A Technical White Paper

Failure and Root Cause Analysis by TCR Engineering

Investigating Material and Component Failure

Written by TCR Engineering Services Technical Team
Published July 2004

Abstract

This white paper provides an extensive study into the different types of material and component failures observed in industrial enterprises. This white paper also provides solutions to manufacturing problems and advises towards selecting the appropriate materials to improve overall product quality, reduce costs, and enhance customer satisfaction. It also discusses welding problems and offers solutions to improve the weld process.

CONTENTS

INTRODUCTION

Failure analysis is an engineering approach to determining how and why equipment or a component has failed. Some general causes for failure are structural loading, wear, corrosion, and latent defects. The goal of a failure analysis is to understand the root cause of the failure so as to prevent similar failures in the future.

In addition to verifying the failure mode it is important to determine the factors that explain the "how and why" of the failure event. Identifying the root cause of the failure event allows us to explain the "how and why" of failure.

Common causes of failure include:

- Misuse or Abuse
- Assembly errors
- Manufacturing defects
- Improper maintenance
- Fastener failure
- Design errors
- Improper material
- Improper heat treatments
- Unforeseen operating conditions
- Inadequate quality assurance
- Inadequate environmental protection/control
- Casting discontinuities

Whether a product defect is due to a forging, casting, or welding defect a failure investigation can identify the root cause of the failure and determine the pertinent structural defect that caused the failure.

Failure investigation are performed by TCR Engineering Services on bearing, bridge, valve, bolt, boiler, gear, shaft, fastener, tank, medical devices, and/or other industrial or consumer products.

The technical staff at TCR has performed manufacturing or metallurgical failure analysis on ASME boiler and pressure vessels, Aircraft /Aerospace, Gas turbine engine components, Oil and gas transmission pipelines, Food processing equipments, Heat exchangers, Medical supplies, Automotive components, Refineries, Petrochemical plants, Offshore structures, Industrial machinery, Weldments and Ships.

TYPICAL ROOT CAUSE METALLURGICAL FAILURE MECHANISMS

Fatigue Failures

Metal fatigue is caused by repeated cycling of the load below its static yield strength. It is a progressive localized damage due to fluctuating stresses and strains on the material. Metal fatigue cracks initiate and propagate in regions where the strain is most severe. The process of fatigue consists of three stages - Initial crack initiation, Progressive crack growth across the part, and Final sudden fracture of the remaining cross section.

Because most engineering materials contain discontinuities most metal fatigue cracks initiate from discontinuities in highly stressed regions of the component. The failure may be due to the discontinuity, design, improper maintenance or other causes.

The most effective method of improving fatigue performance and preventing failure is by making improvements in design:

- Eliminate or reduce stress raisers by streamlining the part
- Avoid sharp surface tears resulting from punching, stamping, shearing, or other processes
- Prevent the development of surface discontinuities during processing.
- Reduce or eliminate tensile residual stresses caused by manufacturing.
- Improve the details of fabrication and fastening procedures

Corrosion Failures

Corrosion is chemically induced damage to a material that results in deterioration of the material and its properties. This may result in failure of the component. Several factors should be considered during a failure analysis to determine the affect corrosion played in a failure. Examples are listed below:

- Type of corrosion
- Corrosion rate
- The extent of the corrosion
- Interaction between corrosion and other failure mechanisms

Corrosion is a normal, natural process. Corrosion can seldom be totally prevented, but it can be minimized or controlled by proper choice of material, design, coatings, and occasionally by changing the environment. Various types of metallic and nonmetallic coatings are regularly used to protect metal parts from corrosion. Identification of the metal or metals, environment the metal was subjected to, foreign matter and/or surface layer of the metal is beneficial in failure determination.

Uniform Corrosion

Uniform or general corrosion is typified by the rusting of steel. Other examples of uniform corrosion are the tarnishing of silver or the green patina associated with the corrosion of copper.

General corrosion is rather predictable. The life of components can be estimated based on relatively simple immersion test results. Allowance for general corrosion is relatively simple and commonly employed when designing a component for a known environment.

Some common methods used to prevent or reduce general corrosion are Coatings, Inhibitors, Cathodic protection and Proper materials selection.

Pitting Corrosion

Pitting is a localized form of corrosive attack. Pitting corrosion is typified by the formation of holes or pits on the metal surface. Pitting can cause failure due to perforation while the total corrosion, as measured by weight loss, might be rather minimal. The rate of penetration may be 10 to 100 times that by general corrosion.

Pits may be rather small and difficult to detect. In some cases pits may be masked due to general corrosion. Pitting may take some time to initiate and develop to an easily viewable size.

Pitting occurs more readily in a stagnant environment. The aggressiveness of the corrodent will affect the rate of pitting. Some methods for reducing the effects of pitting corrosion are listed below:

- Reduce the aggressiveness of the environment
- Use more pitting resistant materials
- Improve the design of the system

Crevice Corrosion

Crevice corrosion is a localized form of corrosive attack. Crevice corrosion occurs at narrow openings or spaces between two metal surfaces or between metals and nonmetal surfaces. A concentration cell forms with the crevice being depleted of oxygen. This differential aeration between the crevice (microenvironment) and the external surface (bulk environment) gives the crevice an anodic character. This can contribute to a highly corrosive condition in the crevice such as Flanges, Deposits, Washers, Rolled tube ends, Threaded joints, O-rings, Gaskets, Lap joints and/or Sediments.

Some methods for reducing the effects of crevice corrosion are listed below:

- Eliminate the crevice from the design
- Select materials more resistant to crevice corrosion
- Reduce the aggressiveness of the environment

Galvanic Corrosion

Galvanic corrosion is frequently referred to as dissimilar metal corrosion. Galvanic corrosion can occur when two dissimilar materials are coupled in a corrosive electrolyte. An illustration of galvanic corrosion would be joining two dissimilar metals in electrical contact in seawater.

In a galvanic couple, one of the metals in the couple becomes the anode and the other metal becomes the cathode. The less noble material becomes the anode. The anodic metal corrodes faster than it would all by itself. The cathodic metal corrodes slower than it would all by itself.

Many boaters use this knowledge to their benefit. Sacrificial zinc anodes are commonly used to protect metal components on boats. The zinc anode corrodes preferentially there by protecting the boat component. The zinc anodes are maintained and replaced as required to insure continued protection. Other alloys are also used as sacrificial anodes. Aluminum or magnesium sacrificial anodes provide better protection in some cases.

Stress Corrosion Cracking

Stress corrosion cracking is a failure mechanism that is caused by environment, susceptible material, and tensile stress. Temperature is a significant environmental factor affecting cracking. Aluminum and stainless steel are well known for stress corrosion cracking problems. However, all metals are susceptible to stress corrosion cracking in the right environment.

For stress corrosion cracking to take place all three conditions must be met simultaneously - The component needs to be in a particular crack promoting environment, the component must be made of a susceptible material, and there must be tensile stresses above some minimum threshold value. An externally applied load is not required as the tensile stresses may be due to residual stresses in the material. The threshold stresses are commonly below the yield stress of the material.

Stress corrosion cracking is an insidious type of failure as it can occur without an externally applied load or at loads significantly below yield stress. Thus, catastrophic failure can occur without significant deformation or obvious deterioration of the component. Pitting is commonly associated with stress corrosion cracking phenomena.

There are several methods to prevent stress corrosion cracking. One common method is proper selection of the appropriate material. A second method is to remove the chemical species that promotes cracking. Another method is to change the manufacturing process or design to reduce the tensile stresses. TCR can provide engineering expertise to prevent or reduce the likelihood of stress corrosion cracking in your components.

Ductile and Brittle Metal Failures

Ductile metals experience observable plastic deformation prior to fracture. Brittle metals experience little or no plastic deformation prior to fracture. At times metals behave in a transitional manner - partially ductile/brittle.

Ductile fracture is characterized by tearing of metal and significant plastic deformation. The ductile fracture may have a gray, fibrous appearance. Ductile fractures are associated with overload of the structure or large discontinuities.

Ductile fracture has dimpled, cup and cone fracture appearance. The dimples can become elongated by a lateral shearing force, or if the crack is in the opening (tearing) mode.

Brittle fracture is characterized by rapid crack propagation with low energy release and without significant plastic deformation. The fracture may have a bright granular appearance. The fractures are generally of the flat type and chevron patterns may be present.

Brittle fracture displays either cleavage (transgranular) or intergranular fracture. This depends upon whether the grain boundaries are stronger or weaker than the grains.

The fracture modes (dimples, cleavage, or intergranular fracture) may be seen on the fracture surface and it is possible all three modes will be present of a given fracture face.

Hydrogen Embrittlement Failures

When tensile stresses are applied to hydrogen embrittled component it may fail prematurely. Hydrogen embrittlement failures are frequently unexpected and sometimes catastrophic. An externally applied load is not required as the tensile stresses may be due to residual stresses in the material. The threshold stresses to cause cracking are commonly below the yield stress of the material.

High strength steel, such as quenched and tempered steels or precipitation hardened steels are particularly susceptible to hydrogen embrittlement. Hydrogen can be introduced into the material in service or during materials processing.

Tensile stresses, susceptible material, and the presence of hydrogen are necessary to cause hydrogen embrittlement. Residual stresses or externally applied loads resulting in stresses significantly below yield stresses can cause cracking. Thus, catastrophic failure can occur without significant deformation or obvious deterioration of the component.

Very small amounts of hydrogen can cause hydrogen embrittlement in high strength steels. Common causes of hydrogen embrittlement are pickling, electroplating and welding, however hydrogen embrittlement is not limited to these processes.

Hydrogen embrittlement is an insidious type of failure as it can occur without an externally applied load or at loads significantly below yield stress. While high strength steels are the most common case of hydrogen embrittlement all materials are susceptible.

Liquid Metal Embrittlement Failures

Liquid metal embrittlement is the decrease in ductility of a metal caused by contact with liquid metal. The decrease in ductility can result in catastrophic brittle failure of a normally ductile material. Very small amounts of liquid metal are sufficient to result in embrittlement.

Some events that may permit liquid metal embrittlement under the appropriate circumstances are Brazing, Soldering, Welding, Heat treatment, hot working and/or Elevated temperature service.

In addition to an event that will allow liquid metal embrittlement to occur, it is also required to have the component in contact with a liquid metal that will embrittle the component.

The liquid metal can not only reduce the ductility but significantly reduce tensile strength. Liquid metal embrittlement is an insidious type of failure as it can occur at loads below yield stress. Thus, catastrophic failure can occur without significant deformation or obvious deterioration of the component.

Intergranular or transgranular cleavage fractures are the common fracture modes associated with liquid metal embrittlement. However reduction in mechanical properties due to decohesion can occur. This results in a ductile fracture mode occurring at reduced tensile strength. An appropriate analysis can determine the effect of liquid metal embrittlement on failure.

High Temperature Failures

Creep occurs under load at high temperature. Boilers, gas turbine engines, and ovens are some of the systems that have components that experience creep. An understanding of high temperature materials behavior is beneficial in evaluating failures in these types of systems.

Failures involving creep are usually easy to identify due to the deformation that occurs. Failures may appear ductile or brittle. Cracking may be either transgranular or intergranular. While creep testing is done at constant temperature and constant load actual components may experience damage at various temperatures and loading conditions.

High temperature progressive deformation of a material at constant stress is called creep. High temperature is a relative term that is dependent on the materials being evaluated.

CASTING FAILURE ANALYSIS

Several factors affect the quality of metal castings, such as:

- Coefficients of thermal conductivity
- Thermal expansion and contraction,
- Chemistry
- Precision of molds and dies
- Shrinkage allowances
- Dryness of molds
- Casting design
- Method of pouring liquid metal
- Design of gates and risers

Imperfections in castings may not be of concern for many types of service. They are commonly referred to as casting defects since castings are not perfect. This is unfortunate as imperfections beyond engineering design specifications should be considered defects, while imperfections within engineering design specifications should not be considered defects.

Some casting imperfections may have no effect on the function or service life of castings. Many imperfections are easily corrected by blast cleaning or grinding. Other imperfections may be acceptable in some locations.

It is not uncommon for engineers to zone a casting drawing. Depending on the criticality of the location or zone the same imperfection would be judged acceptable in one location while unacceptable in another location.

Casting failures can be due to various causes. Improper loading or environment may contribute to the cause of failure. Casting imperfections may or may not contribute to the cause of failure. Some imperfections may be commonly occurring discontinuities or anomalies that are normally expected to be present in castings. Other imperfections are casting defects that result in failure of the casting. Failure analysis can determine the cause of the casting failure and determine if a casting imperfection was the primary or contributing cause of failure.

Casting failures can be due to various causes. Some castings fail due to design deficiencies, while other castings fail due to casting deficiencies. Some common casting deficiencies are Inclusions, Porosity (blow holes, pinholes), Cold Cracking, Hot Cracking, Cold Shuts, Surface irregularities, Distortion, and/or Improper composition.

BOILER FAILURES

Boilers are used to heat water for industrial purposes, and to produce steam in power generating plants. Steels, cast irons, stainless steels and high temperature alloys are used to construct various boiler components.

Some of the common failures associated with boilers are Pitting, Erosion, Stress corrosion cracking, Hydrogen damage, Vibration, Stress rupture, Corrosion fatigue, Caustic gouging, Distortion, Thermal fatigue, Acid dew point corrosion, Over temperature, Fatigue, Maintenance damage, Material flaws and/or Welding flaws.

Design defects, fabrication defects, improper operation and improper maintenance/water treatment are some common causes for boiler failures. Tube rupture and corrosion of the tubes are among the frequent problems with steam boilers.

Failure analysis can determine the effects corrosion, over heating, scaling, fatigue, erosion, stress corrosion cracking, hydrogen, welding, or other factors may have contributed to boiler failure. Elevated temperature and corrosion failures are common failure modes for boilers. Additionally, mechanical failures due phenomena such as fatigue or wear occur as well. Some of the most common failures modes for boilers used for steam generating include overheating, fatigue or corrosion fatigue, corrosion, stress corrosion cracking, and defective or improper materials.

HEAT EXCHANGER FAILURE

Heat exchangers are commonly used to transfer heat from steam, water, or gases, to gases, or liquids. Some of the criteria for selecting materials used for heat exchangers are corrosion resistance, strength, heat conduction, and cost. Corrosion resistance is frequently a difficult criterion to meet. Damage to heat exchangers is frequently difficult to avoid.

The tubes in a heat exchanger transfer heat from the fluid on the inside of the tube to fluid on the shell side (or vice versa). Some heat exchanger designs use fins to provide greater thermal conductivity. To meet corrosion requirements, tubing must be resistant to general corrosion, pitting, stress-corrosion cracking (SCC), selective leaching or dealloying, and oxygen cell attack in service.

Some common causes of failures in heat exchangers are listed below:

- Pipe and tubing imperfections
- Welding
- Fabrication
- Improper design
- Improper materials
- Improper operating conditions
- Pitting
- Stress-corrosion cracking (SCC)
- Corrosion fatigue
- General corrosion
- Crevice corrosion
- Design errors
- Selective leaching, or dealloying
- Erosion corrosion

PRESSURE VESSEL FAILURE

Pressure vessels and pressure piping used in refineries, chemical processing plants, water treatment systems of boilers, low pressure storage tanks commonly used in process, pulp and paper and electric power plants operate over a broad range of pressures and temperatures and experience a variety of operating environments. Shell, head, attachments, and piping are some of the components that commonly fail. Some common types of failures are listed below:

- Cracking
- Explosion
- Rupture
- Leakage
- Faulty design
- Improper fabrication practice
- Faulty inspection
- Damage during shipment and storage
- Damage during field fabrication and erection
- Specifying or using improper materials
- Corrosion
- Stress corrosion cracking
- Hydrogen embrittlement
- Creep and stress rupture
- Fatigue
- Over pressure
- Over temperature
- Welding problems
- Discontinuities
- Stress raisers
- Improper heat treatment
- Caustic embrittlement.
- Brittle fractures
- Erosion

Design errors, fabrication errors, corrosion, and improper maintenance are some of the causes of failures. Brittle fracture, stress corrosion cracking, fatigue, welding problems, erosion, creep, stress rupture, and hydrogen embrittlement are among some of the common failure modes found in pressure vessel components. Failure analysis can identify the root cause or causes that have contributed to your pressure vessel failure.

PIPELINE FAILURE

Gas and oil pipelines have established an impressive safety record over the years. However, failures have occurred for an assortment of reasons. Some of the causes of failure are identified in this commentary.

Since the 1940s, all of the oil and gas transmission lines have been built by welding. In general, American Petroleum Institute (API) 5L specification steels are used in pipelines. Pipeline wall thicknesses are established on the pressure in the line and on the allowable hoop stress levels for the material. The allowable stress levels for gas pipelines vary based on the location of the pipeline and are regulated by the U.S. Department of Transportation (DOT).

Pipelines are pressure tested in addition to nondestructive testing prior to being put into service. Normally, pipelines are hydrostatically stressed to levels above their working pressure and near their specified minimum yield strength. This pressure is held for several hours to ensure that the pipeline does not have defects that may cause failure in use. This proof test of pipelines provides an additional level of confidence that is not found in many other structures.

Some of the causes of pipeline failures are listed below:

- Mechanical damage
- Fatigue cracks
- Material defects
- Weld cracks
- Incomplete fusion
- Improper repair welds
- Incomplete penetration
- External or internal corrosion
- Hydrogen blistering

Mechanical damage normally consists of gouges and dents. They generally are created by excavation or handling equipment during construction.

LIFTING EQUIPMENT FAILURES

Lifting equipment is used to raise, lower, and otherwise transport or manipulate components and equipment in a localized area. There are several types of components used in lifting equipment. Some of these components are listed below:

- Shafts
- Brakes
- Chains
- Gears
- Wire rope
- Hooks
- Couplings
- Bearings
- Wheels

Some typical failure mechanisms in lifting equipment are due to fatigue, wear, corrosion, and ductile or brittle fracture. Components may fail from one or more of these mechanisms or due to other failure mechanisms.

Insuring the lifting equipment is not overloaded, in addition to appropriate inspections, maintenance, removal from service, and repair can help eliminate many failures. The leading cause of lifting equipment failures are due to improper operation. Unfortunately, overloading of a lifting mechanism is not an uncommon practice.

Wear is the most readily recognized condition by operators and maintenance personnel. Excessive wear is usually a relatively easy condition to correct. However, complete elimination of wear in components used in lifting equipment is not feasible.

Fatigue is a more insidious type of failure mechanism as it is more difficult to detect. Periodic inspection by properly trained inspection and maintenance personnel can avert fatigue failures of critical components.

Some other reasons for failures include the following:

- Design issues
- Material selection
- Assembly errors
- Unacceptable material properties
- Improper manufacturing processing
- Improper maintenance or repair

FASTENER FAILURES

Threaded fasteners are considered to be any threaded part that may be removed after assembly. Nuts and bolts are commonly used threaded fasteners. Rivets, pin fasteners, and special purpose fasteners are some other commonly used fasteners. Some common locations for fastener failures are listed below:

- Head to shank failure
- First thread inside the nut
- Transition from thread to shank

A fastener may experience either static loading or fatigue loading. Static loading may be tension, shear, bending, or torsion. These static loading conditions may occur in combination. One example of fatigue loading is vibration. In addition to overload and fatigue, some other common reasons for fastener failures include environmental issues, manufacturing discrepancies, and improper use or incorrect installation.

Some common questions concerning fasteners are listed below:

- How were the fasteners torqued?
- In what order were fasteners tightened?
- What is the best way to verify the torque on fasteners?
- How does torque value vary over time?

Fatigue is one of the most common failure modes for threaded fasteners. Fretting failures may result from small movements between adjacent surfaces. Additionally, atmospheric corrosion, liquid immersion corrosion, galvanic corrosion, crevice corrosion, stress corrosion cracking, and hydrogen damage may contribute to fastener failure

Material selection, heat treatment, cutting or rolling threads, manufacturing, assembly, and design are some of the factors that effect fastener failures. Failure analysis can determine the cause of the fastener failure and determine the primary or contributing causes of fastener failure.

GEAR FAILURES

Gears can fail in several different ways. Increased vibration and noise level from the equipment is commonly associated with gear failures.

Cast irons, nonferrous alloys, powdered-metals, and steels are materials used in gears. Some common types of gears are listed below:

- Worm gears
- Herringbone gears
- Helical gears
- Spur gears
- Bevel gears
- Internal gears

Idealistically, gears make contact at points or along lines. In actual service, gears make contact in small areas or along narrow bands. Each part of the gear tooth surface is only in contact for a short duration of time. Gear tooth surface alignment affects the loading in use. Lubrication and temperature also affect gear teeth as well.

Some of the failure modes in gears are listed below:

- Fatigue
- Wear
- Stress Rupture
- Impact

Tooth bending fatigue, contact fatigue, and thermal fatigue are among some of the types of fatigue failures in gears. Abrasive wear and adhesive wear are the common modes of wear failure of gears. Material, manufacturing, engineering, service environment and heat treatment are some of the causes of gear failures. TCR can provide failure analysis services to determine the cause of your gear failure.

ROLLER AND BALL BEARINGS

Roller and ball bearings are commonly used in various components. The rollers or balls are placed in between two raceways. This allows relative motion by rotation of these pieces.

Some common types of bearings used include:

- Radial contact
- Angular contact
- Thrust
- Cylindrical
- Needle
- Tapered
- Spherical

Today's improved materials provide greater reliability of bearings in use. High temperature materials are available for bearing fabrication, but the practical limit is really determined by the breakdown temperature of the lubricant. Synthetic lubricants are commonly used in high temperature applications.

Bearing load ratings are established on the results of laboratory rolling contact fatigue tests. Real world conditions such as misalignment, vibration, shock loading, insufficient or inefficient lubrication, extremes of temperature, or contamination, will decrease the life expectancy of the bearings. If these conditions are severe, they may lead to premature failure of the bearings.

Some common characteristics of bearing failures are listed below:

- Wear
- Fretting
- Corrosion
- Indentations
- Electrical pitting
- Smearing
- Cracking
- Flaking

Some of the factors that may lead to bearing failure are improper lubrication, impact loading, vibration, excess temperature, contamination, excessive loading, and misalignment. TCR can provide failure analysis services to determine the cause of your bearing failure.

SHAFT FAILURES

Shafts function in wide ranging service conditions, including corrosive environments, and both very high and very low temperatures. Shafts may experience a range of loading conditions. In general, shafts may experience tension, compression, bending, torsion, or a combination of these loading conditions. Additionally, shafts may experience vibratory stresses.

Wear is a common cause of shaft failure. Abrasive wear is one of the forms of wear failures. Abrasive wear, or abrasion, is caused by the displacement of material from a solid surface due to hard particles or protuberances sliding along the surface. Abrasive wear can reduce the size and destroy the shape of a shaft. Some examples of abrasive wear of shafts are foreign particles such as sand, dirt, metallic particles, and other debris in the lubricant. This debris can damage a shaft by wear.

One of the more common causes of shaft failure is due to fatigue. Fatigue failures commonly start at a stress raiser. Other forms of fracture also commonly occur at stress raisers as well. Some typical features in shafts that act as stress raisers are listed below:

- Corners
- Keyways
- Grooves
- Press or shrink fits
- Welding defects
- Nicks or notches
- Splines
- Quench cracks
- Localized corrosion
- Arc strikes

Failures may occur due to misalignment. One cause of misalignment is the mismatch of mating parts. Misalignment can be introduced during original assembly of equipment. Misalignment can be introduced after an overall or repair of equipment. Deflection or deformation of supporting components in service may also cause misalignment. Misalignment can cause vibration resulting in a fatigue failure of the shaft.

Some other causes of shaft failures include the following:

Accidental overload, Corrosion, Creep or stress rupture, Brittle fracture, Stress corrosion cracking, Hydrogen embrittlement

CHEMICAL PLANT CORROSION

Corrosion is a significant concern for the chemical processing industry. Corrosion failures can disrupt production or cause unintended release of chemicals into the environment. There are many variables that may affect corrosion in a chemical plant. Some of these variables are listed below:

- Contamination/Impurities
- Quality of water
- Aeration
- Galvanic couples
- Material selection
- Effects of welding
- Stagnation
- Turbulence
- Flow rate, Line size
- Concentration
- Temperature
- Pressure
- Deposits
- Crevices
- Start-Up/Shutdown

Variation from planned operating variables can have a significant effect on expected results. Materials are commonly selected based on past experience, corrosion tests, and the literature.

Engineers need to have a comprehension of the process to understand the appropriate material choices for a given application. Additionally, proper maintenance and process control are essential.

Materials used in chemical plants vary widely depending on the application. Carbon steels, stainless steels, Nickel alloys, Copper alloys, and Titanium are some of the alloys regularly used in chemical processing plants.

Seasonal variation in temperatures and variations due to start-up/shutdown variables are some examples of issues that can cause unanticipated problems in chemical processing plants. It is not uncommon over time for plants to be operated with process variables different than originally planned. It is not uncommon for flow rates or feed stock composition or impurities to significantly vary over time. This may necessitate a change in materials, design, or operating conditions.

PULP AND PAPER INDUSTRY CORROSION

Corrosion issues in the paper industry are normally most significant in the wet process equipment. Various manufacturing steps have there specific corrosion problems. Temperature, chemical constituents, concentration, size and quality of the wood fibers, and metals used in components are some of the factors affecting corrosion in equipment. Paper recycling and environmental concerns regarding chemical releases have required the pulp and paper industry to change their processes.

There is an understandable development of decreasing the total quantity of process water used, by recycling and reusing the water in closed-loop systems. Closure has resulted in increasing concentration of dissolved organic and inorganic solids, a decrease in pH and an increase in operating temperatures. This results in a more significant corrosion environment for the equipment.

Some of the major steps in the pulp and paper industry are listed below:

- Pulp production
- Pulp processing and chemical recovery
- Pulp bleaching
- Stock preparation
- Paper manufacturing

Paper mills have been historically constructed of a mixture of carbon steel and stainless steels components. There has been a trend to use more stainless steel in paper equipment. Stainless steels have there own corrosion concerns. Proper selection of stainless steels and associated welding processes for these new environments are significant issues to the pulp and paper industry.

Some of the corrosion concerns in the pulp and paper industry are listed below:

- Pitting
- Crevice corrosion
- Stress corrosion cracking
- Microbiological attack
- Corrosion of welds
- Corrosion fatigue

FOOD PROCESSING EQUIPMENT FAILURES

Food processing is a large segment of manufacturing sector. Some of the major concerns of the food processing industry are food product quality, health, and sanitation issues. High levels of process control must be maintained. Equipment failure or corrosion deposits that might be tolerated in other industries are unacceptable in the food industry.

Product quality is the primary concern in food processing plants. Equipment reliability and identifying the root cause of equipment failures are significant issues to the food processing industry. Some common causes of equipment failure are listed below:

- Fatigue
- Corrosion
- Manufacturing defects
- Wear
- Design errors
- Improper maintenance or inspection
- Welding defects

Food processing equipment is commonly made of corrosion resistant materials such as stainless steels. When coatings are used in food processing plants, the coatings must be capable of withstanding high pressure cleaning, microbial attack, and antimicrobial additives used to control bacterial formation. Some food processing plants prefer urethane coatings over epoxy coatings as they find they have greater resistance to cleaning compounds.

The corrosion environment in food and beverage plants includes moderate to high concentrations of chlorides. Chlorides are frequently mixed with significant concentrations of organic acids. Water processing equipment in plants can vary from steam heating to brine cooling. Sulfating agents which can produce sulfur dioxide when used to treat foods include sodium sulfite, sodium bisulfite, sodium metabisulfite, potassium bisulfite, and potassium metabisulfite. These sulfating agents are usually corrosive to food processing plant equipment.

Some commonly encountered corrosion issues in food and beverage processing plants are listed below:

Pitting, Crevice corrosion, Stress corrosion cracking, Uniform corrosion, Galvanic corrosion

SHIP FAILURES

The shipping industry is made up of many types of ships. Tankers, carriers, bulk cargo, and container ships comprise a significant portion of vessels used. These ships have various equipment and components that may experience failure. Some examples of failures are listed below:

- Pumps
- Fuel Tanks
- Piping
- Weldments
- Heat exchangers
- Boilers
- Sensors
- Propulsion systems

The consequences of these failures can vary considerably. When failure of a component may affect ship seaworthiness it is generally recommended the owner perform a failure analyses to ensure the future fail safe operation of the vessel. Not all ship failures need a comprehensive failure analysis. At times a preliminary examination will provide enough information to show a simple analysis is adequate. Some common causes of ship failures are listed below:

- Corrosion
- Welding defects
- Improper maintenance
- Fatigue
- Manufacturing defects
- Unforeseen operating conditions
- Inadequate quality assurance

If you need assistance in understanding component failure contract TCR to provide failure analysis engineering services.

WELD FAILURE ANALYSIS

Help eliminate common welding problems and discontinuities such as:

- Weld Discontinuities
- Undercutting
- Excessive melt-through
- Incomplete fusion
- Incomplete joint penetration
- Porosity
- Weld metal cracks
- Heat affected zone cracks

MIG Welding

Gas Metal Arc Welding (GMAW) is frequently referred to as MIG welding. MIG welding is a commonly used high deposition rate welding process. Wire is continuously fed from a spool. MIG welding is therefore referred to as a semiautomatic welding process. MIG Welding Benefits are:

- All position capability
- Higher deposition rates than SMAW
- Less operator skill required
- Long welds can be made without starts and stops
- Minimal post weld cleaning is required

Common MIG Welding Problems are:

- Heavily oxidized weld deposit
- Irregular wire feed
- Burnback
- Porosity
- Unstable arc
- Difficult arc starting

TIG Welding

Gas Tungsten Arc Welding (GTAW) is frequently referred to as TIG welding. TIG welding is a commonly used high quality welding process. TIG welding has become a popular choice of welding processes when high quality, precision welding is required.

In TIG welding an arc is formed between a nonconsumable tungsten electrode and the metal being welded. Gas is fed through the torch to shield the electrode and molten weld pool. If filler wire is used, it is added to the weld pool separately. TIG Welding Benefits are:

- Superior quality welds
- Welds can be made with or without filler metal
- Precise control of welding variables (heat)
- Free of spatter
- Low distortion

Common TIG Welding Problems are:

- Erratic arc
- Excessive electrode consumption
- Oxidized weld deposit
- Arc wandering
- Porosity
- Difficult arc starting

Stick Welding

Shielded Metal Arc Welding (SMAW) is frequently referred to as stick or covered electrode welding. Stick welding is among the most widely used welding processes.

The flux covering the electrode melts during welding. This forms the gas and slag to shield the arc and molten weld pool. The slag must be chipped off the weld bead after welding. The flux also provides a method of adding scavengers, deoxidizers, and alloying elements to the weld metal. Stick Welding Benefits are:

- Equipment used is simple, inexpensive, and portable
- Electrode provides and regulates its own flux

- Lower sensitivity to wind and drafts than gas shielded welding processes
- All position capability

Common Stick Welding Problems are:

- Arc Blow
- Arc Stability
- Excessive spatter
- Incorrect weld profile
- Rough surface
- Porosity

Submerged Arc Welding

Submerged arc welding (SAW) is a high quality, very high deposition rate welding process. Submerged arc welding is a high deposition rate welding process commonly used to join plate. Submerged Arc Welding Benefits are:

- Extremely high deposition rates possible
- High quality welds
- Easily automated
- Low operator skill required

Common Submerged Arc Welding Problems are:

- Solidification Cracking
- Hydrogen Cracking
- Incomplete fusion
- Irregular wire feed
- Porosity

ROOT CAUSE ANALYSIS

Every system, equipment, or component failure happens for a reason. Proper root cause analysis identifies the basic source or origin of the problem. Root cause analysis is a step by step approach that leads to the identification of a fault's first or root cause. There are specific successions of events that lead to a failure. A root cause analysis investigation follows the cause and effect path from the final failure back to the root cause.

Analysis Procedure

The root cause analysis procedure investigates the failure using facts left behind from the initial flaw. By evaluating the remaining evidence after the fault and information from people associated with the incident, the analyst can identify both the contributing and non-contributing causes that caused the event.

TCR collects the data, analyses the data, develops appropriate corrective action, presents the data clearly and generates practical recommendations. Root cause analysis is a tool to better explain what happened, to determine how it happened, and to understand why it happened.

The root cause analysis methodology provides clients specific, concrete recommendations for preventing incident recurrences. TCR identifies the processes and procedures that need changing to improve clients businesses.

Understanding the existing data of the incident, the root cause analysis method allows safety, quality, and risk and reliability managers an opportunity to implement more reliable and more cost effective policies that result in significant, enduring opportunities for improvement. These procedural improvements increase a business' capability to recover from and prevent disasters with both financial and safety consequences.

Preventing Reoccurrence of the Failure

It is not always necessary to prevent the first, or root cause, from happening. It is merely necessary to break the chain of events at any point and the final failure will not occur. Frequently the root cause analysis identifies an initial design problem. Then a redesign is commonly enacted. Where the root cause analysis leads back to a failure of procedures it is necessary to either address the procedural weakness or to develop an approach to prevent the damage caused by the procedural failure.

Our clients understand why root causes are important, have identified and defined inherent problems, and enacted practical recommendations. TCR has extensive engineering and quality assurance experience to provide clients with proven successful techniques to identify the root cause of their problems and appropriate solutions to these problems.

ABOUT TCR ENGINEERING SERVICES

Founded in 1973, TCR Engineering Services (TCR) is India's most reputed and established, NABL and ISO 17025 accredited independent material testing laboratory. The core services TCR provides include Mechanical Testing, Chemical Analysis, Positive Material Identification, Non Destructive Testing, Metallography, Corrosion Testing, Failure Analysis, Raw Material Inspection, Metallurgical Product evaluation, Engineering Research and Consultancy.

TCR has completed more than 300 failure investigation assignments, including 50 major projects.

More information about TCR Engineering services can be obtained from www.tcreng.com. Please download the company's corporate profile from http://www.tcreng.com/download/Company-Brochure-TCR.pdf

Failure Analysis Team

The Failure Analysis Team at TCR Engineering has experience in the materials, failure analysis, metallurgical, welding, quality assurance, and forensic engineering fields. The team is jointly headed by Mr. Virendra Bafna and Mr. Paresh Haribhakti.

Virendra Bafna, with over 32 years of experience is the Founder and Managing Director at TCR. He is a gold medallist from the University of Indore and has done Master of Engineering from the University of Toronto, Canada and Master of Industrial Management from the Clarkson College of Technology, Potsdam, New York. Mr. Bafna is a member of various professional organizations such as American Society for Testing and Materials (ASTM), Institute of Standard Engineers, ASM International, NACE, Non Destructive Testing Society of India, and Indian Institute of Metals. His vast expertise in the field of laboratory testing has brought numerous laurels to TCR notable amongst them is an award of appreciation from the Indian Space Research Organization (ISRO) for the company's contribution to the Project ASLV.

Mr. Paresh Haribhakti is a B.E. (Metallurgy) M.E. (Materials Technology) From M.S. University, Vadodara. Mr. Haribhakti has done basic research in study of hydrogen embrittlement of steels and stainless steels. Mr. Haribhakti previously worked as trouble shooting metallurgist for India's largest fertilizers and petrochemicals complex, GSFC Ltd., Vadodara for nearly 10 years. His areas of interest are microstructure degradation of components exposed to high temperature and high pressure. He has working experience of more than 250 failure investigation cases of power plants, fertilizers, chemicals and petrochemicals industries. He has solved materials engineering problems and performed failure analysis on components from petrochemical plants, oil and gas transmission pipelines, offshore structures, ships, pharmaceutical plants, food processing equipment, gas turbine engine components, and weldments. Mr. Haribhakti investigates the available physical evidence, and performs the necessary tests to develop the most probable accident scenario. He simplifies complex engineering theory into easy to understand and useable concepts. He uses simple analogies, every day examples, and laymen terms to explain data and findings so clients, corporate executives, government officials or attorneys may easily understand engineering concepts.