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Introduction to Failure Analysis and Prevention

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MACHINES, COMPONENTS, and the materials from which they are constructed cannot "fail" in the same sense as humans. They respond to their environments in ways which designers/engineers/scientists should understand and anticipate. So, the failure presented for analysis is really a failure to meet expectations. Whose expectations? Understanding what expectations existed among various parties is often part of the analysis. Product safety continues to improve, but expectations are also heightened.

Failure Definitions

In the general sense of the word, a failure is defined as an undesirable event or condition. For purposes of discussion related to failure analysis and prevention, it is a general term used to imply that a component is unable to adequately perform its intended function. Thus, the intended function of a component and therefore the definition of failure may range greatly. For instance, discoloration of an architectural feature is a failure of its intended aesthetic function.

Failure can be defined on several different levels. The simplest form of a failure is a system or component that operates but does not perform its intended function (Ref 1). This is considered a loss of function. A jet engine that runs but can produce only partial thrust (insufficient to enable an aircraft to take off) is an example of a loss of function.

The next level of failure involves a system or component that performs its function but is unreliable or unsafe (Ref 1). In this form of failure, the system or component has sustained a loss of service life. For example, a wire rope for an elevator has lost its service life when it has sustained fatigue fractures of some of the individual wires, due to irregularities in the wrapping over the sheave. Even though the wire rope continues to function, the presence of fatigue fractures of some of the wires results in an unsafe condition and is therefore considered a failure if the rope is not replaced through normal scheduled maintenance. Another example of such a failure is the inability of an integrated circuit to function reliably.

In the next level of severity of failure, a system or component is inoperable (Ref 1), such as a pump shaft fracture that causes the impeller to seize or a loss of load-carrying capability of a structural bolt in service due to fracture.

Failure analysis is a systematic, methodical process to determine the physical causes of problems or failures. The process is complex, draws upon many different technical disciplines, and uses a variety of observation, inspection, and laboratory techniques. One of the key factors is keeping an open mind while examining and analyzing the evidence to foster a clear, unbiased perspective of the failure. Collaboration with experts in other disciplines is required in certain circumstances to integrate the analysis of the evidence with a quantitative understanding of the stressors and background information on the design, manufacture, and service history of the failed product or system.

A thorough failure analysis is not necessarily concluded when the physical causes are identified. Root-cause analysis (RCA) techniques are employed to explore some of the deeper contributors to failures, such as the human and latent root causes. Properly performed, physical analysis and RCA are critical steps in the overall problem-solving process and are key ingredients for correcting and preventing failures, achieving higher levels of quality and reliability, and ultimately enhancing customer satisfaction.

This article briefly introduces the concepts of failure analysis, including RCA, and the role of failure analysis as a general engineering tool for enhancing product quality and failure prevention. The discipline of failure analysis has evolved and matured, as it has been employed and formalized as a means for failure prevention. A thorough analysis will typically also include determination regarding which party or parties may be liable for losses, be they loss of production, property damage, injury, or fatality. The discipline has also been used effectively as a teaching tool for new or less experienced engineers.

The importance and value of failure analysis to safety, reliability, performance, and economy are well documented. For example, the importance of investigating failures was vividly illustrated in the pioneering efforts of the Wright Brothers in developing self-propelled flight. In fact, while Wilbur was traveling in France in 1908, Orville was conducting flight tests for the U.S. Army Signal Corps and was injured when his Wright Flyer crashed (Fig. 1). His passenger sustained fatal injuries (Ref 2). Upon receiving word of the mishap, Wilbur immediately ordered the delivery of the failed flyer to France so he could conduct a thorough investigation. This was decades before the formal discipline called "failure analysis" was introduced.

Unfortunately, there are many dramatic examples of catastrophic failures that result in injury, loss of life, and damage to property. For example, a molasses tank failed in Boston in 1919, and *another* molasses tank failed in Bellview, New Jersey, in 1973 (Ref 3). Were the causes identified in 1919? Were lessons learned as a result of the accident? Were corrective actions developed and implemented to prevent recurrence?

Conversely, failures can also lead to improvements in engineering practices. The spectacular failures of the Liberty ships during World War II were studied extensively in subsequent decades, and the outcome of these efforts was a significantly more thorough understanding of the phenomenon of fracture, culminating in part with the development of the engineering discipline of fracture mechanics (Ref 4). Through these and other efforts, insights into the cause and prevention of

Fig. 1 Crash of the Wright Flyer, 1908. Courtesy of the National Air and Space Museum, Smithsonian Institution, Photo A-42555-A

failures continue to evolve. Further discussion can be found in the article "Failures Related to Welding," in *Failure Analysis and Prevention*, Volume 11 of the *ASM Handbook*, 2002.

Nevertheless, failures continue. Recalls of motor vehicles and consumer products are reported on a regular basis and tabulated on various websites. Building and bridge collapses are less common but still occur.

Thus, the need for failure analysis also continues. As our world becomes more complex, failure analysis becomes more complicated. Investigation of a catastrophic event may find many contributing factors. There may also have been multiple opportunities to prevent the failure. The designs of machines and structures are generally intended to incorporate a margin or factor of safety. However, after a design is realized and evolves, the actual margin may not be carefully reevaluated. That is, the actual factor of safety may be much less than anticipated.

A good example of this concept was the August 2007 collapse of the Interstate 35W bridge in Minneapolis, Minnesota. This collapse took the lives of 13 people and was the result of a design error by the original bridge engineering firm (Ref 5). Specifically, the error resulted in several undersized (by approximately half) gusset plates. However, the root cause of the failure was not following existing company procedures to check, double check, and verify all design calculations. These plates then failed by distortion as the bridge grew heavier with previous modifications and was being subjected to heavy loads during maintenance and use.

The original procedural error was compounded by missed opportunities to detect the error from several entities during the 40 year life of the bridge, including the government authority responsible for the safe operation and maintenance of the bridge, an engineering university, and a separate engineering company. None of these fully evaluated the loads and stresses on the gusset plates nor correctly identified signs of excessive loads. If any of these had not assumed that the gussets were better than the members and performed calculations on the gusset plate stress, they would have quickly realized the error.

Analysis of the accident resulted in the reexamination and recalculation of the loads and stresses in gusset plates of all steel truss bridges in the United States and led to significant changes in state and federal rules for evaluating, modifying, and maintaining new and existing bridge structures. The objective evaluation also dispelled a strongly held belief that the gusset plates are always stronger than the members.

Concepts of Failure Analysis and Prevention

Clearly, through the analysis of failures and the implementation of preventive measures, significant improvements have been realized in the quality of products and systems. This required not only an understanding of the role of failure analysis but also an appreciation of quality assurance and user expectations.

Quality and User Expectations of Products and Systems

Primarily starting in the 1980s, corporations, plants, government agencies, and other organizations developed new management systems and processes aimed at improving quality and customer satisfaction. Some of these systems include Total Quality Management (TQM), Continuous Improvement (CI), and Six Sigma. Historically, these initiatives are founded on the philosophies of the quality visionaries W. Edwards Deming (Ref 6) and Joseph Juran (Ref 7).

In their most basic descriptions, TQM and CI represent full organizational commitment to a system focused on "doing the right thing right the first time" and not merely meeting but exceeding customer requirements (Ref 8, 9). They are focused on process improvements, generally in a production environment. Six Sigma adopts these themes and extends the "reach" of the system to all levels of organizations, with a system to achieve, sustain, and maximize business success (Ref 10). Six Sigma is founded on the use of measurements, facts, and statistics to move organizations in directions that constantly improve and reinvent business processes (Ref 10). The roots of this business system are in the statistical limits set for the maximum number of defects in a product, as a fraction of the total number of opportunities for such defects to occur. To the practitioners of this system, "six sigma" is a statistical metric referring to six times the statistical standard deviation of a normal distribution, which allows no more than 3.4 defects per million opportunities (equivalent to 99.9997% reliability). This is indeed a lofty goal for any organization (be it a manufacturing company, a petrochemical plant, a service business, or a government agency), but companies committed to Six Sigma have reported significant gains in productivity with simultaneous improvements in organizational culture (Ref 9–11). More recently, Six Sigma practices have been coupled with lean manufacturing concepts in systems called Lean Six Sigma. Lean manufacturing focuses on process improvement and value-added operations to enhance productivity and reduce waste of all kinds.

The most positive result of these new management systems is that organizations have responded to the higher expectations of consumers and users and have provided higher-quality products and systems, with attendant increases in customer satisfaction. However, this notion of the *quality* of a product or system is multifaceted. Juran described quality as "fitness for use" (Ref 7). The TQM system defines quality as the ability to satisfy the needs of a consumer (Ref 12). These characteristics of quality also apply internally to those in organizations, either in the services, or in manufacturing, operating, or administering products, processes, and systems (Ref 12). Computer software systems for quality control have also gained prominence. The intent is to provide not only products and systems that garner high customer satisfaction but also increase productivity, reduce costs, and meet delivery requirements.

In general, *high quality* refers to products and systems manufactured to higher standards, in response to higher expectations of consumers and users. These expectations include attributes such as:

- Greater safety
- Improved reliability
- Higher performance
- Greater efficiency
- Easier maintenance
- Lower life-cycle cost
- Reduced impact on the environment

Some or all of these qualities at one time appeared mutually exclusive. However, customer demands and the aforementioned new business-management systems have provided a means of measuring and quantifying these attributes, creating a new paradigm for business. With the business-culture changes that have occurred through the implementation of one or more of the aforementioned improvement systems, users in recent years have experienced, in general, improvement in all of these areas simultaneously. That translates to reduced product failure and greater likelihood of preventing failures. It is important to recognize that, with all the gains achieved under these management systems, the full potential for maximizing these attributes is yet to be achieved.

Although all of the various improvement systems are unique, they have two aspects in common. They are all customer focused and are founded on problem solving as a means for improvement.

When addressing customer focus, producers and other organizations have identified that the form, fit, function, and service-life requirements of a product or system are actually defined ultimately by customers. Customer-focused manufacturers strive to meet these requirements in designing, developing, and producing their products or systems. In a broad sense, form, fit, function, and service life represent the technically relevant properties of a product. The form, or physical characteristics of components or products, includes the size and shape of a product as well as the materials of construction and the manufacturing techniques used. The manner in which individual components are assembled into and integrate with the product as a whole describes the fit of components. The function of a product or system is its ability or capability to serve the need for which it was intended. Service life is the duration over which the product or system successfully serves its function. These characteristics define products in the customer's eyes. Arguably the most important characteristics, from a consumer's perspective, are how well a product or system functions and how long it serves a useful life.

Problem Solving, Quality, and Customer Satisfaction

Achieving the levels of quality that meet and exceed customer expectations is paramount to customer satisfaction in a customer-focused management system. Because a customer's perception of quality is strongly tied to the function and service life of a product or system, it follows that failure to provide adequate measures of function and service life presents problems. One proven technique to improve quality is problem solving. Problems can range broadly from incomplete maintenance training, to marginal equipment reliability, to business systems conflicts, to policy inconsistencies, to poor working conditions on the shop floor. When a problem occurs, the responsible organization will analyze the problem to determine the cause and solve it. However, due to various business or cultural pressures, some organizations fall into pitfalls when problems arise (Ref 11), such as:

- Do nothing and perhaps hope that the problem will go away
- Deny that the problem exists, minimize its importance, question the motives of those identifying the problem
- Troubleshoot in a haphazard fashion (i.e., "shotgun" troubleshooting)
- Chase false leads (i.e., "red herrings")

In an enlightened organizational culture, products or systems require a systematic approach to problem solving, based on analysis, to achieve the levels of quality and customer satisfaction defined by the new management systems. The cultural aspect is critical, because those who have identified problems must be encouraged to come forward. Furthermore, resources and commitment are required to formulate the solutions and implement necessary changes.

Problem-Solving Models

A wide range of problem-solving methods and models are available in the literature (Ref 6–8, 10–14), presenting various details of approaches and processes for solving any of the general types of problems defined previously. All of these methods and models are rooted in the scientific method (summarized as) (Ref 8):

1. Define the issue
2. Propose a hypothesis
3. Gather data
4. Test the hypothesis
5. Develop conclusions

A concise problem-solving model, adapted from several of the referenced authors, and that has specific applicability to this Volume, is depicted in Fig. 2. The continuous, circular format in the graphic is significant, indicating that the process reinitiates with the identification of a new problem or problems brought to light as a result of the first problem-solving activity. Note the similarity to the classical scientific method summarized previously.

The major steps in the model define the problem-solving process:

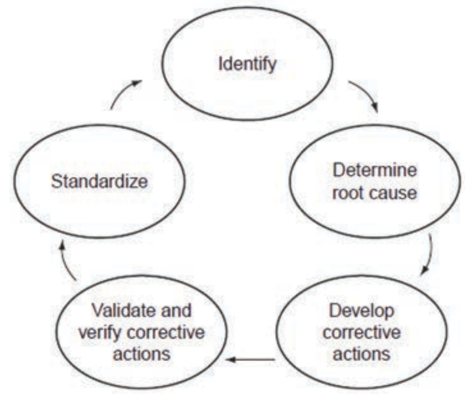

Fig. 2 Problem-solving model

1. *Identify:* Describe the current situation. Define the deficiency in terms of the symptoms (or indicators). Determine the impact of the deficiency on the component, product, system, and customer. Set a goal. Collect data to provide a measurement of the deficiency.
2. *Determine root cause:* Analyze the problem to identify the cause(s).
3. *Develop corrective actions:* List possible solutions to mitigate and prevent recurrence of the problem. Generate alternatives. Develop implementation plan.
4. *Validate and verify corrective actions:* Test corrective actions in pilot study. Measure effectiveness of change. Validate improvements. Verify that the problem is corrected and improves customer satisfaction.
5. *Standardize:* Incorporate the corrective action into the standards documentation system of the company, organization, or industry to prevent recurrence in similar products or systems. Monitor changes to ensure effectiveness.

The second step in the problem-solving model, determine root cause, introduces a very significant process. Solutions to prevent recurrence of problems cannot be developed and applied without identification of the root cause.

Failure and Failure Analysis

A logical failure analysis approach first requires a clear understanding of the failure definition and the distinction between an indicator (i.e., symptom), a cause, a failure mechanism, and a consequence. Although it may be considered by some to be an exercise in semantics, a clear understanding of each piece of the situation associated with a failure greatly enhances the ability to understand causes and mitigating options and to specify appropriate corrective actions.

Consider the example of a butterfly valve that fails in service in a cooling water system at a manufacturing facility (Table 1). Recognizing the indicators, causes, mechanisms,

Table 1 Failure of a butterfly valve in a manufacturing plant cooling water system

Item	Description	Indicators
Cause	Throttling of valve by the operator outside of the design parameters	Flow gages and records Operator logs
	Low-strength copper-nickel alloy construction	Material specifications Laboratory analysis
	Flow-induced cavitation	Rumbling noise in system Vibration of system
Failure mechanism	Erosion-fatigue damage	Laboratory examination of disk, thinning
Consequences	Inability to manufacture at normal production rates	. . .

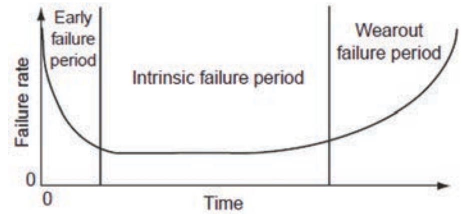

Fig. 3 Typical time distribution of failures ("bathtub curve")

and consequences helps to focus investigative actions:

- *Indicators(s):* Monitor these as precursors and symptoms of failures.
- *Cause(s):* Focus mitigating actions on these.
- *Failure mechanism(s):* These describe how the material failed according to the engineering textbook definitions. If the analysis is correct, the mechanism will be consistent with the cause(s). If the mechanism is not properly understood, then all true cause(s) will not be identified and corrective action will not be fully effective.
- *Consequence(s):* This is what we are trying to avoid.

Life-Cycle Management Concepts

The concept of life-cycle management refers to the idea of managing the service life of a system, structure, or component. There is a cost associated with extending the service life of a component, for example, higher research costs, design costs, material and fabrication costs, and higher maintenance costs. With regard to product failures, it must be understood that failures cannot be totally avoided but must be better understood, anticipated, and controlled. Nothing lasts and functions forever. For some products, consumers may prefer a shorter life at a more modest cost. In contrast, the useful service life of a product such as an aircraft part may be carefully planned in advance and managed accordingly with routine inspections and maintenance, which may increase in frequency over time. In many cases, avoiding failures beyond a certain predetermined desired life provides no benefit, such as when a surgical implant is designed to far outlive the human recipient. There is also a point of diminishing return on investments related to extending the life of a component. One example is when the increasing repair costs for a car exceed its worth. A life-cycle management study of a component would look at these issues as well as other factors, such as the issue of obsolescence. How long will it be before the product is obsolete?

Understanding how the typical distribution of failures for a given product must be factored with time is also important when looking at failure patterns (Fig. 3). Early life failures are often associated with fabrication issues, quality-control issues, or initial "shakedown" stresses, while later life age-related failure rates would increase with time. This is discussed in more detail in the article "Reliability-Centered Maintenance," *Failure Analysis and Prevention*, Volume 11 of *ASM Handbook*, 2002.

Once the concept of a managed life is prudently adopted over a simple failure-prevention concept, design and fabrication costs can be reduced and maintenance and other life-prolonging activities can be optimized.

Diligence in Use of Terminology

Communicating technical information accurately is of paramount importance in all engineering areas, including failure analysis. The choice of technical descriptors, nomenclature, and even what may be considered technical jargon is critical to conveying technical ideas to other engineers, managers, plant personnel, shop personnel, maintenance personnel, attorneys, a jury, and so forth. It is instructive in this introductory article to emphasize that a descriptor can mean something very specific to a technical person and mean something very different to a business manager or an attorney.

For example, the term *flaw* is synonymous with *defect* in general usage. However, to a fracture mechanics specialist, a flaw is a discontinuity such as a crack. Under some circumstances, when the crack is smaller than the critical size (i.e., subcritical), the crack is benign and therefore may not be considered a defect. To the quality-control engineer, flaws are characteristics that are managed continuously on the production line, because every engineered product has flaws, or "deviations from perfection" (Ref 15). On the manufacturing floor, these flaws are measured, compared with the preestablished limits of acceptability, and dispositioned as acceptable or rejectable. A rejectable characteristic is defined as a defect (Ref 15). To the Six Sigma practitioner, a defect is considered anything that inhibits a process or, in a broad sense, any condition that fails to meet a customer expectation (Ref 11). To the attorney, a defect refers to many different types of deficiencies, including improper design, inadequate instructions for use, insufficient warnings, and even inappropriate advertising or marketing (Ref 16). Identification of a defect in a litigation context may be used to establish legal liability.

Similar linguistic nuances may occur in the basic definitions and interpretations of technical terms used in materials failure analysis. Terms such as *ductile* and *brittle*, *crack* and *fracture*, and *stable* and *unstable* crack growth are pervasive in failure analysis. Even these seemingly basic terms are subject to misuse and misinterpretations, as suggested in Ref 17; for example, *brittle cleavage* is a pleonasm that does not explain anything. Another example noted in Ref 17 is the term *overload fracture*, which may be misinterpreted by non-analysts as a failure caused by a load higher than anticipated by the materials or mechanical engineers. This limited interpretation of overload fracture is incomplete, as described in the article "Monotonic Overload and Embrittlement" in this Volume.

Judgmental terminology should be used with prudence when communicating analytical protocols, procedures, findings, and conclusions. Communications during the preliminary stages of an investigation should be factual rather than judgmental. It is important to recognize that some of the terminology used in a failure analysis can be judgmental, and consideration must be given to the implications associated with the use of such terminology. For example, when examining both a failed and an unfailed component returned from service, references to the unfailed sample as "good" and the failed sample as "bad" should be avoided. This is because the investigation may reveal both samples to contain the same rejectable defect, and therefore, both could be considered "bad." Similarly, *neither* may be "bad" if the analysis actually indicates the failed component met all requirements but was subjected to abuse in service. On completion of the failure analysis, judgmental terminology is often appropriate to use if the evidence supports it.

While discussions of the semantics of terminology may seem pedantic, communicating the intended information gleaned from a failure analysis relies heavily on precision in the use of language.

Primary Physical Root Causes of Failure

Categorizing schemes for the root causes of equipment failures varies among failure analysis practitioners, quality engineers, other engineers, and managers, as well as legal and insurance professionals (Ref 1, 16, 18–22). Grouping physical root causes into only a few fundamental categories is advantageous and informative because it defines which aspect of a product or system requires corrective action and prevention strategies. Systematic analysis of equipment failures reveals physical root causes that fall into one of four fundamental categories (Ref 23):

- Design
- Manufacturing/installation
- Service
- Material

An effective graphical representation of the impact of defects on the service life of a component or system is provided in the application-life diagram (Fig. 4) (Ref 24, 25). The diagram is constructed by plotting the service lives of components having specific characteristics in the design/configuration, as related to the severity of a specific service condition that is anticipated for the application. Typical characteristics include strength, corrosion resistance, heat treatment condition, flaw size, surface finish, bend radius, void content (i.e., in a casting), degree of sensitization, and so on. Examples of service conditions include magnitude of stress (either cyclic or static), exposure temperature, aggressiveness of environment, radiation exposure, electrical stress, and so on.

By varying the characteristics, a family of curves is generated, contrasting the lives of components with the various characteristics and service conditions with the intended service life. Each of the curves represents a different design/configuration characteristic, with increasing degrees of durability as the curves move up the ordinate. Failures can be prevented when the curve for a specific design/configuration lies above the severity of service line and to the right of the intended service life line. However, if the anticipated service condition increases (either intentionally during operation or as a result of some other change in the system), the propensity for failure may increase, because the characteristics curves intersect the severity of service condition line "to the left," that is, at an earlier point in the service condition.

Design

Root causes of failures that stem from design deficiencies refer to unacceptable features of a product or system that are a result of the design process. This process encompasses the original concept development, the general configuration definition, and the detail design, including selection and specification of materials and manufacturing processes. Design involves identifying and defining a need for the product or system, followed by definition of the performance requirements, anticipated service conditions in the application(s), the constraints on the design, and the criticality or risks associated with failure (Ref 26). Discussion of the design process as it relates to failure analysis and prevention is provided in the article "Design Review for Failure Analysis and Prevention," *Failure Analysis and Prevention*, Volume 11 of *ASM Handbook*, 2002.

Some examples of design deficiencies include unintended stress raisers due to excessively sharp notches (Ref 27) (e.g., in keyways on shafts) or insufficient radii (e.g., on shafts at bearing journals). Other examples include unanticipated residual stresses associated with heat treating configurations designed with complex geometries, or assembly stresses from configurations that contain unwanted interference. Inappropriate surface treatments could result in failures, such as the use of cadmium plating on an A286 superalloy fastener subjected to service temperatures above 315 °C (600 °F) (the melting temperature of cadmium is 320 °C, or 610 °F). Two metals specified for use in a wear application could sustain galling if the metals are similar (atomic number) and mutually soluble, such as sliding wear of components made from 300-series stainless steels.

Selection of a material that is incapable of providing adequate mechanical properties for the application (including strength, fatigue resistance, fracture toughness, elevated-temperature resistance, etc.) is the most common type of design deficiency. Materials can exhibit anisotropy, or variability in properties within a product, such as between the thick and thin portions of a casting or between longitudinal and transverse properties in a wrought material. Note that a material can be shown to meet the properties required or specified (i.e., a separately cast tensile bar used to certify a casting, or the longitudinal tensile properties to certify a complex aluminum extrusion), but the specific properties required for the application may rely on the strength, toughness, or stress-corrosion cracking resistance in a direction other than that certified.

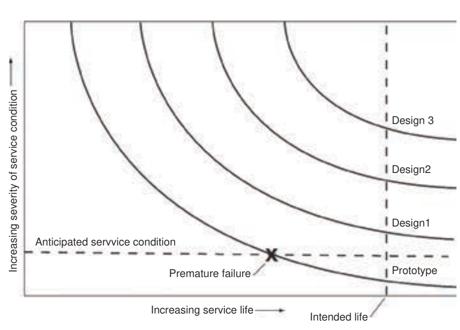

Fig. 4 Application-life diagram comparing the severity of a service condition with the service lives of products having a variable characteristic. This diagram is used in specific examples in the text.

Design-caused failures include inappropriate geometries (as defined on the engineering drawing), which may lead to a compromise of component or system capabilities. Examples of inappropriate geometries include improper joint specification for welding or brazing, such as an insufficient or missing groove for a groove weld, insufficient fit-up relief in a socket weld, or inadequate joint overlap in a brazed joint. Other geometry-caused failures can result from insufficient section thickness for a failure based on gross yielding, excessive section thickness in the presence of a flaw for a material of limited fracture toughness, or a fabrication configuration with an excessively sharp forming bend, with the resulting high residual stresses causing a reduction in the fatigue life.

For the example of the excessively tight cold-formed bend radius just described, an application-life diagram can be constructed, as shown in Fig. 5. The service condition considered is stress, and the characteristic that is varied is the radius of the cold-formed bend. Upon examination of the relationship between the characteristic curves and the intended service life, the components having the large and moderate bend radii are found to meet the intended service life line at the severity of stress that is anticipated in the specific application. However, in this illustration, the component with the small bend radius sustained a premature failure at the anticipated stress level in the application, because the curve intersects the anticipated severity line prior to reaching the intended service life line.

Some of the aforementioned deficiencies in design as well as application-life diagram concepts are illustrated in case histories of Examples 1 and 2.

Example 1: Ice Cream Drink Mixer Blade Failures.

Excessive assembly stresses and inappropriate detail design caused the premature failures of ice cream drink mixer blades shortly after the mixing machines were introduced into service. A mixer blade as-manufactured is shown on the left side of Fig. 6. As-assembled (right side of Fig. 6), the mixer blade is slightly deformed by the contact between the wavy washer at the bottom of the assembly and the bends at the bottom shoulders of the two mixer

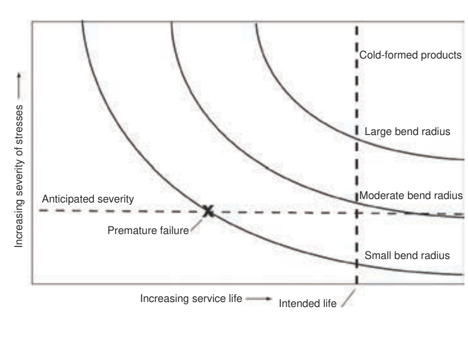

Fig. 5 Application-life diagram for design deficiency

arms. When properly torqued, the screw that fastens the wavy washer and the mixer blade to the spindle in the center of the assembly places an upward force on the bottoms of the arms (as indicated by the pair of upward-facing arrows in Fig. 6). This results in the observed inward deflection of the arms (as indicated by the right- and left-facing arrows). More significantly, this bending force places the inside radii of the two shoulders of the mixing blade arms (at the bottom of the blade) in tension. When the mixer is running, the rotational forces further add to the tensile loads on the inside radii of the shoulders.

Analysis of the failed mixer blades revealed multiple fatigue crack origins on the inside radii of the bends at the bottom shoulders (Fig. 7). Metallographic examination of the arm materials revealed additional problems with the configuration: the shoulders on the arms were cold bent, introducing tensile residual stresses on the inside radii of the shoulders and creating a localized area of fatigue susceptibility due to the inherent notch sensitivity of cold-formed 300-series stainless steel.

Clearly, the physical root cause is the design of the mixer blade, which defined two bend areas that contained tensile residual stresses, tensile assembly stresses, and a notch-sensitive microstructure that added to the normal operating rotational and vibratory stresses. The net effect was a reduction in the life of the blade, causing loss of function. Corrective-action recommendations included the addition of a stand-off washer between the wavy washer and the bottom shoulders of the blade, or modification of the shape of the wavy washer to prevent contact with the blade shoulders as assembled.

Example 2: Sprocket Locking Device Failure (Ref 28).

A design deficiency involving improper materials selection was revealed through the analysis of a failed tapered-ring sprocket locking device. The device is used to attach a chain sprocket to a shaft without the use of a locking key, enabling the shaft to either drive or be driven anywhere on the shaft (Fig. 8). The configuration consists of an assembly of four tapered rings (Fig. 9) that are retained by a series of cap screws. As shown in Fig. 10, when the screws are tightened, the middle wedge-shaped rings are pulled closer, forcing the split inner ring to clamp tightly onto the shaft, and the split outer ring to force tightly against the inside diameter of the sprocket. When properly assembled and torqued, the sprocket is fixed to the shaft.

During initial assembly of a new locking device by the manufacturer during a bench test, one of the wedge-shaped middle rings fractured prior to having been fully torqued, preventing the sprocket from being locked to the shaft. The failed assembly was investigated for root cause. One of the middle rings had cracked (Fig. 9, 11a). Indeed, examination of the fracture revealed "woody" fracture features (Fig. 11b) as a result of decohesion between a high volume fraction of manganese sulfide stringers and the matrix (Fig. 12). The matrix fracture features showed ductile dimpled rupture.

Chemical analysis of the material revealed a resulfurized grade of carbon steel (SAE type 1144, UNS G11440), as required by the manufacturer. This type of steel is marketed as having a rather unusual combination of high strength *and* high machinability. The source of the high strength is in the carbon content and the cold drawing process used to produce the bar material, giving rise to enhanced longitudinal tensile properties. The high volume fraction of manganese sulfide inclusions (Fig. 13) imparts the high machinability properties, due to the well-documented enhancement to chipmaking during machining. The trade-off to this combination of properties, however, is the loss of transverse properties, including strength, ductility, and toughness.

Analysis of the forces present in the tapered-ring locking device revealed that when the fastening screws were torqued, a significant hoop stress was placed on the middle rings due to the wedging action between the inner and outer rings as well as the relatively small cross section of the middle rings at the fastener holes (Fig. 10). Because the large inclusion was present at a minimum section-thickness zone of the middle ring, the stresses applied to the middle rings during normal torquing caused failure at the inclusion. Because the material contained a high volume fraction of these inclusions, this material choice was not appropriate for this application. The material was weak in an orientation of relatively high stress. Failure-prevention recommendations involved specification of a nonresulfurized grade of a low-alloy steel.

Example 2 illustrates some of the complexity and subtlety of RCA. The material was no doubt chosen for its ease of machining. The designer may not have been heavily involved in the material specification or may not have realized the sensitivity of this particular design to material anisotropy. The material itself was not defective or bad, and the part design was reasonable too, except for the material selection, which turned out to be the critical factor in this case.

Manufacturing/Installation

Manufacture refers to the process of creating a product from technical documentation and raw materials, generally performed at a factory. Installation can be considered manufacturing in-place, such as at a construction site or a new plant. Products can be designed properly using sound materials of construction yet be defective as-delivered from the manufacturer, due to rejectable imperfections (i.e., defects) introduced during the manufacturing process or due to errors in the installation of a system at a site. A wide variety of manufacturing-caused defects exist; each and every manufacturing/installation process has many variables that, when allowed to drift toward or to exceed control limits, can result in a defective product (Ref 12).

Some examples of such manufacturing/installation anomalies include (Ref 18, 29):

Metal-removal processes

- Cracks due to abusive machining
- Chatter or checking due to improper speeds and feeds

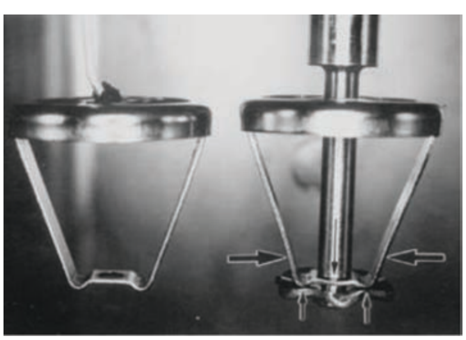

Fig. 6 Ice cream mixer blade as-manufactured (left) and assembled to spindle (right)

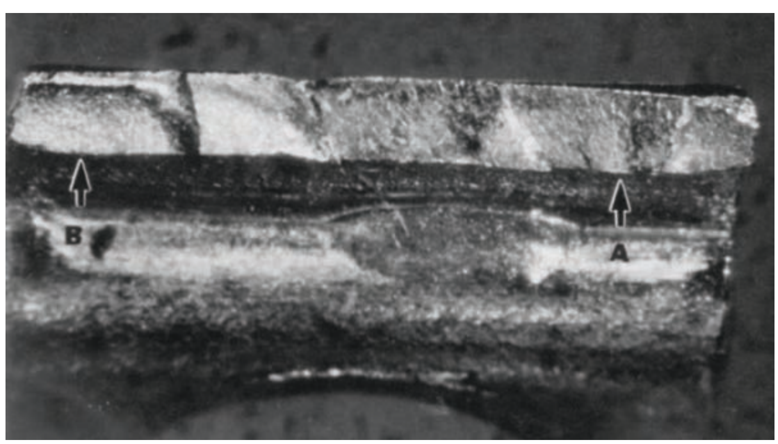

Fig. 7 Fracture surface of failed ice cream mixer blade. Arrows indicate fatigue crack origins. Original magnification: 13×

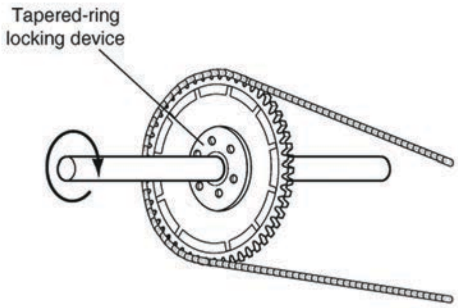

Fig. 8 Sketch of tapered-ring locking device application

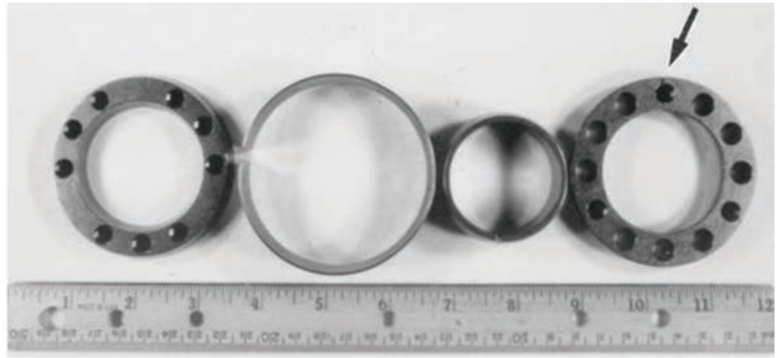

Fig. 9 Four tapered rings of locking device. Arrow indicates crack in one of the middle rings.

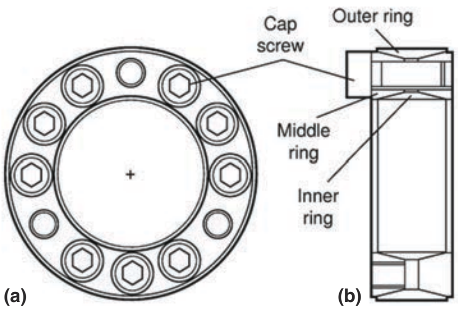

Fig. 10 Tapered-ring locking device assembly, (a) plan view, (b) cross section

- Microstructural damage due to dull tooling
- Grinding burn
- Electrical discharge machining recast or white layer, cracks, redeposited particles, and so on
- Intergranular attack due to electrochemical machining
- Residual-stress cracking due to overheating

Metalworking processes

- Cracking, tears, or necking due to forming/deep drawing
- Laps due to thread rolling/spinning
- Tool marks and scratches from forming
- Surface tears due to poor surface preparation prior to working
- Residual-stress cracking due to flowforming
- Lüders lines due to forming strain rate
- Microstructural damage due to shearing, blanking, piercing
- Overheating damage during spring winding
- Laps and cracks due to shot peening
- Stress-corrosion cracking due to use of improper die lubricants

Heat treatment

- Grain growth
- Incomplete phase transformation
- Quench cracks
- Decarburization
- Untempered martensite
- Temper embrittlement and similar embrittlement conditions

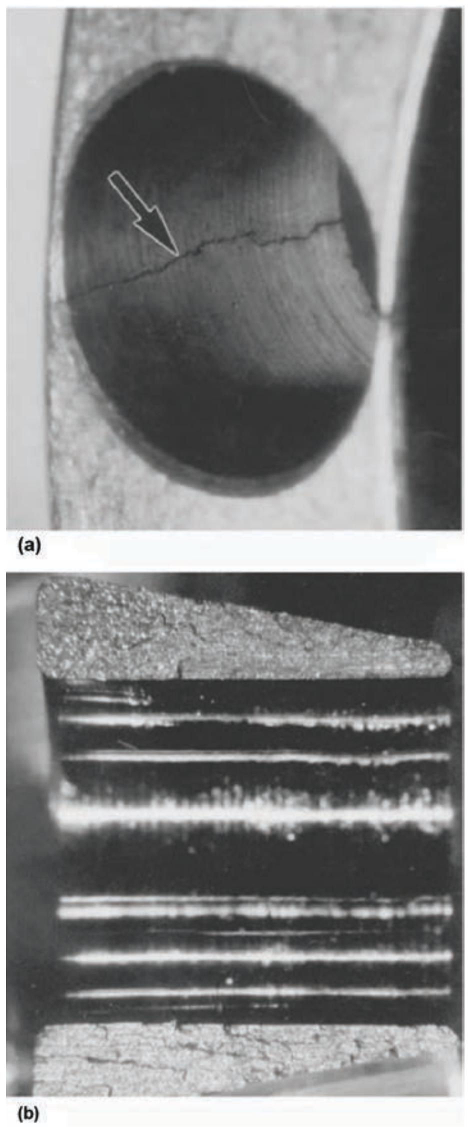

Fig. 11 (a) Crack and (b) broken-open fracture surface of failed wedge-shaped middle tapered ring. Original magnification: 6×

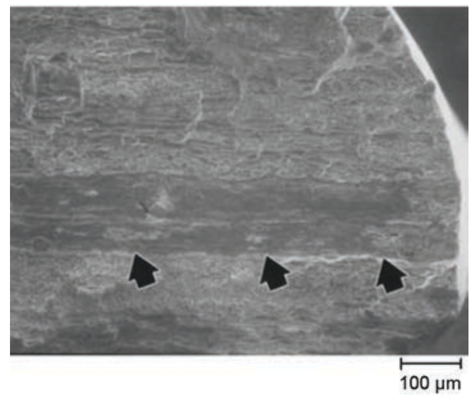

Fig. 12 Higher-magnification view of fracture surface shown in Fig. 11 at origin of cracking. Arrows indicate large manganese sulfide inclusion at origin.

Fig. 13 Significant volume fraction of manganese sulfide inclusions in wedge-shaped tapered ring microstructure. Original magnification: 73×

- Inadequate precipitation
- Sensitized microstructure
- Inhomogeneities in microstructure
- Loss of properties due to overheating during postplating bake

Welding

- Incomplete fusion
- Incomplete penetration
- Brittle cracking in heat-affected zone (HAZ)
- Sensitized HAZ
- Residual-stress cracking
- Slag inclusions
- Cratering of fusion zone at endpoint
- Filler metal contour out of specification
- Hot cracking
- Cracking at low exposure temperatures
- Hydrogen embrittlement due to moisture contamination
- Liquid metal embrittlement from plating contamination

Cleaning/finishing

- Corrosion due to inadequate cleaning prior to painting
- Intergranular attack or hydrogen embrittlement due to acid cleaning
- Hydrogen embrittlement due to plating
- Stress corrosion from caustic autoclave core leaching of castings

Assembly at factory/installation at site

- Misalignment
- Missing/wrong parts
- Improper fit-up
- Inappropriate fastening system, improper torque
- Improper tools
- Inappropriate modification
- Inadequate surface preparation

Inspection techniques

- Arc burn due to magnetic-particle inspection
- Intergranular attack or embrittlement due to macroetch
- Fatigue or quench crack from steel stamp mark
- Crack initiation at hardness test indentations

Failures associated with metalworking, welding, and heat treating operations are discussed in more detail in other articles in this Volume. Example 3 also illustrates the effects of manufacturing anomalies on the life of a component.

Example 3: Forming Process Anomalies in Diesel Fuel Injection Control Sleeve (Ref 23).

A user complained of a diesel engine that failed to start in cold weather. Troubleshooting isolated the problem to the diesel fuel control assembly, which was changed out, fixing the problem. Teardown of the fuel control assembly by the manufacturer revealed that a small subcomponent known as the cold start advance solenoid sleeve (Fig. 14) was leaking through the wall. The sleeve operates under relatively high pressure cycles in service. This component is a tubular product with a "bulb" section at one end and threads on the other. The manufacturing method used to create the bulb shape was hydroforming, using a 300-series stainless steel tube in the full-hard condition.

The leak was attributed to a crack in the sleeve (Fig. 15), in the radius between the bulb area and the cylindrical portion of the sleeve. Scanning electron microscope examination of the broken-open crack revealed fatigue cracks initiated at multiple sites near the outside diameter (OD) of the sleeve (Fig. 16). The crack origins were determined to be extending from shallow (0.013 mm, or 0.0005 in.) zones exhibiting ductile shear (see area between arrows in Fig. 16). Viewing the OD surface of the sleeve adjacent to the fracture plane revealed an extensive network of microcracks on the OD in the radius between the bulb and cylindrical portions (Fig. 17). A cross section through one of the fatigue crack origins revealed slip bands emanating from the microcracks (Fig. 18).

The analysis revealed that during the hydroforming process, heavy biaxial strains were imparted to the sleeve wall, in the radius between the bulb and cylindrical portions of the sleeve. When combined with the heavy strains inherently present in the full-hard 300-series stainless steel, the hydroforming strains in the radius caused the microcracking. The ductile shear areas observed at the origins (Fig. 16) are microcracks that served to intensify the cyclic service stresses, resulting in fatigue cracks initiating and propagating from these flaws through the wall, causing the leak.

The physical root cause for this failure is a manufacturing process that omitted an intermediate stress-relief or annealing treatment prior to hydroforming to the final shape.

Some time later, a similar complaint was received at the factory for a nonstart condition in cold weather. The sleeve was again identified to be leaking due to a through-wall crack. Analysis of the broken-open crack (Fig. 19) revealed fatigue cracks initiated on the inside diameter (ID) of the sleeve. This time, the flaw that led to the failure was shallow (approximately 0.005 mm, or 0.0002 in.) intergranular attack on the ID surfaces due to overly aggressive acid cleaning or insufficient rinsing after the acid-cleaning operation. Examination of the OD

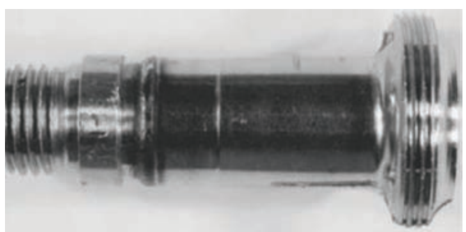

Fig. 14 Cold start advance solenoid sleeve. Original magnification: 0.85×

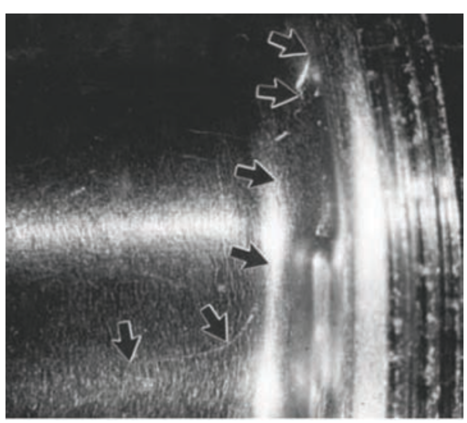

Fig. 15 Crack in sleeve (arrows). Original magnification: 2.5×

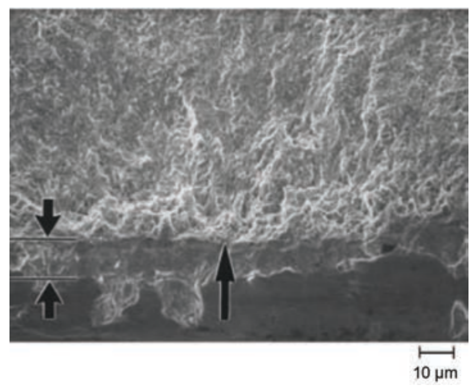

Fig. 16 Fatigue cracking from the outside diameter (OD) of the sleeve (large arrow). Area between small arrows shows evidence of ductile shear at OD surface.

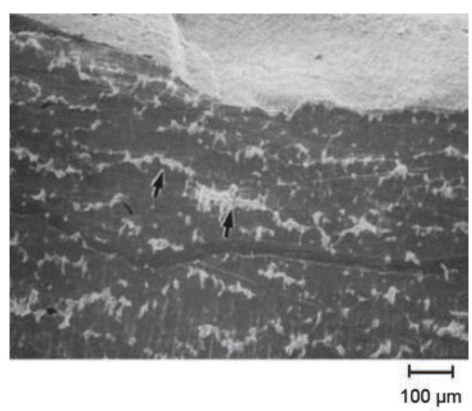

Fig. 17 Network of microcracks (arrows) on the outside-diameter surface of the sleeve (lower portion of micrograph)

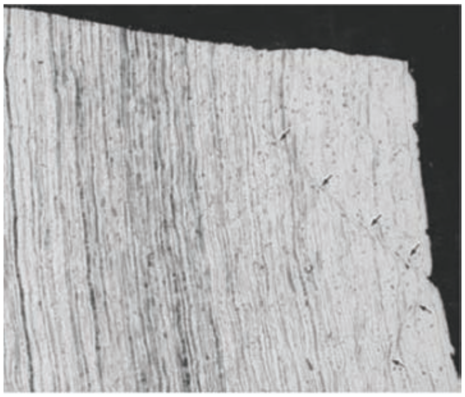

Fig. 18 Microstructure of cross section through outside-diameter surface of sleeve adjacent to fracture. Fracture surface is along top of micrograph. Outside-diameter surface is along right side of micrograph. Note slip banding (arrows) emanating from microcrack. Original magnification: 116×

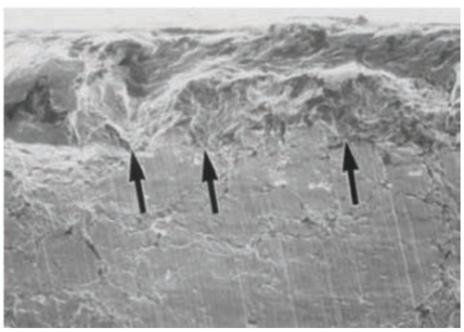

Fig. 19 Multiple fatigue crack origins (arrows) initiating in a network of intergranular attack on the inside diameter of the sleeve. Original magnification: 155×

surfaces revealed no microcracking or evidence of localized strain. Thus, a second manufacturing defect affecting the same component was identified through failure analysis to have caused the identical complaint from the field.

Using the application-life diagram, the strong effects of minute surface anomalies in this fracture-critical component is clearly apparent (Fig. 20). As a result of the severity of the pressure cycles in service, the sleeve cannot tolerate surface flaws.

Service

The life of a component or system is heavily dependent on the conditions under which the product operates in service. The service life of a product includes its operation, maintenance, inspection, repair, and modification. Failures due to anomalies in any one of these aspects of service life are unique from those created during the design, procurement of materials, and manufacture of products. Examples of the types of root causes of failures that result from unanticipated service conditions (Ref 25) are summarized in the following paragraphs.

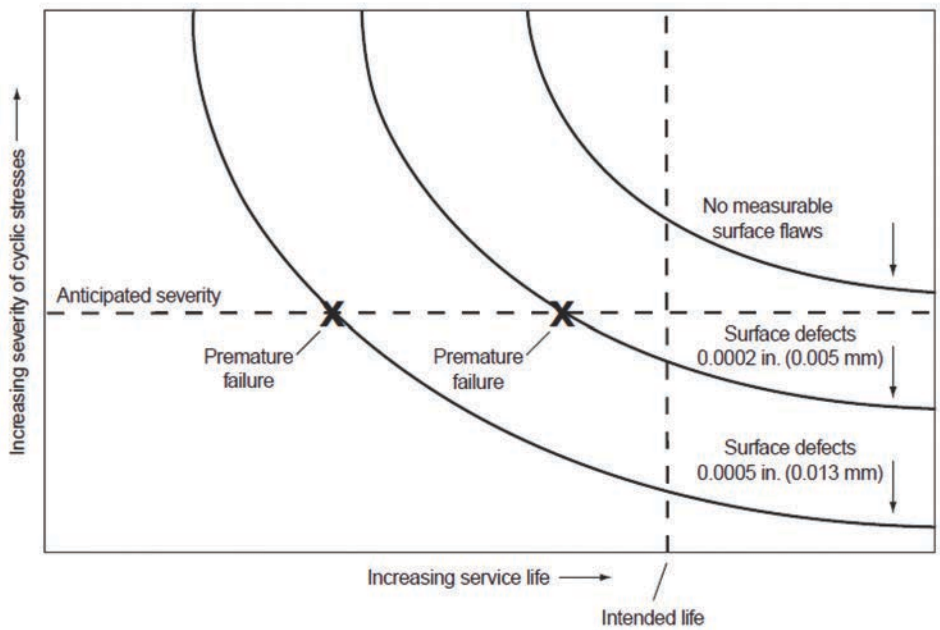

Fig. 20 Application-life diagram showing effects of manufacturing-caused surface discontinuities on service life

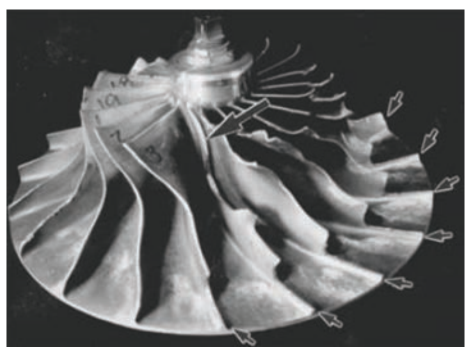

Fig. 21 Failed compressor rotor. Arrows indicate fractured portions of blades. Original magnification: 36×

Operation of the equipment outside of the manufacturer's design parameters would include an example such as a military fighter aircraft in a turn that causes "g" forces that are outside of the operating envelope of the aircraft. Another example is inlet-flow blockage on a high-performance air compressor resulting in excessive cyclic loads applied to the blades, causing blade (Fig. 21, 22) and drive shaft (Fig. 23) failures. Failure analysis revealed both the compressor rotor and the shaft sustained fatigue failures.

Careful fracture analysis revealed fatigue cracks initiated on the low-pressure side of the blades, which are in compression during normal compressor operation. However, when the inlet flow is blocked, particularly when the blockage is only partial, the blades sustain alternating tensile forces, one load cycle per revolution, on the low-pressure side of the blades, resulting in the observed blade fractures. The shaft subsequently failed, due to the severe imbalance and rubbing caused by the blade failures.

Fig. 22 Compressor blade fracture surface showing fatigue origins on low-pressure (i.e., right) side of blade, as indicated by the arrows. Original magnification: 13×

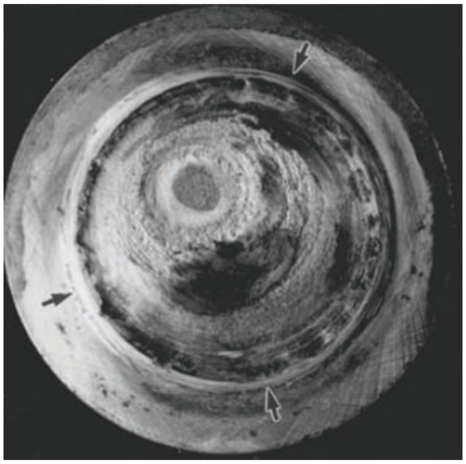

Fig. 23 Failed compressor rotor shaft. Fracture occurred at radius between large and small diameters. Arrows indicate some of fatigue origins. Original magnification: 1×

Exposure of the product or system to environments more aggressive than anticipated would include examples such as:

- Microbiologically influenced corrosion in a cooling water system using river water in which the ecosystem has changed
- A titanium centrifuge bowl exposed to an organic, chloride-containing environment, resulting in stress-corrosion cracking
- Faulty sensor cable resulting in an overtemperature condition in a jet engine, which consumes the high-pressure turbine blade life

Improper maintenance would include examples such as:

- Installing a metallic fuel line onto the mating fitting by forcing the tube to align with the mating fitting. Adding the installation stress to the normal cyclic stresses results in a leak due to fatigue cracking.
- Weld repair of a material that is sensitive to high heat cycles, causing brittle cracks and subsequent fatigue failure
- Misalignment of a bearing during rebuild, causing bending loads on the shaft and resulting in failure by rotating-bending fatigue

An example of inappropriate modifications would be through-wall drill holes in a bicycle handlebar stem resulting in fatigue initiation at the holes and subsequent fracture (Fig. 24, 25).

The application-life diagram is useful in exploring the effects of service-life anomalies on the lives of products. For the compressor inlet blockage case described previously, Fig. 26 depicts the significant loss of service life when the rotor blades sustain the unintended cyclic stresses that occur during an inlet blockage event.

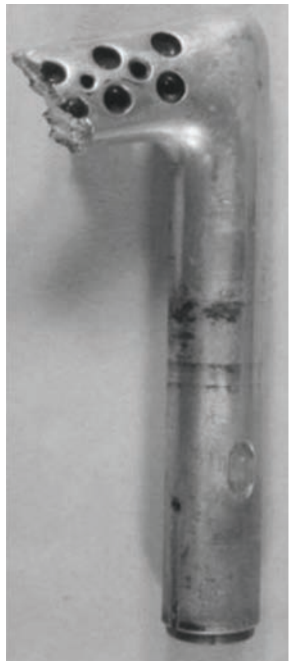

Fig. 24 User-modified bicycle handlebar stem failed in service

Material

Imperfections or discontinuities in materials that deviate from specifications or cause failure are defects. Of the four fundamental categories of failure causes or roots (design, manufacturing, service, and material), material is the least common (Ref 30). Some of the classical types of material discontinuities that have been identified as causal factor(s) in failures are included in Table 2.

More detailed descriptions, with physical characteristics and mechanisms for the creation of these defects, are contained in other articles in this Volume. Problems that may develop during subsequent processing, such as heat treating and welding, are discussed in the section "Manufacturing/Installation" in this article.

These material defects can be generally described as discontinuities that degrade the performance of a product in some way. Despite steps taken to control, document, measure, analyze, and improve the processes involved in manufacturing the metal product (such as in TQM and Six Sigma systems), material defects occur. Many defective products are prevented from leaving the mill, foundry, or forge through diligence in adhering to internal procedures and quality-assurance systems. Yet, defective materials are sometimes delivered. Depending on the criticality, periodic field inspection may be required and may reveal defects not previously identified. A case study of one such occurrence illustrates the effectiveness of a maintenance plan that includes periodic inspection.

Fig. 25 Multiple fatigue initiations at through-wall drill holes in user-modified bicycle handlebar stem. Original magnification: 3×

Table 2 Material discontinuities that cause failures in metal products

Metal product form	Types of discontinuities
Forgings	Laps
	Bursts
	Cracks
	Flow-through defects
	Extrusion-type defects
	Cold shuts
	Flakes
	Segregation
	Cavity shrinkage
	Centerline pipe
	Parting-line grain flow
	Inclusions
Castings	Porosity, gas, and microshrinkage
	Shrinkage cavities
	Porosity
	Blowholes
	Hot tears
	Segregation
	Cold shuts
	Inclusions
	Sand adherence
Plate and sheet	Edge cracking
	Laminations
	Flakes
	Stringers
Extrusions and drawn products	Edge cracking
	Seams
	Steps
	Central bursts

Example 4: Forging Laps in Ski Chair Lift Grip Components.

Alloy steel forgings used as structural members of a ski chair lift grip mechanism were identified to have contained forging laps during an annual magnetic-particle inspection of all chair lift grip structural members at a mountain resort. A lap in one of the lift grip components (Fig. 27) measured 4.8 mm ($^3/_{16}$ in.) long on the surface. An example of the metallurgical cross section through a similar lap is provided in Fig. 28. In accordance with the ASTM International standard for magnetic-particle inspection, the paint on the forgings was stripped prior to performing the magnetic-particle inspection, because the thickness of the paint slightly exceeded the maximum allowable 0.05 mm (0.002 in.) thick paint layer. It should be noted that prior annual inspections, performed at a contracted magnetic-particle inspection facility, revealed no significant indications on these forgings. However, the paint was not stripped prior to the magnetic-particle inspection at that time.

The presence of the laps, which are rejectable according to the manufacturer's drawings, indicates the forgings were delivered from the manufacturer in this condition. Aside from the obvious procedural roots related to the quality system of the manufacturer, the present issue was whether or not the laps (i.e., sharp-notched discontinuities) had "grown" in a progressive manner, such as by fatigue or stress-corrosion cracking, during the five years that the components had been in service.

The material was confirmed to be 34CrNiMo6 (a European Cr-Ni-Mo alloy steel containing 0.34% C), as required. The broken-open lap (Fig. 29) revealed a darkened area on the fracture surface that was consistent with the dimensions of the lap. The darkened area extended 0.89 mm (0.035 in.) deep. Adjacent to the darkened area, a small area of bright, fibrous fracture features was observed, as well as a transition to a bright, faceted fracture appearance. Scanning electron microscope examination in conjunction with energy-dispersive x-ray spectroscopy revealed a heavy oxide on the dark area of the fracture surface (Fig. 30). The bright area adjacent to the dark area contained dimpled rupture, which changed to cleavage fracture beyond this area. It was determined through stereomicroscopy, fractography, and metallography that the oxidized portion of the fracture was the preexisting forging lap and that both bright fracture areas were created in the laboratory during the breaking-open process. A cross-sectional view of the broken-open lap is shown in Fig. 31, depicting the field of oxides in the material beneath the lap surface.

This case is particularly significant in that it is a successful example of failure prevention through periodic field inspections. The previously unknown defects were discovered only after magnetic-particle inspection procedures adhering to ASTM International standard practices were rigorously followed. Subsequent investigation and analysis of the indications revealed no growth of the laps in service. Nevertheless, the corrective action defined that all forgings showing laps be removed from service. Preventive measures involved critical review and revision of the forging process (so that future lots would be properly forged) and revisions to the nondestructive evaluation (NDE) procedures at the forging supplier.

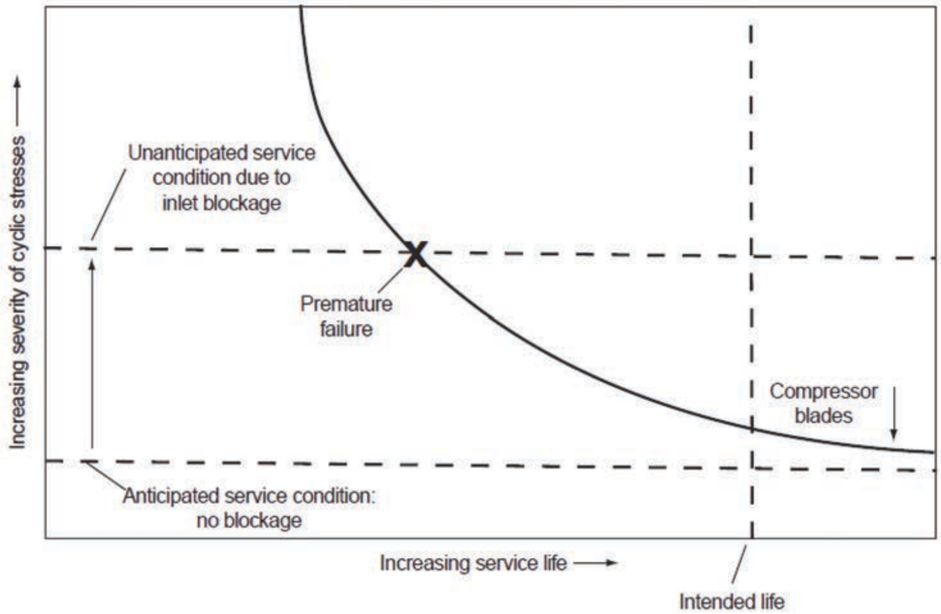

Fig. 26 Application-life diagram showing effects of increasing the severity of the service condition

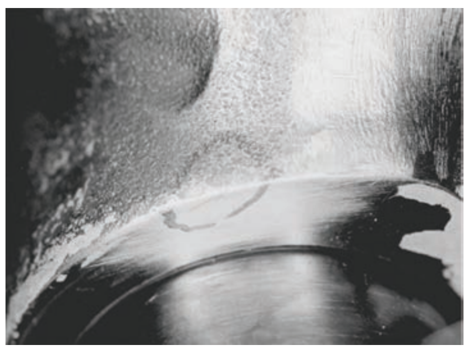

Fig. 27 Forging lap on ski lift fixed jaw

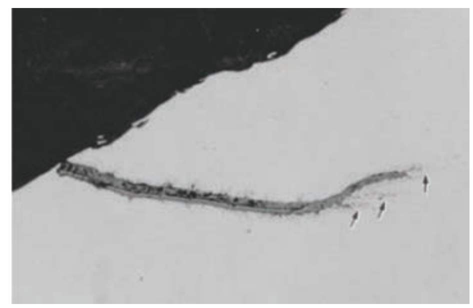

Fig. 28 Microstructure of forging lap in another ski lift grip component. As-polished. Original magnification: 111×

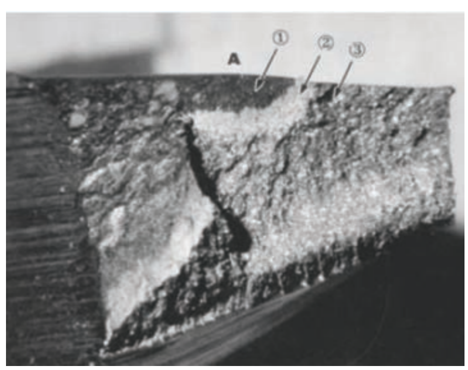

Fig. 29 Broken-open lap. Original magnification: 6×

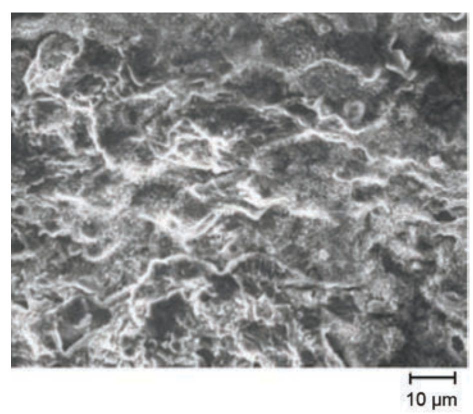

Fig. 30 Scanning electron micrograph of surface features in dark area

Building an application-life diagram around this case (Fig. 32) (Ref 24), one can explore the impact of material defects of various sizes on service life. In one possible scenario, the