deflection or fracture of the part interferes with proper function. A list of potential mechanical failure modes that have been observed in various machine parts and machines is presented in the next section, followed by a brief description of each one.

### 2.3 Modes of Mechanical Failure

Failure modes are the physical processes that take place or combine their effects to produce failure, as just discussed. The following list\(^2\) includes the failure modes most commonly observed in machines and machine parts.

1. Force- and/or temperature-induced elastic deformation
2. Yielding
3. Brinelling
4. Ductile rupture
5. Brittle fracture
6. Fatigue:
   a. High-cycle fatigue
   b. Low-cycle fatigue
   c. Thermal fatigue
   d. Surface fatigue
   e. Impact fatigue
   f. Corrosion fatigue
   g. Fretting fatigue
7. Corrosion:
   a. Direct chemical attack
   b. Galvanic corrosion
   c. Pitting corrosion
   d. Intergranular corrosion
   e. Selective leaching
   f. Erosion corrosion
   g. Cavitation corrosion
   h. Hydrogen damage
   i. Biological corrosion
   j. Stress corrosion
8. Wear:
   a. Adhesive wear
   b. Abrasive wear
   c. Corrosive wear
   d. Surface fatigue wear
   e. Deformation wear
   f. Impact wear
   g. Fretting wear
9. Impact:
   a. Impact fracture
   b. Impact deformation
   c. Impact wear
   d. Impact fretting
   e. Impact fatigue
10. Fretting:
    a. Fretting fatigue
    b. Fretting wear
    c. Fretting corrosion
11. Creep
12. Thermal relaxation
13. Stress rupture
14. Thermal shock
15. Galling and seizure
16. Spalling
17. Radiation damage
18. Buckling
19. Creep buckling
20. Stress corrosion
21. Corrosion wear
22. Corrosion fatigue
23. Combined creep and fatigue

\(^2\) Extracted from ref. 1, with permission.
As these terms are used in this text, and as commonly used in engineering practice, the failure modes just listed may be defined and described briefly as follows. It should be emphasized that these potential failure modes only produce failure when they generate a set of circumstances that interferes with the proper functioning of a machine or device.

**Force- and/or temperature-induced elastic deformation** failure occurs whenever the elastic (recoverable) deformation in a machine member, brought about by the imposed operational loads or temperatures, becomes great enough to interfere with the ability of the machine to satisfactorily perform its intended function.

**Yielding** failure occurs when the plastic (unrecoverable) deformation in a ductile machine member, brought about by the imposed operational loads or motions, becomes great enough to interfere with the ability of the machine to satisfactorily perform its intended function.

**Brinelling** failure occurs when the static forces between two curved surfaces in contact result in local yielding of one or both mating members to produce a permanent surface discontinuity of significant size. For example, if a ball bearing is statically loaded so that a ball is forced to permanently indent the race through local plastic flow, the race is brinnelled. Subsequent operation of the bearing might result in intolerably increased vibration, noise, and heating, and, therefore, failure would have occurred.

**Ductile rupture** failure occurs when the plastic deformation, in a machine part that exhibits ductile behavior, is carried to the extreme so that the member separates into two pieces. Initiation and coalescence of internal voids slowly propagate to failure, leaving a dull, fibrous rupture surface.

**Brittle fracture** failure occurs when the elastic deformation, in a machine part which exhibits brittle behavior, is carried to the extreme so that the primary interatomic bonds are broken and the member separates into two or more pieces. Preexisting flaws or growing cracks provide initiation sites for very rapid crack propagation to catastrophic failure, leaving a granular, multifaceted fracture surface.

**Fatigue** failure is a general term given to the sudden and catastrophic separation of a machine part into two or more pieces as a result of the application of fluctuating loads or deformations over a period of time. Failure takes place by the initiation and propagation of a crack until it becomes unstable and propagates suddenly to failure. The loads and deformations that cause failure by fatigue are typically far below the static failure levels. When loads or deformations are of such magnitude that more than about 50,000 cycles are required to produce failure, the phenomenon is usually termed **high-cycle fatigue**. When loads or deformations are of such magnitude that less than about 10,000 cycles are required to produce failure, the phenomenon is usually termed **low-cycle fatigue**. When load or strain cycling is produced by a fluctuating temperature field in the machine part, the process is usually termed **thermal fatigue**. **Surface fatigue** failure, usually associated with rolling surfaces in contact (but sometimes associated with sliding contact), manifests itself as pitting, cracking, and spalling of the contacting surfaces as a result of the cyclic Hertz contact stresses that result in maximum values of cyclic shear stresses slightly below the surface. The cyclic subsurface shear stresses generate cracks that propagate to the con-
tacting surface, dislodging particles in the process, to produce surface pitting. This phenomenon is often viewed as a type of wear. Impact fatigue, corrosion fatigue, and fretting fatigue are described later.

Corrosion failure, a very broad term, implies that a machine part is rendered incapable of performing its intended function because of the undesired deterioration of the material as a result of chemical or electrochemical interaction with the environment. Corrosion often interacts with other failure modes such as wear or fatigue. The many forms of corrosion include the following: Direct chemical attack, perhaps the most common type of corrosion, involves corrosive attack of the surface of the machine part exposed to the corrosive medium, more or less uniformly over the entire exposed surface. Galvanic corrosion is an accelerated electrochemical corrosion that occurs when two dissimilar metals in electrical contact are made part of a circuit completed by a connecting pool or film of electrolyte or corrosive medium, leading to current flow and ensuing corrosion. Crevice corrosion is the accelerated corrosion process highly localized within crevices, cracks, or joints where small volume regions of stagnant solution are trapped in contact with the corroding metal. Pitting corrosion is a very localized attack that leads to the development of an array of holes or pits that penetrate the metal. Intergranular corrosion is the localized attack occurring at grain boundaries of certain copper, chromium, nickel, aluminum, magnesium, and zinc alloys when they are improperly heat treated or welded. Formation of local galvanic cells that precipitate corrosion products at the grain boundaries seriously degrades the material strength because of the intergranular corrosive process.

Selective leaching is a corrosion process in which one element of a solid alloy is removed, such as in dezincification of brass alloys or graphitization of gray cast irons. Erosion corrosion is the accelerated chemical attack that results when an abrasive or viscous material flows past a containing surface continuously baring fresh, unprotected material to the corrosive medium. Cavitation corrosion is the accelerated chemical corrosion that results when, because of differences in vapor pressure, certain bubbles and cavities within a fluid collapse adjacent to the pressure vessel walls, causing particles of the surface to be expelled, baring fresh, unprotected surface to the corrosive medium. Hydrogen damage, while not considered to be a form of direct corrosion, is induced by corrosion. Hydrogen damage includes hydrogen blistering, hydrogen embrittlement, hydrogen attack, and decarburization. Biological corrosion is a corrosion process that results from the activity of living organisms, usually by virtue of their processes of food ingestion and waste elimination, in which the waste products are corrosive acids or hydroxides. Stress corrosion, an extremely important type of corrosion, is described separately later.

Wear is the undesired cumulative change in dimensions brought about by the gradual removal of discrete particles from contacting surfaces in motion, usually sliding, predominantly as a result of mechanical action. Wear is not a single process, but a number of different processes that can take place independently or in combination, resulting in material removal from contacting surfaces through a complex combination of local shearing, plowing, gouging, welding, tearing, and others. Adhesive wear takes place because of high local pressure and welding at asperity contact sites, followed by motion-induced plastic deformation and rupture of asperity junctions, with resulting metal removal or transfer. Abrasive wear takes place when the wear particles are removed from the surface by plowing, gouging, and cutting action of the asperities of a harder mating surface or by hard particles entrapped between the mating surfaces. When the conditions for either adhesive wear or abrasive wear coexist with conditions that lead to corrosion, the processes interact synergistically to produce corrosive wear. As described earlier, surface fatigue wear is
a wear phenomenon associated with curved surfaces in rolling or sliding contact, in which subsurface cyclic shear stresses initiate microcracks that propagate to the surface to spall out macroscopic particles and form wear pits. Deformation wear arises as a result of repeated elastic deformation at the wearing surface that produces a matrix of cracks that grow in accordance with the surface fatigue description just given. Fretting wear is described later.

Impact failure results when a machine member is subjected to nonstatic loads that produce in the part stresses or deformations of such magnitude that the member no longer is capable of performing its function. The failure is brought about by the interaction of stress or strain waves generated by dynamic or suddenly applied loads, which may induce local stresses and strains many times greater than would be induced by static application of the same loads. If the magnitudes of the stresses and strains are sufficiently high to cause separation into two or more parts, the failure is called impact fracture. If the impact produces intolerable elastic or plastic deformation, the resulting failure is called impact deformation. If repeated impacts induce cyclic elastic strains that lead to initiation of a matrix of fatigue cracks, which grow to failure by the surface fatigue phenomenon described earlier, the process is called impact wear. If fretting action, as described in the next paragraph, is induced by the small lateral relative displacements between two surfaces as they impact together, where the small displacements are caused by Poisson strains or small tangential “glancing” velocity components, the phenomenon is called impact fretting. Impact fatigue failure occurs when impact loading is repetitively applied to a machine member until failure occurs by the nucleation and propagation of a fatigue crack.

Fretting action may occur at the interface between any two solid bodies whenever they are pressed together by a normal force and subjected to small-amplitude cyclic relative motion with respect to each other. Fretting usually takes place in joints that are not intended to move but, because of vibrational loads or deformations, experience minute cyclic relative motions. Typically, debris produced by fretting action is trapped between the surfaces because of the small motions involved. Fretting fatigue failure is the premature fatigue fracture of a machine member subjected to fluctuating loads or strains together with conditions that simultaneously produce fretting action. The surface discontinuities and microcracks generated by the fretting action act as fatigue crack nuclei that propagate to failure under conditions of fatigue loading that would otherwise be acceptable. Fretting fatigue failure is an insidious failure mode because the fretting action is usually hidden within a joint where it cannot be seen, leading to premature, and often unexpected, fatigue failure of a sudden and catastrophic nature. Fretting wear failure results when the changes in dimensions of the mating parts, because of the presence of fretting action, become large enough to interfere with proper design function or large enough to produce geometrical stress concentration of such magnitude that failure ensues as a result of excessive local stress levels. Fretting corrosion failure occurs when a machine part is rendered incapable of performing its intended function because of the surface degradation of the material from which the part is made, as a result of fretting action.

Creep failure results whenever the plastic deformation in a machine member accrues over a period of time under the influence of stress and temperature until the accumulated dimensional changes interfere with the ability of the machine part to satisfactorily perform its intended function. Three stages of creep are often observed: (1) transient or primary creep, during which time the rate of strain decreases, (2) steady-state or secondary creep, during which time the rate of strain is virtually constant, and (3) tertiary creep, during
which time the creep strain rate increases, often rapidly, until rupture occurs. This terminal rupture is often called creep rupture and may or may not occur, depending on the stress-time-temperature conditions.

**Thermal relaxation or stress relaxation** failure occurs when the dimensional changes due to the creep process result in the relaxation of a prestrained or prestressed member until it no longer is able to perform its intended function. For example, if the prestressed flange bolts of a high-temperature pressure vessel relax over a period of time because of creep in the bolts, so that finally the peak pressure surges exceed the bolt preload to violate the flange seal, the bolts will have failed because of thermal relaxation.

**Stress rupture** failure is intimately related to the creep process except that the combination of stress, time, and temperature is such that rupture into two parts is assured. In stress rupture failures the combination of stress and temperature is often such that the period of steady-state creep is short or nonexistent.

**Thermal shock** failure occurs when the thermal gradients generated in a machine part are so pronounced that differential thermal strains exceed the ability of the material to sustain them without yielding or fracture.

**Galling** failure occurs when two sliding surfaces are subjected to such a combination of loads, sliding velocities, temperatures, environments, and lubricants that massive surface destruction is caused by welding and tearing, plowing, gouging, significant plastic deformation of surface asperities, and metal transfer between the two surfaces. Galling may be thought of as a severe extension of the adhesive wear process. When such action results in significant impairment to intended surface sliding, or in seizure, the joint is said to have failed by galling. **Seizure** is an extension of the galling process to such a level of severity that the two parts are virtually welded together, and relative motion is no longer possible.

**Spalling** failure occurs whenever a particle is spontaneously dislodged from the surface of a machine part so as to prevent the proper function of the member. Armor plate fails by spalling, for example, when a striking missile on the exposed side of an armor shield generates a stress wave that propagates across the plate in such a way as to dislodge or spall a secondary missile of lethal potential on the protected side. Other examples of spalling failure are manifested in rolling contact bearings and gear teeth because of the action of surface fatigue as described earlier.

**Radiation damage** failure occurs when the changes in material properties induced by exposure to a nuclear radiation field are of such a type and magnitude that the machine part is no longer able to perform its intended function, usually as a result of the triggering of some other failure mode, and often related to loss in ductility associated with radiation exposure. Elastomers and polymers are typically more susceptible to radiation damage than are metals whose strength properties are sometimes enhanced rather than damaged by exposure to a radiation field, though ductility is usually decreased.

**Buckling** failure occurs when, because of a critical combination of magnitude and/or point-of-load application, together with the geometrical configuration of a machine member, the deflection of the member suddenly increases greatly with only a slight increase in load. This nonlinear response results in a buckling failure if the buckled member is no longer capable of performing its design function.
Creep buckling failure occurs when, after a period of time, the creep process results in an unstable combination of the loading and geometry of a machine part so that the critical buckling limit is exceeded and failure ensures.

Stress corrosion failure occurs when the applied stresses on a machine part in a corrosive environment generate a field of localized surface cracks, usually along grain boundaries, that render the part incapable of performing its function, often because of triggering some other failure mode. Stress corrosion is a very important type of corrosion failure mode because so many different metals are susceptible to it. For example, a variety of iron, steel, stainless steel, copper, and aluminum alloys are subject to stress corrosion cracking if placed in certain adverse corrosive media.

Corrosion wear failure is a combination failure mode in which corrosion and wear combine their deleterious effects to incapacitate a machine part. The corrosion process often produces a hard, abrasive corrosion product that accelerates the wear, while the wear process constantly removes the protective corrosion layer from the surface, baring fresh metal to the corrosive medium and thus accelerating the corrosion. The two modes combine to make the result more serious than the sum of the modes would have been otherwise.

Corrosion fatigue is a combination failure mode in which corrosion and fatigue combine their deleterious effects to cause failure of a machine part. The corrosion process often forms pits and surface discontinuities that act as stress raisers that in turn accelerate fatigue failure. Further, cracks in the usually brittle corrosion layer also act as fatigue crack nuclei that propagate into the base material. On the other hand, the cyclic loads or strains cause cracking and flaking of the corrosion layer, which bares fresh metal to the corrosive medium. Thus, each process accelerates the other, often making the result disproportionately serious.

Combined creep and fatigue failure is a combination failure mode in which all of the conditions for both creep failure and fatigue failure exist simultaneously, each process influencing the other to produce accelerated failure. The interaction of creep and fatigue is probably synergistic but is not well understood.

Identification of the most probable governing failure mode (in many cases there may be more than one candidate) by a designer is an essential step that should be undertaken early in the design of any machine part. Selection of material and establishment of the shape and size of the part must then be tailored to provide safe, reliable, cost-effective operation throughout the design lifetime. The following sections provide some basic concepts and equations useful in designing to avoid failure by the more commonly encountered failure modes.

2.4 Elastic Deformation, Yielding, and Ductile Rupture

In the seventeenth century it was experimentally established that if a direct axial external force \( F \) is applied to a machine element, whether it is a traditional spring (see Chapter 14) or a straight cylindrical bar such as the one shown in Figure 2.1, changes in the length of the machine element are produced. Further, for a broad class of materials, a linear relationship exists between the applied force, \( F \), and the induced change in length, \( y \), as long as the material is not stressed beyond its elastic range.\(^3\) The elastic deflection, \( y \), and the

\(^3\)See Hooke’s Law discussion of 4.5.