Failure Analysis and Prevention: Fundamental causes of failure

This chapter defines the failure and elaborates the conditions for failure of mechanical components. Further, the fundamental causes of failure associated with design, materials, manufacturing and service have been described in detail.

Keywords: Failure analysis, causes of failure, modes of failure, fatigue, creep, SCC, design deficiency, improper material, defective raw material, poor maintenance, improper processing, failure mechanism vs. design criteria

39.1 Introduction

The failure of engineering components frequently leads to disruption in services to the public at large. To avoid reoccurrence of the failure of engineering component during service, it is important that whenever failure occurs, the same is thoroughly investigated to establish primary factor and other important factors that led to failure so that suitable recommendations can be made to avoid similar failure in future. Failure analysis and its prevention needs a systematic approach of investigation for establish the important causes of the failure. Therefore, it is worth to familiarize with fundamental causes of failure of mechanical, general approach to be used for the failure analysis and failure analysis of welded joints.

39.2 Fundamental causes of the failure

In general, an engineering component or assembly is considered to have failed under any of the following three conditions when the component is a) inoperable, b) operates but doesn't perform the intended function and c) operates but safety and reliability is very poor. However, metallurgical failure of a mechanical component can occurs in many ways a) elastic deformation is beyond acceptable limit, b) excessive and unacceptable level of plastic deformation, c) complete fracture has taken place and d) loss of dimension due to wear and tear besides variety of reasons. In two chapters, failure analysis shall be oriented mainly towards the metallurgical failure of mechanical components.

39.2.1 Elastic deformation

Elastic deformation occurs when stiffness of the component is less and the same is primarily determined by modulus of elasticity and cross section. Elastic deformation can lead to the failure of mechanical components especially in high precision assemblies and machinery where even small elastic deformation under operating conditions is not acceptable.

39.2.2 Plastic deformation

Excessive plastic deformation of the mechanical components can lead to the failure in two conditions a) externally applied stress is beyond the yield strength limit and b) component is subjected to applied stress lower than yield stress but exposed to high temperature conditions enough to cause creep. Both the cases should be handled using different approaches. To avoid the failure by plastic deformation owing to externally applied stress more than yield strength, the cross section should be designed after taking proper factor of safety and considering the yield strength of materials of which component is to be made. For mechanical components that are expected to be exposed in high temperature creep resistant materials should be selected so that under identical load condition, low steady state creep rate of creep resistant materials can allow desired longer creep life.

39.2.3 Fracture

Fracture of mechanical components is usually caused by a) overloading, b) fatigue and c) stress rupture.

Failure due to overloading can occur in many ways such as accidental loading, gradual reduction in load resisting cross sectional area of component due to wear and tear, deterioration in mechanical properties of component due to unfavorable metallurgical transformations during service. To avoid failure due to overloading well thought out design should be developed in light prevailing technological understanding and stress calculations while regular monitoring the condition of component during the service should also be done using suitable techniques and proper inspection and testing schedules.

39.2.4 Fatigue, SCC and Creep

The catastrophic fractures due to fatigue take place without any plastic deformation. The fatigue fracture occurs only when the extent of variation of the load on the component in respect of the loading parameters like stress range, stress amplitude, range of stress intensity factor and maximum stress, is large enough and type of load is mainly tensile or shear. As first stage of fatigue, crack nucleation and subsequent table growth of the crack during fatigue can occur only under tensile and shear load by mode I and mode II or mode III respectively. Fatigue failure can occur not just in components with stress raiser and internal defects but also in well polished component having uniform cross-section. However, fatigue life of the components having stress raiser and defects is generally found lower than those of smooth surface and uniform cross section. Engineering components that are expected to experience the fatigue loading are designed for specific life e.g. 1 million load cycles, 2 million load cycles, 10 million load cycles and infinite life. The fatigue life (Number of load cycle) of a weld joint is primarily decided by the stress range for a given joint configuration. Accordingly, weld cross section is designed to have stress range within the specified limit for typical particular designed fatigue life. Fracture surface of a component failed by fatigue exhibits concentric circular arcs usually called beach marks.

Stress rupture is another mechanism causing fracture of those components which are subjected to high temperature exposure at high stresses. The stress rupture is third and last stage of the creep where creep takes place at increasing rate as function of time by grain boundary sliding mechanism that nucleates voids and subsequently coalescence of voids lead to fracture. Generally, the surface of a component subjected to stress rupture has many cracks and severe necking near the fracture surface which can be seen even by naked eyes.

39.2.5 Loss of Dimension

Loss of dimension takes placed primarily due to removal of the material from the functional surface by variety of wear mechanisms such as abrasion, adhesion, corrosion erosion etc. Gradual loss of the material from the functional surface eventually can lead to reduction in load resisting cross sectional area to such an extent that failure takes place by any of the above mentioned mechanisms like excessive elastic deformation, plastic deformation, overloading, fatigue, creep or stress rupture singly or in combination with other mechanisms. Moreover, the resistance to wear of materials by a particular mechanism is determined by a combination of mechanical and chemical properties of materials.

39.3 Fundamental Causes of failure

The failure of an engineering component in actual working conditions can occur due to very large of factors related with design, materials, manufacturing, service conditions etc. To have systematic understanding on various factors which can lead to metallurgical failure of engineering components, these can be groups under following headings:

- ☑ Improper design
- ☑ Improper selection of materials
- ☑ Defects and discontinuities in metal itself
- ☑ Improper processing of materials
- ☑ Poor service conditions
- ☑ Poor assembling
- ☑ Poor maintenance

39.3.1 Lack of Design

A deficient design frequently causes failure of engineering components under external load. The deficiency in design of a component can be in various forms such as presence of stress raisers owing to sharp change in cross section, changing the design without proper consideration of its influence on stress distribution especially in high stress areas of the component, duplicating a successful design for more severe loading conditions, design is developed without full knowledge of stress conditions owing to complexity of the geometry and inability to use proper criteria for designing the engineering components.

It is believed that in general more than 50% of the metallurgical failures of engineering components occur due to localization of the stresses in presence of stress raisers such as sharp fillets, notches, keyways, holes etc. Localization of the stress initiates the cracks and facilitates their propagation hence premature fracture is encouraged by presence of stress raisers. Fatigue failure is mostly triggered by these stress raisers present either at the surface or in sub-surface region.

Premature failures are also observed when management encouraged by excellent performance of an engineering component with one system decides to put the same component on some other similar kind of system but of higher capacity without giving full consideration to the stress analysis which will be developed in the component on the new system. In new conditions may not be compatible to the same components in respect of material, design, and service conditions etc. which can lead to premature failure.

Sometimes even slight modification in design made to facilitate the manufacturing at the shop floor either (in absence or ambiguity in design specification) can lead to excessive stress concentration and so the premature failure engineering components.

A deficient design can also results from important factors like inability to calculate the type and magnitude of stresses accurately and dependence of designer on under of tensile data for the design purpose which may not always be equally relevant. Designers frequently also come across the situation when accurate calculations and clear analysis of stress (under prevailing technological understanding and capabilities) is not practicable due to complexity in geometry of the component.

39.3.3 Improper selection of the materials

Selection of a material for developing the design of a mechanical component during service in light of operating conditions should be based on expected failure mechanisms such as ductile or brittle fracture, creep, fatigue, wear etc. For each type of expected failure mechanism a combination of the mechanical, physical and chemical properties should be possessed by the material to be selected for developing a design. For example, if failure of a component is expected to occur by excessive plastic deformation at room temperature and high temperature conditions then yield strength and creep respectively will be important criterion for design. Similarly, if failure of a component is expected to occur by fracture under overloads, fluctuating loads and impact loads then ultimate strength, endurance strength and impact strength respectively should be considered for design purpose. Deficient material selection can occur due to reliance on tensile data for selection of materials, and inability to select of metal in light of the expected failure mechanism and so as to develop suitable criteria for the design purpose. The problem of the materials selection is further complicated when the performance of materials varies as function of time e.g. creep, corrosion, embrittlement etc.

The selection of the material for design purpose is still being made on the basis of the tensile data available in metal hand books despite of the fact that tensile data does not correctly reflect the performance of the materials under different types of load and service conditions. The criteria for the selection of metal for designing a component for a particular service conditions must be based on the expected failure mechanism. Practically there are no fixed criteria for selection of metal while designing the component. Design criteria for working condition of each component should be analyzed carefully and then based expected failure mechanism suitable design criteria may be developed. Only as a guide following table shows few failure mechanisms and the corresponding design criteria that may be useful for designing of the engineering component.

S. No.	Failure mechanism	Design criteria
1	Ductile fracture	Yield strength (in tension, compression, shear as per type of load)
2	Brittle fracture	Fracture toughness (critical stress intensity factor K_{1c}), Izode / Charpy notch toughness, ductility, ductile to brittle transition temperature
3	Fatigue	Endurance limit / fatigue strength with stress raiser, hardness
4	Thermal fatigue	Ductility, peak plastic strain (under operating conditions)
5	Creep	Creep rate at given temperature
6	Plastic deformation	Yield strength
7	Stress corrosion cracking	K_{1SCC}, corrosion resistance to specific environment

39.3.3 Presence of defects and discontinuities in raw/stock metal

Metal being used for fabrication of an engineering component may be deficient in many ways depending upon the thermal and mechanical stresses experienced by it during manufacturing steps used for developing the stock. For example rods, plates, and flats produced by bulk deformation based processes like rolling, forging and extrusion may have unfavorable flow of grains, surface cracks etc. while castings may have blow holes, porosity and dissolved gases in solid state. Components developed using such raw materials and stocks having internal discontinuity and minute surface defects generally offer poor mechanical performance especially under fatigue load conditions as these discontinuities provide easy path for fracture. Therefore, raw materials away from fracture location and near the fracture surface of the failed part must be studied using suitable techniques. To identify the presence of such discontinuities in raw/stock material more attention should be paid to the location wherefrom cracks have grown to cause fracture.

39.3.4 Unfavorable manufacturing processing conditions

A wide range of manufacturing processes are used for obtaining the desired size, shape and properties in stock material which includes primary and secondary shaping processes such as castings, forming, machining and welding apart from the processes like heat treatment, case hardening, surface coating etc. that are primarily designed to impart the desired combination of properties either at the surface or core of the raw materials as dictated by the requirement of the applications. The selection of inappropriate combination of the process parameters for each of above mentioned manufacturing processes can lead to development of discontinuities, defects, unfavorable transformation and metallurgical changes and so deterioration in the performance of final product during the service. These imperfections and discontinuities are mostly process specific and can exist in variety of forms due to improper selection of manufacturing process and their parameters. Therefore, due care must be taken by failure analyst to investigate the presence of any defect, discontinuity or unfavorable features in end produced by manufacturing processes and failed prematurely during the service. Presence of any undesirable feature or discontinuity in failed component not just near the fracture surface but also in new one or at the location away from the fracture surface indicates selection of inappropriate manufacturing process conditions. Further, to establish the reason for development of discontinuities and defects, manufacturing process and its parameters should be analyzed carefully to see whether these were compatible with the raw material or not. Hence, the failure analyst or investigation team members must have expertise in materials and manufacturing process in question in order to establish the cause of failure owing to deficiency in manufacturing stage of material. Just to have an idea, few manufacturing processes along with commonly found defects and discontinuities that can be potential sources of the failure occurring due to abused manufacturing condition have been described in the following sections.

Forming and forging

These are bulk deformation based groups of manufacturing processes in which desired size and shape is obtained by applying mostly compressive, shear and tensile force to ensure the plastic flow of metal as per needs. In manufacturing of defect and discontinuity free formed/forged products, the ductility of the raw material plays a very crucial role. Forming/forging can be performed either at room temperature or elevated temperature according to the ductility and yield strength of the raw material. To increase the ductility and reduce yield strength so as to facilitate bulk deformation is commonly performed at high temperature. Apart from ductility and temperature, the rate of deformation also significantly determines the success of bulk deformation based processes. Lack of ductility owing to inappropriate stock temperature and excessively high rate of deformation can lead to cracks and other continuities in end product.

Machining

Machining is a secondary shaping process and is also considered as negative process as unwanted material is removal form stock materials to get the desired size and shape. Further, the material from the stock is removed in the form of small chips by largely shear mechanism. However in some of the advanced machining processes the application of the localized intense heat is also used for removing the material from the stock by melting and ablation. Improper machining procedure including unsuitable selection of machining process, tool, cutting fluid, process parameters etc. can lead to development of undesirable features such as feed marks, overheating, decarburization, residual stresses and loss of alloying elements from the surfaces of the machined components. These can act as a source of stress raiser and provide easy site for nucleation of the cracks, softening of materials due to loss of alloying element. In case, failure triggered by discontinuities generated during machining, the failure analyst should look into the compatibility of machining procedure for a given material to establish the cause of the failure and make suitable recommendations to avoid the reoccurrence of the similar failure.

Welding

The development of a joint by welding and allied processes like brazing and soldering, thermal spraying etc. generally involves application of localized heat, pressure or both, with or without filler. However, the weld joint itself is frequently considered as discontinuity owing to presence of heterogeneity in respect of the mechanical, chemical, structural properties and residual stress state a compared to the base metal or the components being joined besides the existence of weld discontinuities within the acceptable limit in form of notches, porosities, poor weld bead profile, cracks etc. Owing to presence of the above undesirable features in weld joints joint efficiency is generally found less than 100%. Therefore, weld joints are not considered very reliable for critical applications. The most of the weld discontinuities are welding process and base metal specific. If failure has been triggered by weld discontinuities then failure analysis must look into welding procedure specification and work man ship related aspects to establish the causes of failure.

Heat treatment

Heat treatment of many metal systems like iron, aluminium, magnesium, copper, titanium etc is a common industrial practice to obtain the desired combination of properties as per needs of the end application of the component. Heat treatment mostly involves a sequence of the controlled heating up to predetermined temperature followed by holding for some time (soaking) and then controlled cooling. Each step of heat treatment from heating to the controlled cooling is determined by the purpose of heat treatment, method of manufacturing, size and shape of the component. Thus, inappropriate selection of any steps of heat treatment namely heating rate, peak temperature, soaking time and cooling rate can result in unfavorable metallurgical transformation and mechanical properties that can eventually lead to failure. For example, overheating of hardenable steel components for prolong duration can cause oxidation, decarburization, excessive grain growth, dissolution of the fine precipitates, increased hardenability, high temperature gradient during quenching and thus increased cracking tendency. Similarly, unfavorable cooling rate can produce undesirable combination of the properties which may be lead to poor performance of the component during the service. Therefore, hardness test on the failed component is commonly performed to conform of heat treatment was done properly. In case, failure investigation indicating that it was triggered by unfavorable properties and structure generated during heat treatment, then failure analyst should look into the compatibility of heat treatment parameters with material, size and shape of the component to establish the cause potential of the failure and make suitable recommendations.

Chemical cleaning

Surface of the engineering components is frequently cleaned using mild hydrogen based chemical and acids. Sometimes, during the cleaning hydrogen gets diffused into the sub-surface region of the metal if the same is not removed by post cleaning heat treatment or followed by development of the coatings immediately then hydrogen is left in the subsurface zone which can subsequently be the cause of the failure by hydrogen embrittlement or cold cracking. If the failure investigation indicates the possibility of hydrogen embrittlement or cold cracking then failure analyst should look into the detailed procedure used for chemical cleaning of the failed engineering components besides measuring the hydrogen dissolved in subsurface region using suitable method.

39.3.5 Poor assembling

Error in assembly can result due to various reasons such as ambiguous, insufficient or inappropriate assembly procedure, misalignment, poor workmanship. Sometimes, failures are also caused by the inadvertent error performed by the workers during the assembly. For example, failure of nut and stud assembly (used for holding the car wheel) by fatigue can occur owing to lack of information regarding sequence of tightening the nuts and torque to be used for tightening purpose; under such conditions any sort of loosening of nut which is subjected to external load will lead to fatigue failure.

39.3.6 Poor service conditions

Failure of an engineering component can occur due to abnormal service condition experienced by them for which they are not designed. These abnormal service conditions may appear in the form of exposure of component to excessively high rate of loading, unfavorable oxidative, corrosive, erosive environment at high or low temperature conditions for which it has not been designed. The contribution of any abnormality in service conditions on the failure can only be established after thorough investigation regarding compatibility of the design, manufacturing (such as heat treatment) and material of the failed components with condition experienced by them during the service. To avoid any catastrophic failure of critical components during the service usually well planned and thought out maintenance plan is developed which involves periodic inspection and testing of the components that is crucial for uninterrupted operations of entire plant. For a sound maintenance strategy, it is important that procedure of inspection and testing methods developed in such a way that they indicate the conditions of the component from the failure tendency point of view by the anticipated and expected failure mechanism. Any inspection and testing that doesn’t give information about the condition of the components with respect to failure tendency by the anticipated failure mechanism should considered redundant. For example, a typical sound test is conducted in Indian railways on arrival training at each big station for indentifying the assembly condition; similarly, the soundness of the earthen pot is also assessed by sound test.

39.3.7 Poor maintenance strategy

The failure of many moving mechanical components takes place due to poor maintenance plan. A well developed maintenance plan indicating each and every important step to be used for maintenance such what, when, where, who and how for maintenance, is specified explicitly. Lack of information on proper schedule of maintenance, procedure of the maintenance, frequently causes premature failure of moving components. For example, absence of lubrication of proper kind in right quantity and conditions frequently leads to the failure of assemblies working under sliding or rolling friction conditions.

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