each failed component should be different and the same must be developed after giving proper thought on possible sequence of events before failure along with proper evaluation of the situation and consideration of material, manufacturing process, service history and actual working condition etc. Since the failure analysis involves lot of efforts, time and use of resources therefore at the end of analysis failure analyst should be in position to come up with few most potential causes of the failure so that suitable recommendations can be made to avoid reoccurrence of the similar failure. It has been observed that on receipt of failed components, failure analyst tends to jump into conclusions based on half information and try to prepare the samples for metallographic studies to look explore the deficiency in the material itself. This kind of quickness is uncalled for and in this process vital clues, evidence and information can be lost from the surface of the fractured components. In this chapter, general practice for metallurgical failure analysis of failed component has been described besides common features of various types of fractures and important tools and equipments available for analysis and characterization.

40.2 General step of failure investigation

As a broad guidelines, steps generally used in metallurgical failure analysis of mechanical components are described in the following section. These steps are generic and need not to be followed in the specified; moreover the sequence of steps will largely be determined by the findings of the investigation at any stage, with main objective of collecting evidences for potential causes of the failure so the sequence of events prior to the failure can be established and suitable recommendations can be made to prevent the similar failure in the future.

1. Collection of back ground information about failed components
2. Preliminary examination of failed components
3. Selection, preservation and cleaning of the sample
4. Assessing the presence of discontinuity and defect in failed component by non-destructive testing
5. Evaluation of the mechanical properties of the failed components
6. Macroscopic observation of fracture surfaces
7. Microscopic examination of fracture surfaces
8. Metallographic examination of failed components
9. Establishing the fracture mechanism
10. Failure analysis using fracture mechanics approach
11. Conducting test under simulated conditions if required
12. Analysis of findings of investigation
13. Report writing with recommendation

40.1 Collection of back ground information of failed components

Failure analysis should begin with collection of information mainly on manufacturing procedures used for development the failed components, design aspects and service conditions of the same with objectives to familiarize with components under investigation and to make an effort to develop the “draft sequence” of events which would have led to the failure. Depending upon the level of record keeping practices, the extent of information available on above aspects may vary appreciably.

Information collection on manufacturing aspects should include details of drawing, material, manufacturing process and process parameters, assembling method used for obtaining the desired size and shape. Since manufacturing steps used for developing various components of an assembly are found in the form of many processes therefore information collection can be grouped under three heading based on nature of manufacturing process a) mechanical processes such as forging, forming, machining etc. wherein external stresses are applied during manufacturing, b) thermal processes such as welding, brazing, heat treatment etc. that are based on the application of heat to control the structure and properties and c) chemical processes such as cleaning, electroplating, machining etc which use mixture of chemical solutions for variety of purposes. Segregation of the information on mechanical, thermal and chemical basis helps to estimate the structure, mechanical and chemical changes that can be experienced by materials during manufacturing which can produce desirable or undesirable changes in the end product.

The collection of information about past service conditions to a great extent depends how meticulously record keeping of working conditions has been maintained. The failure analyst should try to collect information about loading and environmental conditions, duration of service, temperature, maintenance plan etc. Sometimes, failure analyst gets only fragmented information on service conditions, in such case based on the experience and skill, failure analyst needs to estimate/guess the working conditions in order to establish the sequence of events that led to the failure. However, in absence of information any error in estimation can be totally misleading to the investigation hence failure analysts are cautioned against such kind of estimation if they are not confident.

40.2 Preliminary examination of failed components

This step involves observation of failed components, their fragments and position occupied them after failure. Detailed photographic record showing the condition and location/position of the failed components should be obtained. A detailed and systematic photographing is important in failure analysis because the failure which is appearing to be a common and casual accident, subsequent investigation may indicate serious implications and tampering possibilities. Schematic diagrams can also be used to locations wherefrom photographs have been taken for better representation of the failed components and their fragments as per needs.

40.3 Preservation, cutting and cleaning of the sample

Usually in post-accident scenario, failed components are found in very bad condition of shape, debris, impurities etc. Based on the preliminary examination failure analyst should take decisions on location wherefrom sample need to be collected from fractured components for further analysis. The sample may be taken from the near fracture surface or significantly away from the fracture zone keeping in mind collection of the evidence that would help in establishing the sequence of events besides indicating the potential causes of failure. The skill, experience and gut feeling of the failure analyst play very crucial role in decision making on areas/locations wherefrom samples need to be collected. Once decision is taken, next step would be to obtain the samples by cutting from the failed component or assembly which can be done using mechanical or thermal methods. Due care should be taken to avoid any chemical or mechanical damage when mechanical methods (machining, cutting) are used for cutting the sample. Thermal cutting methods like gas cutting is considered to be more damaging than mechanical methods because application of heat for cutting the samples by thermal methods can change the structure up to a greater distance than mechanical methods. Additionally thermal methods will have the possibility of falling of spatter on the fracture surface. Hence, sample cutting by thermal methods should be made at greater distance than mechanical methods.

Cleaning of the fractured specimen should be avoided as far as possible as cleaning will remove the foreign matters like oxide, paints, chemical etc. present on the fracture surface which can play an important role in establishing the root cause and sequence of events prior to the failure. If cleaning is necessary to proceed with investigations and to carry out studies then dry or wet cleaning can be applied as per requirement with due care to avoid any kind of damage to fractured specimens. Dry cleaning using jet of compressed dry air can be applied to remove the foreign particles while wet cleaning can be done using mild acidic or basic solution followed by rinsing in fresh water or acetone followed by drying before putting samples into desiccators.

Sometimes plastic replica method is also used for cleaning fractured surfaces. In this approach one softened acetate sheet of about 1mm thickness is pressed over the fracture surface and then taken off once the sheet is dried after curing for 8-12 hours. Removal of sheet from the fractured surface takes away some of the foreign matter present on the surface. The shape of sheet generally corresponds to that of fractured surface. These sheets with attached foreign matter can be preserved for record and further studies of fracture surface and foreign matter as per needs in future.

40.4 Assessing the surface and sub-surface imperfections using NDT

To determine the possibility of the failure caused by presence few surface and surface imperfections, non-destructive testing of fractured component especially near the fracture surface can carried out using variety of techniques as per needs. Common non-destructive testing methods includes dye penetrant test (DPT), magnetic particle test (MPT), eddy current test (ECT), ultrasonic test (UT), radiographic test (RT) etc. Each test has unique advantages and limitations which dictate their applications as indicated in table.

NDT test	Advantage	Limitation	Applications
DPT	• Simple, • cost effective • portable	• Not for subsurface defects • Difficult to assess fine cracks • Surface cleaning in important	Surface discontinuities cracks, fine porosities
MPT	• Easy to apply • Quick • Simple	• Only for near surface defects • Only for ferromagnetic materials • Chances of arcing at contact point • Difficult to assess deep sub-surface defects	Fine surface defects closed by impurities
ECT	• Very sensitive method • Continuous production • Simi-skilled worker can use	• Difficult to interpret the results as output is influenced by many factors • Only for ferromagnetic and electrical conducting materials	For surface and sub-surface defects in continuous and long slender shape products like shaft and gears
UT	• Very sensitive method • Precisely locates the defects	• Difficult to interpret the results and accuracy depends on many factors • Needs expertise and skill to interpret findings	For both surface and subsurface defects like porosity, internal defects etc.

RT	• Positive record of test is obtained • No limit on thickness of the material which can be evaluated	• Difficult to interpret the results and accuracy depends on many factors • Needs expertise and skill to interpret findings • Specially precaution is needed to handle radiations and protect operators	Internal defects can be located precisely

40.5 Destructive test in failure analysis

Destructive tests such as hardness, tensile, toughness, fracture toughness and tests under simulated conditions are extensively used in failure analysis for variety of purposes. In general, destructive tests are carried out to generate the data on mechanical performance of the specimen under investigation and to assess their suitability for given service load conditions. Additionally, destructive tests can also be use to a) indentify / confirm the manufacturing process used for developed the component under investigation, b) confirm if a particular heat treatment was performed properly. Hardness test is commonly carried out on small fractured specimen for evaluating heat treatment, estimating ultimate tensile strength and determines the extent of work hardening or decarburization occurred on the fractured component during the service, if any. Since it becomes difficult to find large amount of material from the failed components for tensile and fatigue tests therefore failure analysts mostly rely on hardness tests. However, sometime tensile, toughness, fatigue tests are conducted at low, high temperature and in specific environments to assess the performance under simulated conditions. Further, it is advised that care should be taken in interpretation of laboratory test results of mechanical properties and attributing the same to failure owing to minor difference in scale/size of material in laboratory test and real service conditions. Minor difference in actual and recommended value of mechanical properties in fact may not be responsible for failure. Tri-axial stress state and related embrittlement of material should not be overlooked during interpretation of tensile test results.

40.6 Macroscopic observation of fracture surfaces

Macroscopic observation of the fracture surfaces are generally carried out in range of 1-50 magnification with the help of lenses, stereoscope and optical microscope (with external lighting) and now more commonly used system is scanning electron microscope. Plastic replicas coated with gold layer of about 200^0A can also be used for macroscopic observation. A careful macroscopic examination can reveal important information on stress state under which failure has taken place, location wherefrom fracture had initiated, direction of crack growth and operational fracture mechanism during various stages of fracture.

The stress state under which failure has taken place can be plain stress and plain strain condition. The plain stress condition generally observed in ductile metals of thin section like sheet, wire and thin plates, and is recognized by slating fracture surface appearance while plain stain condition usually noticed with hard, brittle metals of heavy sections and is recognized by flat fracture surface largely normal to external applied stress. The fracture surface of a typical tensile test specimen of mild steel shows more commonly known cup and cone fracture involving a combination of flat fracture surface in central part corresponds to plain strain condition and slanting fracture surface near the outer surface belongs to the plain stress condition. Most of the fractures of real components generally occur under combined plain stress and plain strain condition.

Presence of chevron marks on the brittle fracture surface can easily indicate the location wherefrom fracture had initiated and direction of growth of crack. Cracks usually grow in the direction opposite of orientation of the chevron marks. Region where these marks converge indicates the site of fracture initiation. It is important to note here that above trend is common but always not true. The chevron marks can indicate the reverse trend also; conversely these can show last part of the fracture instead of starting part of the fracture surface.

Each fracture mechanism (such as fatigue fracture, stress corrosion cracking, hydrogen embrittlement, brittle fracture etc.) results in specific kind of fracture surface morphology in respect of surface roughness and texture. Macroscopic examination based on surface roughness and texture can reveal the extent and area where a particular fracture mechanism might have been operational during fracture. For example, typical fatigue fracture surface exhibits different roughnesses and textures in three areas of fatigue fracture namely fracture crack initiation, stable crack growth and sudden fracture zones.

40.7 Microscopic observation of fracture surfaces

The microscopic examination of the fracture surface helps to identify the operating micro-mechanism of the fracture and is usually carried out using devices like transmission electron microscope and scanning electron microscope. Both electron microscopes have different capabilities in terms of magnification and resolving power. The transmission electron microscope offers higher resolving power (up to 10^{0}A) and magnification (3×10^{5}) than the scanning electron microscope (up to 150 ^{0}A resolution and 1×10^{5} magnification). Specimens are usually coated with thin layer of gold of about 50 ^{0}A to make them electrical conducting with better reflection. Scanning electron microscopy (SEM) is more popular as compared to transmission electron microscopy (TEM) due to two reasons related with sample preparation a) sample preparation for TEM is very tedious and time consuming and b) no sample preparation is needed for SEM except that it should be small enough to get accommodated in vacuum chamber.

Depending upon the type of materials and locating conditions, the fracture surface may reveal variety of microscopic fracture mechanisms such as dimple fracture, cleavage fracture, inter-granular fracture and fatigue fracture. The fracture based on macro-scale deformation of the material (before fracture) can be classified as ductile fracture and brittle fracture. Amongst the four microscopic mechanisms of the fracture, dimple fracture belong to ductile fracture while other three namely cleavage, intergranular and fatigue fracture corresponds to brittle fracture.

Dimple fracture is usually associated with extensive plastic deformation of materials prior to fracture which is indicated by the presence of conical shape deep cavities in one part of the fracture surface and corresponding conical shape protrusions in another opposite part fracture surface. Number, size and depth of dimple suggest the extent of plastic deformation and load carrying capacity.

Dimple fracture is considered as high energy fracture as it consumes lot of energy in causing plastic deformation prior to fracture. Fracture tough material of high load carrying capacity and good ductility predominantly exhibits dimple fracture.

Cleavage fracture is associated with brittle fracture and is characterized by the presence of typical river like pattern on the fracture surface that formed due to intermittent growth of crack and development of steps under the influence of external load. In cleavage fracture, cracks propagate through the grains that come across them conversely it is a result of trans-granular fracture. Cleavage fracture is considered as low energy fracture as it consumes little energy prior to fracture. The cleavage fracture usually offers low load carrying capacity and limited deformation prior to fracture.

Intergranular fracture is also associated with brittle fracture and material subjected to is characterized by the presence of typical flat surface ball shape grain on the fracture surface formed by de-cohesion of grains under the influence of external load owing to the presence of some poor or brittle phases/compounds at grain boundary. Since in the type of fracture, cracks propagate mostly along the grain boundaries to cause the fracture hence is termed as inter-granular fracture. Fracture occurring due to hydrogen induced cracking, stress corrosion cracking and sensitization of stainless steel etc. fall under the category of Intergranular fracture. Like cleavage fracture, Intergranular fracture is also considered a low energy fracture with poor load carrying capacity and limited ductility.

Fatigue fracture is mostly catastrophic and is generally characterized by the three distinct regions on the fracture surface corresponding to fatigue fracture initiation site, stable crack growth zone, and sudden fracture zone. Fracture owing to the fatigue typically exhibits concentric circles commonly termed as beach marks at low magnification and similar features observed at high magnification are called striations. These features are developed during second stage of fatigue fracture i.e. stable crack growth. According to the nature of material, third region correspond to sudden fracture may show either dimple or cleavage fracture.

40.8 Metallographic examination of failed components

Metallographic examination of the failed as well as new components is one of the most important tools available to the failure analyst as it is helps:

- to assess the class of the material (for the presence of desirable or undesirable features such as unfavorable orientation of grains, porosity etc.)
- to get idea about the suitability of composition
- to study the effect of service and aging conditions such as decarburization, excessive grain growth etc. if any
- to obtain the information about method of manufacturing and heat treatment carried out the on the failed component
- to determine the contribution of environmental effect on failure such as corrosion, oxidation, work hardening etc.
- to identify the microstructural constituents contributing to the crack nucleation and propagation, if any

It is practically not feasible to generalize the site wherefrom sample should be taken for metallographic studies from failed components for the failure analysis because each failure becomes unique and specific and therefore, needs different approach to establish the causes of failure. Moreover, few general guidelines for selection of sample for common failures can be given. The sample either from near fracture surface or away from it should be taken in such away that it represents to characteristics of the entire component correctly. Examination of crack tip near the fracture surface at high magnification can indicate if a) crack is growing in trans-granular or Intergranular manner and b) crack has some preferential path for growth in material.

Image analyzing software can be very useful to quantify the morphological characteristics of the micro-constituents that can be related with failure. The morphological features such as grain size, shape (aspect ratio, circularity, nodularity, form factor, shape factor etc.), number of particles per unit area, relative proportion of various phases and their distribution. Additionally, image analyzers can also help in measuring the geometrical dimensions of inclusion, cracks and proportions of various micro-mechanisms (such as dimple, cleavage etc.) present on the fracture surface.

40.9 Establishing the fracture mechanism

Using observations and data collected in so far from above stages of investigation, attempts are made to establish fracture mechanism and conditions which led to the failure during service. For this purpose, information collected from preliminary study of the failed component, macro and microscopy examination of fracture surface, metallographic study of samples, efforts should be made to establish the chain activities that have contributed to failure.

40.10 Failure analysis using fracture mechanics approach

In light of discontinuities if any found during investigation in failed component, fracture toughness & yield strength of material involved in failure, efforts should be made to analysis the situation using principle of fracture mechanics to establish that if presence of discontinuities in material have contributed to failure of the component under given service load conditions.

40.11 Conducting test under simulated conditions

Attempts can also be made to simulate the conditions under which a component has failed to understand what might have led to the failure if investigators are unable to find any logical reason for the failure of the component using normal investigation procedures on materials, manufacturing and service related aspects.

40.12 Analysis of findings of investigation

Analysis of all the information, facts, technical observations collected through the investigation is performed to establish the sequence of events that might have led to failure of a component. This can provide us an insight on few potential factors that have caused of failure of component.

40.13 Report writing with recommendation

The report of failure analysis of must include the following

- Few most potential causes of failure
- Sequence of events that have lead to failure

- Recommendation to take suitable steps so as avoid recurrence of the same kind of failure in future

References and books for further reading

- ASM handbook, Failure Analysis and Prevention, American Society for Metals, 2002, Volume 11.
- Sindo Kou, Welding metallurgy, John Willey, 2003, 2nd edition, USA.
- J F Lancaster, Metallurgy of Welding, Abington Publishing, 1999, 6th edition, England.
- Metals Handbook-Welding, Brazing and Soldering, American Society for Metals, 1993, 10th edition, Volume 6, USA.
- R S Parmar, Welding engineering & technology, Khanna Publisher, 2002, 2nd edition, New Delhi.
- George E. Dieter, Mechanical metallurgy, McGraw-Hill Book Company, SI Metric Edition Printed in Singapore.
- http://www.springerlink.com/content/1547-7029/?MUD=MP
- http://research.me.udel.edu/~jglancey/FailureAnalysis.pdf
- http://www.asminternational.org/content/ASM/StoreFiles/ACF512C.PDF
- http://www.fainstruments.com/PDF/rel98a.PDF

Source:
http://nptel.ac.in/courses/112107090/40