

C • H • A • P • T • E • R • 5

# **MATERIALS OF CONSTRUCTION**

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# SECTION 5.1

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# METALLIC MATERIALS OF PUMP CONSTRUCTION (AND THEIR DAMAGE MECHANISMS)

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The requirements for a successful pump installation are *performance* and *life*. Performance is the rating of the pump head, capacity, and efficiency. Life is the total number of hours of operation before one or more pump components must be replaced to maintain an acceptable performance. The initial performance is the responsibility of the pump manufacturer and is inherent in the pump design. Life is primarily a measure of the resistance of the materials of construction to corrosion, erosion, wear, and other factors that can influence the materials when the pump has been placed in service. The need to maximize reliability and extend the pump life makes the selection of appropriate materials of construction crucial.

The selection of materials that are both cost-effective and technically suitable for the application requires a knowledge not only of the pump design and manufacturing processes, but also of the engineering properties of the material, particularly its corrosion and wear resistance properties when subjected to the conditions encountered in the pump. Sufficient information is available in the corrosion and metallurgical literature as well as from the experience of pump manufacturers to make appropriate material choices for virtually any pumping application.

It is known that several factors lead to a long pump life. These include

- Neutral liquids at near-ambient temperatures
- Appropriate material selections for pumps in aggressive services
- The absence of abrasive particles
- Continuous operation at or near the maximum efficiency capacity of the pump
- An adequate margin of available *NPSH* over *NPSH* required as stated on the manufacturer's rating curve
- A low velocity (developed head/rotative speed)

Pumping installations that satisfy all these criteria will have a long life. A typical example would be a waterworks pump. Some waterworks pumps with bronze impellers

and cast-iron casings have a life of 50 years or more. At the other extreme might be a chemical pump handling a hot corrosive liquid with abrasive particles carried in suspension. The life of this pump might be measured in months rather than in years, despite the fact that construction was based on the most resistant materials available.

Most pumping applications fall somewhere between these two extremes. The pump designer needs to be familiar with the various types of degradation that can affect the components of the pump and reduce its useful life. These can be grouped into the general categories of corrosion, wear, and fatigue, with corrosion and wear being the predominant life-limiting mechanisms.

## TYPES OF CORROSION

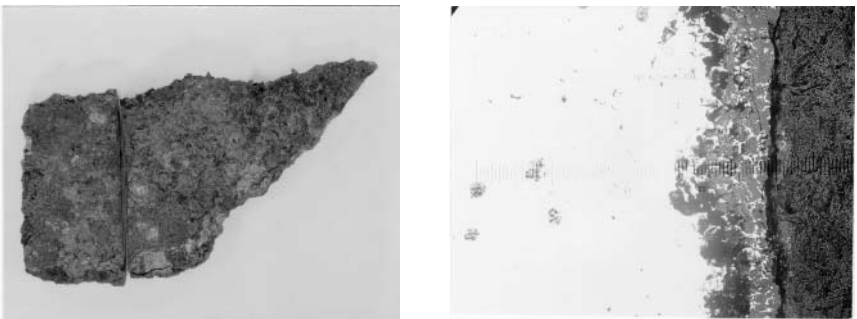
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**General Corrosion** General corrosion is corrosion that proceeds without an appreciable localization of attack. This type of corrosion occurs on metals or alloys that do not develop an effective passive film on the surface. Usually, the corrosion mechanism is oxidation with the formation of metal oxide corrosion products. General corrosion is most often encountered in pumps with carbon steels and copper base alloys. Cast irons also experience a specialized form of general corrosion, known as *graphitic corrosion*, which will be considered separately.

Carbon steel does not develop a protective oxide film and will corrode at a rate dependent upon several characteristics of the water or other fluid, including temperature, oxygen content, pH, and fluid chemistry. Several empirical indices based on water chemistry exist and can be used to calculate the relative corrosivity of natural waters to carbon steel and similar ferrous alloys. The Langelier Index is best known. The rate of corrosion is also very dependent on velocity and increases with an increasing velocity. In most pump applications, with the notable exception of hydrocarbons, the corrosion rate of carbon steel is too high for this material to provide a useful life. However, carbon steel is frequently used, particularly in vertical pumps, with some form of protective coating to prevent corrosion. Coal tar epoxy is a preferred coating for many water services.

Copper alloys, including both brasses and bronzes, are also subject to general corrosion in the water applications where they are most commonly used in the pump industry. The corrosion rate will be increased by the presence of small amounts of sulfides in the water. Copper alloys gradually develop a protective copper oxide corrosion film in most applications. The corrosion rate gradually decreases over time as this film develops. The rate of general corrosion varies with the specific type or grade of copper alloy. Among the alloys commonly used in pumps, nickel aluminum bronzes have the lowest corrosion rate and best tolerance for higher velocities.

The general corrosion of a Ductile Ni-Resist casing from a vertical pump is shown in Figure 1. A metallographic cross section was removed to show the depth of the corrosion attack.



**FIGURE 1** A small fragment of Ductile Ni-Resist from the lower casing of a vertical pump. The microstructure is also shown on the right side of this figure, illustrating the depth of the corrosion's penetration. This is a classic example of general corrosion (right photo at 100 $\times$ ).

**Dealloying** Dealloying is the preferential removal of one phase from a multi-phase alloy, or one element from a material. Several types of dealloying occur in the pump industry. One of the most common is the graphitic corrosion of gray cast iron. This material is low cost, easy to machine, and well suited for a variety of applications, especially in the waterworks industry. It is probably the most widely used material in the pump industry.

Gray cast iron corrodes by a fundamentally different mechanism than carbon steel or ductile cast iron. The structure of gray cast iron consists of interconnected graphite flakes in a matrix that is predominantly iron. In the presence of an electrolyte, which is usually water, a galvanic cell is established between the iron and graphite. The iron corrodes, and the corrosion products are largely flushed away with the fluid passing through the pump. The original casting is gradually reduced to a porous graphite structure that may contain some iron oxide corrosion product. This is frequently referred to as *graphitization*. The surface of a gray iron casting that has suffered graphitic corrosion will retain its original shape and dimensions, but the surface will be largely graphite, which can be cut with a knife. The casting will lose some fraction of its mechanical properties and become increasingly susceptible to brittle failure, resulting from modest shock or impact loads. This is also the corrosion mechanism for Ni-Resist in seawater. Figure 2 shows the interface between the sound base metal and the graphitized front.

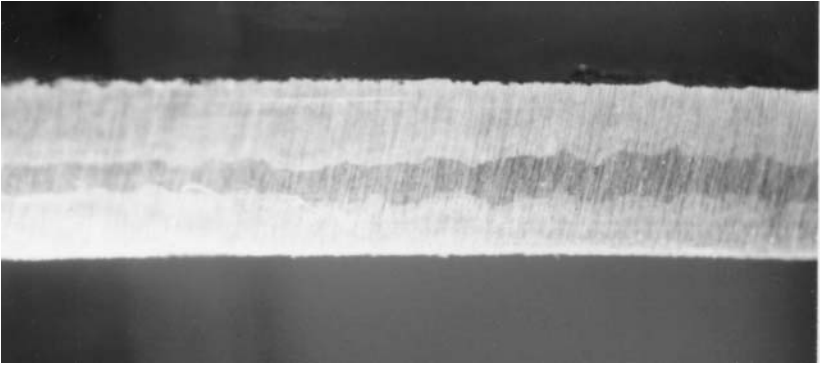
It is important to recognize that the rate of graphitic corrosion varies with the water chemistry, and that this type of corrosion can occur in both fresh and salt waters. The high conductivity of salt water corresponds to a higher corrosion rate. Graphitic corrosion will proceed at a slower pace in waters that have a high mineral content. Minerals tend to plug the graphitic layer on the surface, sealing off the base metal from exposure to the fluid, thereby reducing the corrosion rate.

As the surface of a cast-iron component, such as a pump casing, gradually graphitizes, the galvanic relationships with other components within the pump will be altered. It has been observed that the bronze impeller originally supplied in a cast-iron pump handling seawater will provide a significantly longer life than bronze impellers that are installed after the pump has been in service for several years. The reduced life of the replacement impellers is caused by an altered galvanic relationship with the pump casing. Initially, the casing was cast iron, which is anodic to a bronze impeller. With time, as the casing graphitizes, it gradually becomes cathodic, due to the influence of the graphite. The bronze impeller is now the anode and corrodes at a much higher rate. This example highlights the influence that graphitic corrosion can have on other components within the pump and the importance of carefully selecting materials for use in conductive fluids, such as salt water.

Several other types of dealloying can also occur in pumps. Brass and bronze alloys containing more than about 14 percent zinc are subject to a form of dealloying known as *dezincification*. The zinc is preferentially corroded from the matrix of the material, leaving a spongy, copper-rich residue. Dezincification can occur either uniformly in a shallow layer



**FIGURE 2** The interface between the advancing graphitized front and the sound base metal. Graphitic corrosion propagates along the path of the graphite flakes (50 $\times$ ).



**FIGURE 3** The dealloying of a vertical turbine pump impeller. Note the change in color across the cross section. The unaffected bronze (light color) material is surrounded by a dezincified layer (1.3 $\times$ ).

over the surface of the casting or as a distinct plug confined to a small area. Plug-type dezincification is a more serious problem because the plug is weak and will cause leakage if it penetrates a pressure boundary, but it should be emphasized that copper alloys containing less than 14 percent zinc are not susceptible to this form of corrosion. Consequently, the requirement often imposed upon pump manufacturers for zinc-free bronzes to avoid dezincification is without technical justification. Figure 3 shows the dealloying of an impeller.

The final type of dealloying that occasionally occurs in pumps is dealuminification in aluminum bronzes. These are metallurgically complex materials. Some compositions can form an aluminum-rich phase that can be preferentially corroded in aggressive fluids, especially seawater. The detrimental phase can be mitigated by a special heat treatment known as *temper annealing*. This heat treatment must be specified by the designer for susceptible compositions, because it is not a mandatory requirement of national material specifications. The chemistry of some aluminum bronze alloys from Europe has been adjusted to preclude the formation of the detrimental aluminum-rich phase without the need for the temper annealing heat treatment. The temper anneal can serve as a stress relief operation for fabricated aluminum bronze structures, which is a secondary benefit for products in this category.

**Galvanic Corrosion** *Galvanic corrosion* refers to the corrosion that occurs when one alloy is electrically coupled to another and exposed in a conductive liquid. Usually, the corrosion rate of the more noble alloy will be less than if it were exposed uncoupled. The corrosion rate of the less noble material will be greater than if it were exposed uncoupled.

Several factors influence the rate of galvanic corrosion of both metals. This corrosion is greatly influenced by the conductivity of the fluid. In a fluid such as fresh water, which has a low conductivity, galvanic corrosion will be less severe and generally confined to the immediate location where the metals contact one another. However, in a highly conductive fluid, such as seawater, galvanic corrosion will be more severe and will occur over a wider area. The pump designer needs to consider the possibility of such corrosion when using dissimilar metals in a conductive fluid.

Galvanic corrosion problems in seawater and other conductive fluids can be avoided by the careful use of materials. Galvanic corrosion is related to the area ratios of the coupled metals. It is always desirable to have the area of the anode, or less noble metal, equal to or greater than that of the more noble metal. In this way, the additional corrosion experienced by the less noble metal will be spread over a relatively large area and will not be excessive because of being coupled. An example of the effective use of this galvanic relationship involves centrifugal pumps having a Ni-Resist casing and austenitic stainless steel internals. This combination is often specified for seawater services. The Ni-Resist is

anodic to the stainless steel and will protect it from localized corrosion when the pump is shut down and contains stagnant water. The area of Ni-Resist is considerably larger than that of stainless steel. The increased galvanic corrosion of the Ni-Resist is spread over a large area and is negligible.

The amount of corrosion that will occur in a galvanic couple also depends on the freely corroding potentials of the coupled metals. Less corrosion-resistant metals, such as zinc, cast iron, and steel will usually have more negative potentials when measured against a standard reference electrode. More corrosion-resistant metals, such as stainless steels, will have less negative potentials.

The corrosion potentials for many commonly used engineering alloys in slowly moving seawater are shown in Table 1. The alloys are listed in the order of the potential that they exhibit in flowing seawater. Certain alloys (indicated by solid colored boxes preceding the name of the alloy) in low-velocity or poorly aerated water and at shielded areas may become active and exhibit a potential near  $-0.5$  volts. The extent of galvanic corrosion that will occur when two metals are electrically coupled will depend on the potential difference between the metals. The corrosion rate of zinc coupled to stainless steel will increase dramatically because of the large potential difference between these two metals. A nickel aluminum bronze coupled to austenitic stainless steel will experience little galvanic corrosion because the potentials of these two metals are close to one another. The pump designer needs to be aware of the corrosion potentials of dissimilar metals used in conductive fluids in order to avoid unanticipated galvanic corrosion problems.

The use of coatings can decisively alter the galvanic relationships in a pump. If the more anodic component, such as a steel casing, is coated, one can expect a high rate of corrosion at those locations where the coating eventually begins to fail. This will be caused by a very unfavorable area ratio, with a small area of exposed carbon steel coupled to a large area of some more noble metal, such as stainless steel or bronze. For this reason, coatings should be employed with caution in pumps handling conductive fluids that are constructed of dissimilar metals. It is generally advisable in these applications not to coat the anodic component. Figure 4 documents the galvanic corrosion on the interior diameter of a carbon steel flange connected to a stainless steel shroud. The accelerated corrosion is due to the unfavorable ratio of stainless steel to carbon steel in this component.

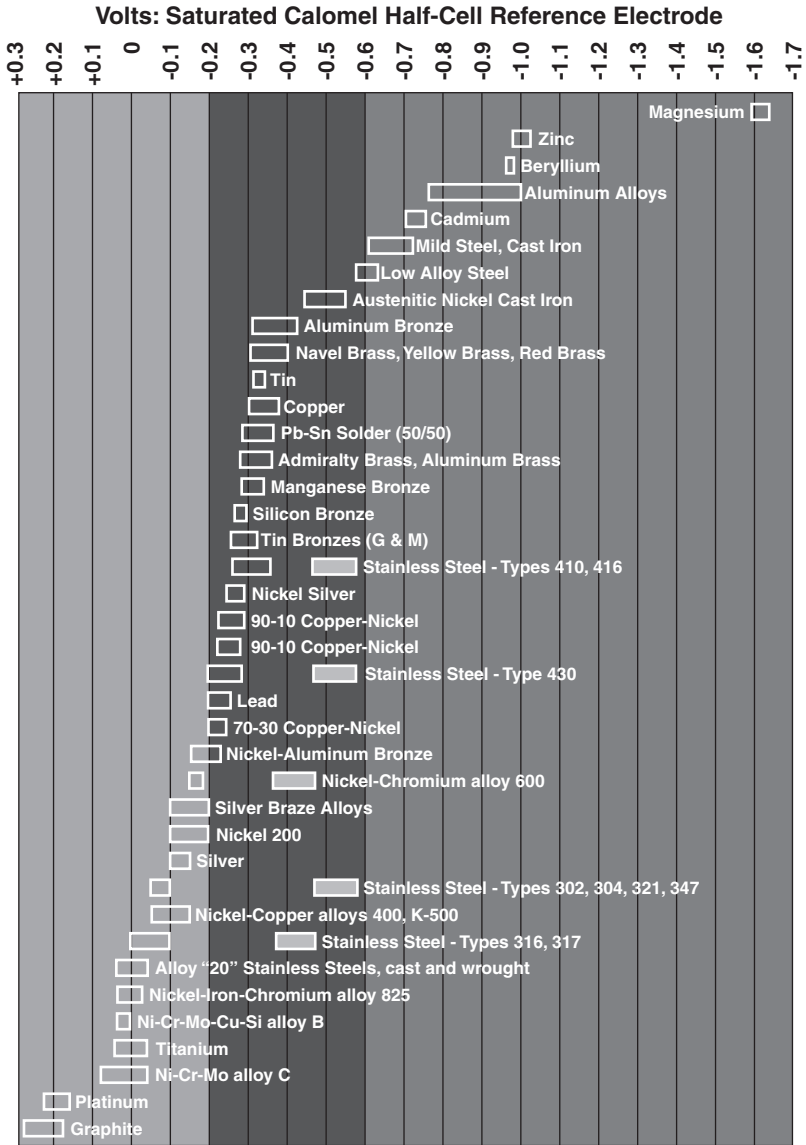
**Stress Corrosion Cracking** *Stress corrosion cracking* (SCC) is a particularly dangerous form of corrosion because it is not easily detected before it has progressed to such an extent that it can cause sudden catastrophic damage. Although relatively uncommon in pumps, it can occur in several classes of materials. The pump designer should be aware of the potential combinations of material and environment that can cause SCC.

Stress corrosion requires that several factors be present. These include tensile stress, which can be either residual or applied, a susceptible material, an environment capable of causing stress corrosion, and time.

The materials used in the pump industry that may experience SCC include austenitic and martensitic stainless steels, some copper base alloys, and, occasionally, Ni-Resist. The austenitic stainless steels are susceptible to stress corrosion in aqueous chlorides at temperatures above about  $140^{\circ}\text{F}$  ( $60^{\circ}\text{C}$ ). Cast alloys, which contain some fraction of ferrite in the microstructure, are significantly more resistant to stress corrosion than their wrought counterparts. The possibility of cracking is increased in situations where chlorides are concentrated, as by evaporation. High residual stress, often present in as-welded structures, also enhances the possibility of cracking. Increasing nickel content in austenitic stainless alloys enhances the resistance to SCC. The high nickel grade, commonly known as Alloy 20, is often used in chemical applications where the optimum resistance to stress corrosion is necessary. The SCC of austenitic stainless steels in pumps is relatively uncommon.

Martensitic stainless steels are susceptible to cracking in the presence of hydrogen sulfide and is often referred to as *sulfide stress corrosion cracking* (SSC). These steels, particularly CA-15 and CA-6NM, are commonly used in pumping applications in oil production and refining where hydrogen sulfide can be present. SCC can be avoided by giving these materials a special heat treatment intended to reduce hardness below a certain threshold level, below which cracking will not occur. This has also been correlated to the yield strength of a material. It is often seen in literature that ferrous materials used

**TABLE 1** Corrosion potentials in flowing seawater (8–13 ft/s, 50–80°F/2.4–4.0 m/s, 10–26°C)



in these services should have a hardness no greater than 22  $R_c$  or a yield strength no higher than 90,000 lb/in<sup>2</sup> (620MPa). Technical standards, including API 610 and NACE MR-01-75, can be used to specify appropriate requirements for martensitic steels, which will be used in environments containing hydrogen sulfide.



**FIGURE 4** Galvanic corrosion is evident on this pump section. Note the high corrosion rate on the interior diameter of the carbon steel flange that is attached to the stainless steel shroud.

Copper alloys are susceptible to SCC in the presence of ammonia, although considerable variations take place in the susceptibility of the various types of bronzes, with aluminum bronzes being the most resistant. Polluted natural waters can contain ammonia, and for this reason, bronze pumps are usually not a good choice for these applications.

High-strength manganese bronzes are susceptible to cracking in natural waters. Cast impellers in these alloys have been known to suffer severe cracking. Residual stress in the casting may also be sufficient to induce cracking. These alloys should not be used in pumps because of their susceptibility to such problems.

Ni-Resist is an austenitic cast iron that contains 15 to 20% nickel. This material is commonly used in large, seawater vertical pumps. Experience has shown that it is subject to SCC, especially in the diffuser section of these pumps, unless the castings are furnace stress-relieved. This must be specified by the purchaser, as it is not a requirement of national material specifications.

**Hydrogen Embrittlement** Hydrogen damage is a form of environmentally assisted failure that results from the combined action of hydrogen and residual or applied tensile stress. Hydrogen damage to specific alloys or groups of alloys manifests itself in many ways, such as cracking, blistering, hydriding, or as a loss of tensile ductility. Collectively, these various forms of damage are often referred to as *hydrogen embrittlement*.

Damage caused by hydrogen is occasionally encountered in pumps. Some plating processes, such as chrome plating, which is often used to rebuild pump shafts, generate hydrogen. This hydrogen can enter the surface of the metal. Microscopic cracks can occur in higher strength steels (greater than a 90,000-lb/in<sup>2</sup> or 620-MPa yield strength). Abusive grinding can work-harden the surface of lower strength steels and increase the probability that hydrogen will cause cracking. Microscopic cracks resulting from hydrogen damage act as stress risers and can propagate failure catastrophically by mechanical fatigue. This problem can be avoided by utilizing proper grinding practices before plating. Higher strength steels should be baked, to drive off hydrogen, immediately after plating.

Hydrogen can also be introduced into metals during welding. In order to avoid the hydrogen damage associated with welding, ferritic and martensitic steels should be welded with low hydrogen electrodes. Coated electrodes should be baked, in accordance

with manufacturer's instructions, prior to usage in order to drive off moisture, which is the major source of hydrogen contamination of welds.

**Microbiologically Induced Corrosion** Living organisms can promote corrosion in many different environments. A variety of biological organisms thrive in both aerobic and anaerobic environments. Corrosion attributable to microbiological activity occurs most frequently in stagnant water, which remains in a pump when it is shut down for an extended length of time.

Sulfate-reducing bacteria are found in many waters. They will form slimy, reddish hemispherical shaped mounds or colonies on cast iron or carbon steel. These are known as *tubercles*. If scraped off, there will invariably be a saucer-shaped pit beneath the tubercle. The inside of the pit will contain a wet, black deposit. The pitting is caused by traces of sulfuric acid excreted by the bacteria. This type of corrosion will usually not result in premature failure.

Several more serious types of microbiologically induced corrosion afflict stainless steels. A certain class of metal ion concentrating/oxidizing microbes appears to concentrate ferric and manganic chlorides, both of which are potent pitting agents. These bacteria form colonies preferentially at welds in austenitic stainless steels and are capable of causing severe pitting corrosion in a relatively short time. This problem has been encountered in a variety of equipment in both salt and fresh water. It is often discovered only when the welds begin leaking. Pumps employing welded stainless steel fabrications can be afflicted by this problem if permitted to sit idle with stagnant water, either fresh or salt, for an extended period. Biocides can be used to mitigate this problem in some instances.

Finally, the decay of biological organisms can generate hydrogen sulfide, which adversely affects the protective oxide film on copper base alloys. The enhanced biological activity in warmer tropical waters, especially under stagnant conditions, can impair the corrosion resistance of bronzes and reduce the threshold velocity at which accelerated corrosion will occur. Bronzes should be used with caution in applications where microbiological activity is anticipated and the possibility of extended shutdowns is possible.

**Intergranular Corrosion** This infrequent type of corrosion preferentially attacks a material at the grain boundaries. This is caused by local chemical differences such as the chrome-depleted regions of an austenitic stainless steel. Bronze alloys susceptible to this type of corrosion include aluminum bronzes, silicon bronzes, Muntz metal, and admiralty metal. Two things are necessary: a sensitized material and a corrosive media, such as seawater. Sensitization can occur during heat treatment or more commonly during weld repair. This type of corrosion often leads to corrosion-assisted fatigue cracks when cyclic loading is present.

The improper heat treatment of 300 series austenitic stainless steels can result in sensitization to intergranular corrosion. Sensitization occurs when stainless steels that contain more than .03% carbon are held at temperatures between 800 and 1550°F (between 425 and 850°C). At these temperatures, chrome carbides precipitate along the grain boundaries, resulting in chrome depletion in the adjacent areas. These adjacent areas have reduced corrosion resistance. Austenitic stainless steels contain approximately 16 to 18% chrome. The chromium content in the areas surrounding a chrome carbide particle can drop below the 12% necessary to maintain a passive state. A galvanic cell is set up with a large cathode (grains) and a small anode (grain boundaries). In this undesirable scenario, corrosion occurs along the anodic grain boundaries. The extent of the corrosion damage depends on the length of time held within the sensitization temperature range. The degree of sensitization is a function of the carbon content; the higher the carbon content, the shorter the period of time the material can be held within this range without sensitization occurring. A graph of the temperature versus time for various carbon contents illustrates this point in Figure 5. Intergranular corrosion of an improperly heat-treated stuffing box cover is shown in Figure 6.

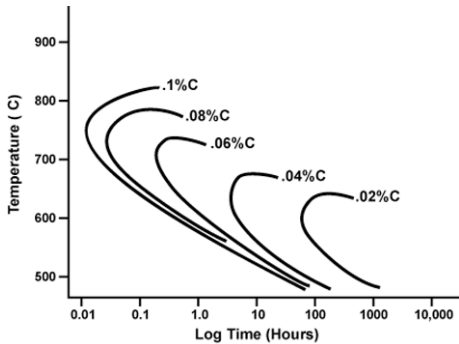
Austenitic stainless steels can also be sensitized during normal welding procedures. Care must be taken to avoid the sensitization range during welding followed by proper post-weld heat treatment when necessary.

Sensitization can be avoided or corrected by several methods:

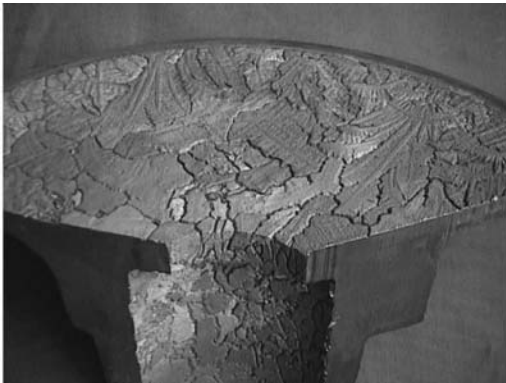
- Heat the material to a temperature high enough to dissolve the chrome carbides, typically 1900 to 2100°F (1040 to 1150°C), followed by rapid cooling through the sensitization range. Localized heat treatment of welded areas will not desensitize a material.
- Use a stainless steel that is stabilized by the addition of niobium or titanium. These two elements will tie up the carbon, thus preventing chrome carbides.
- Reduce the carbon content to a low level (less than .03 percent). The lower the carbon content, the longer it takes chrome carbide precipitation to occur.

When austenitic stainless steels are necessary in the pump industry, materials commonly used in services where intergranular attack is anticipated include 316L, 304L, CF-3, and CF-3M. Intergranular corrosion is not a concern in alloys containing 25% or more chromium.

**Cavitation Erosion** Cavitation erosion is primarily a mechanical process, although it acts synergistically with corrosion and is often considered with other forms of corrosion. Cavitation erosion can be defined as metal removal from the surface caused by high



**FIGURE 5** Time-temperature sensitization curves as determined by the Strauss Test for 18-8 stainless steel. Note that a low carbon grade of stainless (0.03% C) requires five to 10 hours exposure, while a standard grade (0.08%) need only minutes of exposure time.



**FIGURE 6** The surface of a stuffing box cover that experienced intergranular corrosion due to sensitization. The grains are clearly evident on the interior of the bore as well.



**FIGURE 7** Cavitation erosion of an impeller, indicated by the porous appearance of cavitated regions on the surface

stresses associated with the collapse of vapor bubbles in the fluid. Cavitation occurs in a pump when the local pressure of the fluid is reduced to the vapor pressure. In a multi-stage pump, vapor bubbles form in the low-pressure areas at the impeller inlet and are swept by the flow into regions of higher pressure where they collapse. A great many bubbles may form and collapse in a small area, producing many microjets of high kinetic energy. The energy released by the bubble collapse is expended as impact loading on the metal surface. This situation is aggravated if protective oxide films are present because these are damaged, exposing fresh metal to the corrosive action of the fluid. This cyclic loading eventually causes the formation of microscopic fatigue cracks. These cracks propagate and intersect, resulting in the removal of metal from the surface and the characteristic spongy or porous appearance of cavitation damage. An example of a cavitated impeller is shown in Figure 7.

Although every effort should be made in the design and application of centrifugal pumps to prevent cavitation, it is not always possible to do so at capacities less than the rated maximum efficiency capacity of the pump. It must be recognized that at a low flow operation, the stated *NPSH* required curve is not usually sufficient to suppress all cavitation damage. The stated *NPSH* required is that needed to produce the head, capacity, and efficiency shown on the rating curve. At low flows, some cavitation damage should be expected. It may be impractical to supply an *NPSH* that would suppress all cavitation at these low flows, as it could be many times that it is required at the best efficiency point. Therefore, the possibility of cavitation damage frequently becomes a consideration when selecting material for impellers.

Open-type mixed flow impellers that produce heads in excess of 35 ft (10.7 m) are particularly susceptible to cavitation erosion in the clearance space between the rotating vanes and the stationary housing. This is usually referred to as *vane tip erosion* and is caused by a cavitating vortex in the clearance space between the vane and the housing. It is also impractical in this instance to provide sufficient *NPSH* to eliminate the cavitation. Any evaluation of the impeller and housing for a pump of this type should include the possibility of vane tip erosion.

It was conventional wisdom in the pump industry until recent years that the cavitation resistance of a material was directly related to its hardness. A more sophisticated under-

standing has been developed in recent years that has led to the development of a new class of nonstandard stainless steels with exceptional cavitation resistance.

The relationship between cavitation resistance and hardness was first critically investigated in the 1970s when it was observed that cobalt base alloys of a modest hardness developed a very high resistance to cavitation damage. Cavitation resistance was related to the capability of the material to transform at the surface when subject to cavitation loading into a harder, more resistant metallurgical phase. This work was extended to austenitic stainless steels, whose chemical composition was adjusted to promote the formation of a stress-induced martensite under cavitation loading. New alloys were developed initially as weld filler metals to repair cavitation damage and later as impeller castings for pumps. These alloys have relatively low hardness in the solution-annealed condition, comparable to standard austenitic grades, but transform to a much harder martensite at the surface upon exposure to cavitation loading. The hard surface layer resists the initiation of fatigue cracks. If these cracks eventually develop after extended exposure to cavitation bubbles, propagation into the soft ductile base metal is difficult. Cavitation-resistant austenitic stainless steel castings, alloyed with chrome and manganese, develop cavitation resistance similar to that of cobalt base alloys.

Extensive laboratory tests of the resistance of a wide range of materials to cavitation erosion have produced data for all the materials commonly used in centrifugal pump construction. It is possible to make a good correlation between the laboratory data and field experience to develop the following tabulation of the cavitation-resistance properties of pump materials, listed in order of decreasing cavitation resistance:

- Stellite
- Chrome-manganese austenitic stainless
- Carburized 12% chrome stainless casting
- Titanium 6AL-4V
- Cast nickel-aluminum bronze
- Cast duplex stainless steel
- Cast precipitation hardening stainless steel
- Ductile NiResist
- Cast CF-8M
- Cast CA6-NM
- Cast CA-15
- Monel
- Manganese bronze
- Carbon steel (cast)
- Leaded bronze
- Cast iron

Selecting materials with adequate cavitation resistance will afford the pump designer much greater leeway in the range of conditions under which the pump can be operated. It also permits the design of smaller, lighter pumps that can be operated at higher speeds. The judicious use of materials significantly extends the time between outages caused by cavitation damage and can dramatically reduce maintenance costs.

## **TYPES OF WEAR**

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Rotating equipment, including pumps, can suffer from damage as a result of mechanisms unrelated to corrosion. The relative motion between parts that are in close proximity to each other can produce wear when these components come into contact with one another.

Catastrophic damage may occur if the parts make contact under high loading conditions or when foreign bodies are entrapped between the rotating and stationary components. An accelerated material loss or catastrophic seizure of these components can result in costly repairs or replacements. Erosion, due to the presence of solid particles in the liquid being pumped, can also limit the life of internal pump components.

Wear mechanisms have been categorized into more than 20 individual processes.<sup>1</sup> However, only a few mechanisms are frequently recognized as damaging to a pump:

- Adhesive wear: material-to-material contact
- Abrasive wear: solids interacting with internal components
- Erosion: solid particle impingement
- Fretting: small amplitude motion of parts causing oxidation damage

Identifying the wear mechanism is somewhat difficult at times as wear, or the loss of material, within a pump can result from more than one mechanism at a time.

The study of friction and wear as a science, known as *tribology*, had its beginning in the late 1930s. These early studies fostered an increased awareness of wear damage mechanisms that, in addition to corrosion and material fatigue, account for the life-limiting factors of pumps. Additional information on the study of wear can be found in current trade journals and texts.

**Adhesive Wear** One of the primary causes of material loss on rotating components in a pump handling clear liquids (with no solids entrained in the fluid stream) is adhesive wear. This material loss is due to material-to-material contact producing surface disruptions, material grooving, a transfer of material, and possibly galling. Two important characteristics to consider for a pair of materials that may come into contact are their adhesive wear traits and their galling threshold. Galling of a material is considered a severe case of adhesive wear.

The wear of two surfaces in relative motion is complex. Some alternative theories of sliding wear have been proposed in addition to the adhesive wear model. They are the delamination theory, the oxidation theory, the surface delamination theory, a fatigue model, and combinations of several of the theories mentioned. However, only the adhesive wear theory offers a general wear equation to quantitatively predict wear, thus providing a means to rank materials with respect to their wear characteristics.

A multitude of adhesive wear tests exist, including ring and block, pin and vee block, 4-ball, and pin on disk. Wear tests are performed in order to screen material combinations for potential usage. Therefore, wear tests are designed to simulate, as closely as possible, the actual service conditions and parameters.

The wear testing of materials under adhesive wear conditions has resulted in several generalities that are safeguards to the successful use of materials that may experience contact during service. Studies supported by EPRI, U.S. Naval research, and private industries result in lists of materials that are considered acceptable with regard to wear compatibility when contact does occur. From this testing, the material's hardness is determined to be the critical parameter for successful running combinations. The following guidelines should be used when selecting materials for services where adhesive wear is expected:

1. Like materials are not expected to run well under adhesive wear conditions (except for materials designed for antigalling resistance such as Nitronic 60 and Waukesha 88).
2. Combinations with hardness values less than  $45 R_c$  require a hardness differential of at least  $10 R_c$ .
3. Combinations with hardness values greater than  $45 R_c$  can have the same hardness.

Based upon extensive empirical testing and field experiences, several sound rules of thumb have been developed through the years when selecting pump wear ring materials. Three factors are used to select materials for wear surfaces in clear liquid environments:

- Corrosiveness of the fluid
- Amount of wear allowed
- Galling stress

Corrosion determines the class of material to be used. These classes generally fall into three groupings: non-corrosive, mildly corrosive, and corrosive. Of course, additional constraints occur when selecting an appropriate material within the corrosive material grouping that will need to be addressed by application experience.

Other material characteristics, such as additives, can significantly affect performance with regard to adhesive wear and galling. For example, copper alloys with lead additions are considered to be bearing alloys because of the capability of the lead to provide lubricity between contacting surfaces. Alternatives are being evaluated today to replace leaded bronze alloys to avoid the health considerations of lead usage. This is also true of tin and bismuth additions to nickel-based alloys.

A general guide for materials in several environments is as follows:

Environment	Materials	Hardness
Non-corrosive	Cast iron/leaded bronze	Unimportant
Mildly corrosive	Martensitic stainless steels (locally or through hardened)	Less than 45 $R_c$ , 10-point differential Greater than 45 $R_c$ , same hardness acceptable
Corrosive	Corrosion-resistant, non-galling austenitic stainless steel (Nitronic 50/Nitronic 60 or Waukesha 88/Nitronic 50)	Not applicable
Severely corrosive	Highly alloyed austenitic stainless steel with hard-faced materials such as Stellite or Colmonoy	Not applicable

Using these industry-wide accepted rules of thumb will help avoid catastrophic damage normally resulting in costly repairs.

Some special applications have produced unique material applications for given environments. These include low specific gravity applications where the use of mechanical carbon materials is desirable because of the non-lubricating nature of these fluids. Common practice is to make the stationary component metal-filled graphite if the specific gravity is 0.5 or less. Stationary mechanical carbon components are also used in liquid  $CO_2$  services and other potential dry start applications, such as the upper bearing in vertical pumps. Currently, non-metallic wear components, such as advanced polymers and ceramics, are being looked at to solve nagging problems encountered in a variety of applications. Usually, these are glass-filled polymers or ceramic composites with various additives to enhance their wear resistance.

**Fretting** Fretting can be considered a special case of adhesive wear. It occurs when two parts in contact experience a repeated, small amplitude relative motion between close-fitting surfaces such as a loose impeller on a shaft. Researchers have described fretting damage as a four-stage event:<sup>2</sup>

1. Adhesive wear of the asperities on the mating materials
2. Abrasive wear caused by the wear debris produced in step one
3. Abraded particles filling the asperity valleys
4. Elastic contact producing cold working of the surface and micro-pitting

In a pump, there is the potential for small amplitude motion at loose fitting impellers, beneath loose bearings, and between impeller wear rings and the impeller hub. The design engineer does not intentionally create a circumstance that will generate this type of motion, but when it occurs, fretting damage can lead to other problems.

Fretting can be identified by a red powdery oxide that forms along the fretted surface. In a pump, the red-colored debris is often washed away, but a distinct damaged surface appearance will develop on the fretted surfaces. This damage is often described as having a mottled appearance and is best depicted as a flat, eroded surface with no directionality to the damage. Although the oxide may be washed from the surface, some staining of the adjacent component can be observed after disassembly of the pump. This has led to the misinterpretation that fretting is a corrosion mechanism, but it is actually a special wear phenomenon.

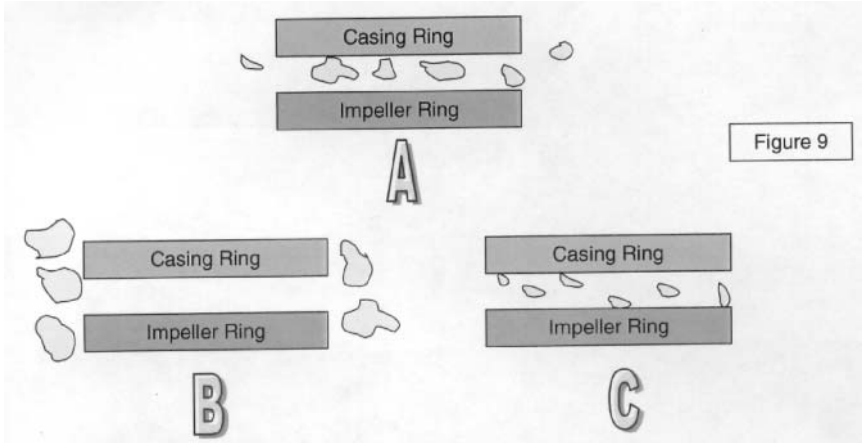
Figure 8 shows the fretting damage of a pump shaft along the impeller-fitted area where a loose fit enables the oscillation of the impeller during operation. Since the motion necessary to cause fretting can be of a small amplitude, large vibrations in the pump may not be present. This makes the detection of fretting during any operation impossible. The impeller in this example would have similar damage along its bore.

Fretting damage can be avoided with a few relatively simple guidelines. You should eliminate or prevent the possibility of motion between the two components by either tighter clearances, or shrink fitting the assembly, which increases the clamping force. If fretting is unavoidable in a particular design, methods of mitigation can be used. These include various coatings or providing the contact zone with an appropriate lubricant. Coatings that may be used include flame-sprayed high-nickel alloys, silver plating, or possibly adding a thin, dense chrome plating to one or both of the faces in contact.

**Abrasive Wear** Abrasive wear is often categorized into two main classifications: *two-body* and *three-body wear*. The name indicates the mechanism of wear. For the most part, three-body abrasive wear is the primary mechanism of damage in centrifugal pumps. This can occur when hard solid particles entrained in the fluid enter between ring fit areas or impeller keyway faces. In fluids with high concentrations of solids, another form of three-



**FIGURE 8** The fretting damage of a shaft beneath an impeller that experienced small amplitude motion. The mottled appearance is typical of the damage caused by fretting (2.2 $\times$ ).



**FIGURE 9** Three possible conditions between wear surface clearances and solid particle size. Condition "A" is conducive to maximum three-body abrasive wear.

body wear is produced. Solids carried in the fluid stream can strike the internal pump surfaces. This is more commonly referred to as *erosion*. This type of damage is observed in the impeller and cutwaters of the casing. The degree of material damage, due to this mechanism, depends upon the bulk hardness of the material, the carbon content, and the characteristics of the solids present. Important particle characteristics include size, shape, hardness, and mass.

To minimize three-body abrasive wear, a couple of variables must be taken into consideration. The wear ring clearance influences damage. The relationship between the size of the particles in the fluid stream and the gap into which they can enter is important. This is graphically illustrated in Figure 9, which shows three types of particle-to-gap relationships. Condition A is logically the most damaging three-body abrasive case. A high rate of damage will result as these particles are entrapped between the two components. In condition B, large particles relative to the ring clearance will not enter and produce damage. This condition enables the particles to flow with the fluid stream through the eye of the impeller and exit the pump. In condition C, very fine or relatively small particles will not be entrapped and ground between the rings and will not result in collateral damage of the components.

For the most part, particles in a fluid service will be in a range of sizes, so all the conditions will exist. Typically, a particle size and distribution analysis is performed to characterize the amount of particles that will cause condition A to exist. This is relatively simple to accomplish by extracting the solids from a fluid sample and performing a sieve analysis. The percentage of solids present in the fluid stream is extremely important for determining the appropriate material and design considerations. This will be addressed later with guidelines given for appropriate material selections.

Wear particle hardness is also extremely important. If particles are soft and friable, such as talc, little damage would be expected to occur on metal pump components because of three-body abrasive wear. The amount of damage is expected to be greater if the particles are extremely hard. These particles include welding scale or silicon dioxide ( $\text{SiO}_2$ ), which is sand. The particle geometry also contributes to the amount of damage that can result in three-body abrasive wear. Often, particles of  $\text{SiO}_2$  are found in a rounded condition. Pumps used to handle river water or seawater on ships frequently encounter these configurations. Hard, round particles are less damaging than particles of equal hardness with sharp, angular configurations. Fly ash, a very hard, sharp, angular particle, is one of the most abrasive services encountered in the pump industry.

A material's resistance to abrasive wear can be characterized by a standard ASTM test procedure. Each testing procedure attempts to simulate the mechanism that most appropriately addresses the class of abrasive wear. In general, materials that are resistant to two-body abrasive wear are resistant to three-body abrasive wear also.

Test results show that the primary property responsible for increasing resistance to abrasive wear is the hardness of a metal alloy. Zum Gahr has provided test results to graphically illustrate this fact.<sup>3</sup> Small microstructural differences, alloying, and surface-condition differences within alloy groups also can influence the abrasion resistance of a material. Some of these conclusions include the following:

- Abrasion resistance is increased with increasing bulk material hardness.
- At the same bulk hardness, steels with higher carbon content have higher abrasion resistance.
- Cold working, which increases a material's surface hardness, does not significantly increase the abrasion resistance of the alloy.
- Precipitation hardening increases the bulk material hardness and abrasion resistance of an alloy.
- Gray cast irons show a decreasing abrasion resistance at higher hardnesses.
- Softer, austenitic, white cast irons exhibit improved abrasion resistance over martensitic, white cast irons.
- Carbides are important for the wear resistance of steels and chromium-alloyed, white cast irons.
- A carbide volume fraction of 30% maximizes the abrasive wear resistance for materials with a soft matrix.

An example of three-body abrasive wear is shown in Figure 10. It shows a laser-hardened shaft sleeve after approximately one year of service in a mine dewatering operation where abrasive wear caused a significant wear of other material combinations. The abrasive wear was caused by fine tailings in this gold mine application. To increase the life of rings in services like this, the use of hardened wear rings is a good start. This is the reason why pump producers use coated rings in applications where significant abrasive wear is anticipated. However, depending upon the severity of the service, a choice of a ring material containing carbides may be necessary.

For mildly abrasive services, the following materials should be considered:

- Ni-Resist—Its resistance is due to chromium carbides in the matrix. It has good adhesive wear resistance also.
- Selectively hardening the surface of AISI 420 (laser hardened 50–55  $R_c$ ). Surface hardening is not susceptible to hydrogen embrittlement or SCC.
- Carburized and hardened 12% chromium stainless steel.

For more abrasive services, the following is often considered:

- Hardened AISI-440C (50–55  $R_c$ )
- Stellite or colmonoy-coated (hard-faced) austenitic stainless steel
- Solid stellite
- Tungsten carbide
- Silicon carbide
- Partially stabilized zirconia (PSZ)

Recent advances involving the use of ceramics, metal-matrix composite materials, laser-surface alloying, and laser-surface modifications to a substrate that normally could not survive in an abrasive service are examples of ongoing material developments.



**FIGURE 10** The three-body abrasive wear of a laser-hardened shaft sleeve in an abrasive service. Note the fine concentric scoring of the hardened surface. The helix pattern is the laser-beam overlapped zone produced by the laser process.

**Erosion** Most fluids handled by pumps are considered clear liquids, meaning they do not have significant amounts of solid particulates present. The corrosive nature of these fluids dictates the required pump materials. Guidelines for many of these services are embodied in “Corrosion in Pumps,” a tutorial published in the Ninth International Pump Users Symposium.<sup>4</sup>

However, many fluid-handling applications requiring pumps are far from clear liquids. Solid particulates can be removed with costly filtration systems that must work flawlessly at all times. Fabricated piping systems may introduce suspended solids from weld slag and pipe burn. Naturally occurring suspended solids are those found in water sources such as river water or seawater, as mentioned previously in the abrasive wear section.

The following factors should be considered during the material and pump selection phase of the procurement process:

- The hardness of the particles
- The quantity of particles
- Size distribution
- Nature (geometry)
- The velocity of the pumpage
- The angle of fluid impingement

The first four items listed deal with the suspended solids. These variables can vary from application to application. The hardness of the particles is important to understand in determining the materials necessary to yield an acceptable pump lifespan. Hardness can range from relatively soft substances, such as cellulose fiber in pulp and paper applications, to very hard abrasive particles such as silicon or rock in mining pumps. The Miller

number index, as described in ASTM G75,<sup>5</sup> is used to characterize the abrasivity of hard particles.

The Miller number was developed to determine the relative abrasivity and attrition of solid particles making up a slurry. In a closed loop test, the abrasivity of the particles becomes less damaging with time due to the fracturing and rounding (or friability) of the particles as they strike each other and/or impinge on a pump or casing wall.

The Miller number is therefore reported with two numbers. The first number characterizes the abrasivity of the particles and the second is the loss of abrasivity (attrition) of the particles during the slurry test. The abrasivity portion of the Miller number is useful in practical applications because this more closely characterizes a slurry's damaging potential. The attrition number has found little use other than characterizing a test loop's influence on a slurry. A slurry with a Miller number less than 50 is not considered abrasive in a reciprocating pump. Examples of slurries with a Miller number below 50 are limestone, sulfur, and detergent. It has been determined that a slurry consisting of finer particles is less abrasive than one containing larger particles. Test data shows that Corundum at 220 mesh is about four times as abrasive as the same material at 400 mesh.<sup>5</sup>

Particle velocity plays a major role in the degree of damage that occurs in a pump handling slurries. In this case, the potential energy is converted into kinetic energy, producing a material loss by the transfer of energy from the particle to the component. The amount of material damage on an individual particle scale depends specifically upon particle velocity,  $v$ , and mass,  $m$  (kinetic energy, defined as  $mv^2$ ). This is demonstrated by Finnie's equation<sup>6</sup> for hard materials:

$$\text{Wear rate} = (\# \text{ of impinging particles}) \times (\text{average particle mass}) \\ \times (\text{impingement velocity})^2 \times (\text{angle of impingement})$$

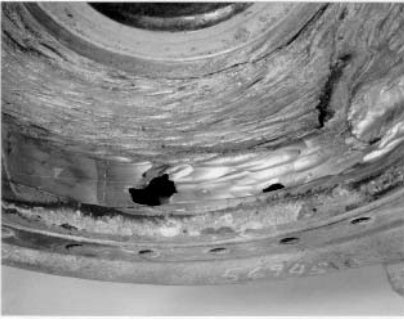
Of course, the pump part that absorbs the kinetic energy resulting from the particle impact has a role to play also. The material hardness and/or resilience of the pump component in absorbing the particle's impact energy will also determine the amount of material loss.

Chen and Hu<sup>7</sup> have performed laboratory tests on materials while changing the particle variables previously described. Their test results show the following:

- An increased particle hardness increases the material loss up to 1700-kg/mm<sup>2</sup> micro-hardness (greater than 75  $R_c$ ). Beyond this hardness, a decrease in wear occurs. This is most likely the result of the hard, brittle particle fracturing, which absorbs some of the kinetic energy.
- Sharp, angular particles increase the erosion rate over round particles.
- Erosion increases with increasing concentrations of abrasive particles.
- An increased fluid (and particle) velocity increases the erosion rate.
- Minimal erosion occurs at an impingement angle of 0° (tangent to the target surface) and increases to a maximum amount of wear at a 65° angle.

A review of the literature shows that several authors have plotted the solid particle impingement angle versus the amount of erosion.<sup>8,9</sup> These plots show that for ductile materials, erosion increases with the increasing impingement angle to a maximum material loss at an angle of 25°. Then the erosion damage decreases to the 65° impingement angle previously mentioned. Brittle materials, such as glass, are quite different. As the impingement angle increases from 0° to 90°, the volume of material loss continuously increases.

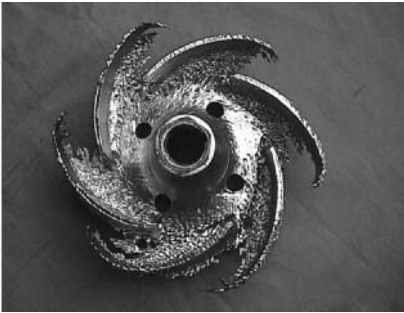
The characteristic features of erosion damage due to solid particle impingement are usually recognizable. However, when an aggressive fluid is present, the effects of solid particle impingement may not be easily identified. These effects can appear very much like corrosion-erosion, which is a fluid velocity-controlled damage mechanism where entrained solids are not present. If this damage is misdiagnosed, an improper material substitution can be made that may not solve the real problem. Conversely, a more likely situation is



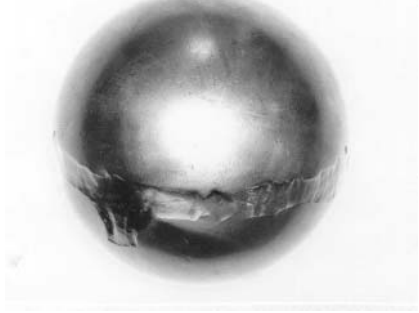
**FIGURE 11** The severe erosion of a carbon steel casing in a 17% bauxite and sand service. Note the gouging due to the local turbulence of the slurry.



**FIGURE 12** Erosion at the exit vane tips of a duplex, stainless steel CD4MCu impeller in a bauxite service.



**FIGURE 13** An austenitic stainless steel impeller in an abrasive fly ash service that shows severe erosion. Increased erosion occurs with an increasing fluid velocity near the periphery of the impeller.



**FIGURE 14** Erosion damage of an AISI-type, 440C stainless steel ball valve in a coal slurry service

that the observed damage resulting from the erosion-corrosion is misinterpreted as solid particle erosion. A full understanding of the pumpage including the fluid velocity, fluid corrosiveness, content, and nature of the solid particles present is necessary for the appropriate action to be taken in improving the life of a damaged pump.

An example of solid particle erosion in a pump is shown in Figures 11 and 12. The severe erosion damage of a casing is illustrated by the gouging of surfaces that were directly impinged or scoured by glancing blows of the solid particles in the fluid stream. This pump handles a bauxite slurry where the percentage and velocity of alumina ( $\text{Al}_2\text{O}_3$ ) and sand are too high for the carbon steel casing and CD4MCu impeller.

Figure 13 shows a CF3M impeller in a fly ash service. This shows that the greatest damage to the impeller is at the outer periphery, which corresponds to the highest velocity of the slurry. The least amount of damage is near the impeller inlet eye. Figure 13 also shows that the lower velocity region of the impeller inlet eye has the least damage. This confirms the laboratory data that shows an increased erosion with an increased slurry velocity. Note that the damage increases near the outside of the inlet eye and is almost nonexistent at the impeller hub where the fluid velocities are lower.

Erosion damage can also be encountered in reciprocating pumps. Figure 14 shows extensive erosion of an AISI-type, 440C stainless steel ball from a ball valve after it

became stuck and unable to rotate in a coal slurry application. This caused a slurry impingement on a concentrated region of the ball.

The particle velocity and impingement angle are design factors that can be used to mitigate erosion in pumps. The challenge in the coal liquefaction program investigated by the Department of Energy in the 1970s was to develop a high-speed pump for handling coal-oil slurries.<sup>8</sup> This was attempted because traditional slurry pumps are usually large, slow-moving machines that increased the capital and operating costs of pilot plants built during that era. Most of the slurry pump industry utilizes large, slow-moving, single-stage pumps to address the solid particle erosion problem. Many of these pumps are rubber-lined to absorb the particle's impingement energy.

Erosion damage, once identified, has a limited number of solutions to prolong the longevity of pump materials. This can be accomplished by the selection of hard, wear-resistant replaceable liners, elastomeric liners, or, in cases where liners cannot be utilized, hard materials. Such metallic materials include white cast iron (such as Ni-Hard), high chromium (13 to 28 percent) alloy steels, cobalt-based super alloys (such as Stellite), and nickel-based alloys.

## FATIGUE

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Centrifugal and reciprocating pumps are subjected to cyclical loading, which, if not considered during design, will result in a limited life due to material fatigue. In combination with a corrosive environment, material fatigue can be accelerated due to what is commonly referred to as *environmentally assisted fatigue*.

The one essential parameter in component fatigue is the presence of an alternating or cyclic load. In general, pumps are machines that have either fluid or mechanically induced cyclic loading on their components. Although centrifugal pumps are for the most part steady-state rotational equipment, pulsations or fluctuating applied stresses are encountered. The source of these cyclic stresses can be from fluid interaction between impeller exit vanes and diffuser vanes or, in a volute pump, the impeller vanes and the casing cut-water. Mechanically induced forces are due to bending moments acting on the pump shaft or possibly a component imbalance in the rotor assembly. Reciprocating pumps experience a cyclic loading of the internal and external components from the action of the machinery. In fact, these pumps can be thought of as large fatigue-testing machines due to the pulsating action of the pumping process.

When cyclic forces are applied to materials in a pump over a period of time, a crack may initiate at the component's surface. After initiation, the crack will grow with continued cyclic loading until the part finally fractures. Fractures can occur, even though the loading produces stresses that are far less than the tensile strength of the material. Engineers have been aware of this potential mode of component fracture for many years and have developed design criteria that take this anomaly into account. The study of cyclic loading and material behavior based upon cyclic stress history and flaw size is beyond the scope of this text. It should be noted, however, that the field of fracture mechanics offers an engineering design tool that can predict the life of an engineered component.

Fatigue is a three-stage process consisting of (1) crack initiation, sometimes associated with preexisting defects, (2) crack propagation, and (3) the final fracture, associated with crack instability, as suggested by Wohler.<sup>10</sup> The applied stress level, sample geometry, flaw size, and mechanical properties determine the existence and extent of these stages.

Fatigue was first studied by August Wohler in 1852.<sup>11</sup> Wohler's work included the concept of alternating applied stress,  $S$ , and the number of cycles,  $N$ , applied to a sample until a fracture occurs. This work is the basis for today's  $S/N$  curves used by design engineers. A laboratory-generated  $S/N$  curve is shown in Figure 15. This curve was generated by smooth, rotating-beam test specimens. These specimens are machined carefully to avoid metallurgical notches on their surfaces that would lower the applied stresses required to produce a failure during testing.

When a corrosive media is introduced, many crack initiation sites are produced. The lower curve shows the resulting drop in the endurance limit. Since corrosion over time can

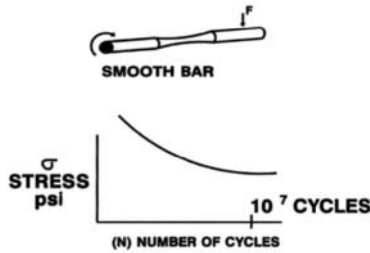


FIGURE 15 A laboratory-generated  $S/N$  curve for a smooth bar rotating beam test specimen

TABLE 2 Corrosion fatigue strength of alloys in sea water\*

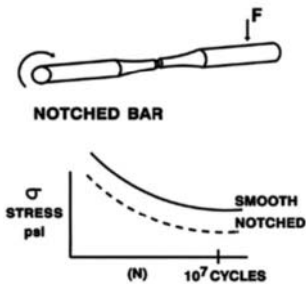
Alloy	UTS	CFS
Ti-6Al-4V	154	88
Inconel 718	189	60
Inconel 625	149	50
Hastelloy C	108	32
Monel alloy K-500	176	26
Ni Al bronze (cast)	115	15
304 Stainless	79	15
316 Stainless	85	14
304L Stainless	75	14
316L Stainless	79	13
17-4PH - cast		10
70-30 Cu-Ni (cast)	83	9
Ni Mn Bronze	82	9
Mn Bronze	73	8
D-2 Ni-Resist		7.5
Mild steel		2

\*Test parameters: ambient temperature, 1750 rpm, 2–3 ft/s (0.6–0.9 m/s). Corrosion fatigue strength (CFS) given at 100,000,000 cycles. All values are in ksi; 1 ksi = 6.894759 mPa. (UTS is ultimate tensile strength of material in air.)

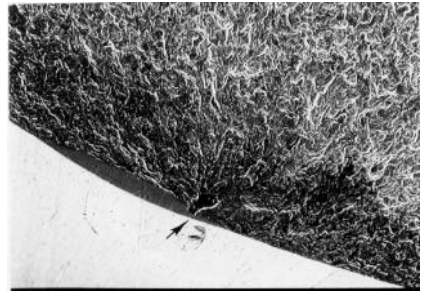
increasingly damage the material, the endurance limit will correspondingly decrease with the exposure time. No true fatigue limit exists for materials in a corrosive environment. For this reason, the corrosion-assisted fatigue life of a material is usually published with cautionary statements. Given enough time, corrosion can penetrate completely through a fatigue test specimen, resulting in a data point of zero load and zero cycles. For this reason, corrosion-influenced fatigue test results usually specify the corrosive media, the test temperature, the details of the sample pre-exposure to the corrosive media, and the test frequency with respect to the applied cyclic loading.

Published data varies because laboratories that use a low frequency of applied stresses increase the influence that corrosion has upon the test specimens. This is in comparison to laboratories that conduct these tests at a high frequency that minimizes the influence of the corrosive media. Published values for the ultimate tensile strength and corrosion fatigue strength of various alloys are shown in Table 2.<sup>12</sup>

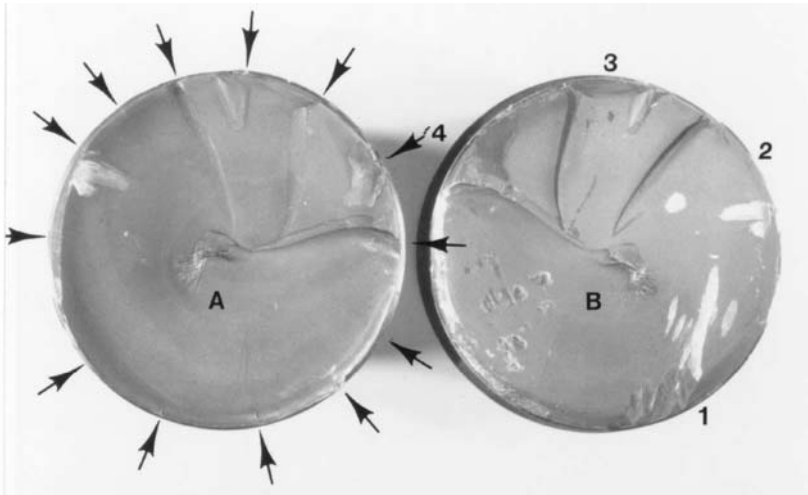
Wohler's investigation shows that a mechanical notch can reduce a material's fatigue.<sup>10</sup> This is shown in Figure 16 as a shift in the  $S/N$  curve below the curve produced by a smooth bar specimen. The severity of the notch determines the amount of divergence from the smooth bar curve. As shown, the surface degradation mechanisms lower the stress



**FIGURE 16** A shift in the  $S/N$  curve below the curve produced by a smooth bar specimen. The severity of the notch determines the amount of divergence from the smooth bar curve.



**FIGURE 17** SEM photo of a fracture smooth fatigue test specimen with a single origin. The arrow indicates the fatigue crack origin.



**FIGURE 18** Multiple origin fatigue fracture of a pump shaft. The arrows show the locations of the many fatigue crack origins. A and B correspond to the final fracture zone of each fracture face.

needed to produce the specimen failure after a certain number of cycles. This in turn reflects a lowering of the material's endurance limit.

The three stages of fatigue cracking can be observed on the fracture face, rendering them easily identifiable. This is especially true if no other secondary damage masks the characteristic appearance. Especially in fractures that occur over long periods, lines are visible on the fracture surface. These bands are sometimes referred to as *clamshell markings*, *crack arrest lines*, or *beach marks* and reflect different periods of crack growth. Ratchet lines, which represent the joining of two different crack fronts on different planes into one, are observed in multiple origin fatigue cracks. Multiple origin fatigue fractures are often associated with rotating components.

Figure 17 shows a high magnified view of a smooth bar fatigue specimen after a fracture. The arrow shows a single origin of this specimen. This fatigue crack propagated across the entire specimen diameter until the final fracture occurred, shown as a small circle. The final fracture is sometimes referred to as the *ductile overload zone* or the *fast fracture zone*.

An example of a fatigue fracture on a pump shaft is shown in Figure 18. The arrows in this figure indicate the location of many crack origins. The flat, smooth surface appearance

of this fracture face is characteristic of most fatigue fractures. This flat fracture appearance is sometimes mistaken for a brittle fracture because no evidence of plastic deformation is observed on or near the break. Shown almost directly in the center of the fractured shaft section is a small area of ductile overload, marked A and B, which corresponds to the final fracture area. The relatively small size of this area indicates the crack propagated under low alternating loads. In other words, the only material holding the two halves of the shaft together was the last area to fracture. This is a mere fraction of the total cross-sectional area of this shaft. The multiple arrows at the OD of the shaft shows the many crack origins. Fatigue ratchet marks are at each of these locations. This type of fatigue fracture is referred to as *multiple origin, high cycle fatigue*.

As mentioned before, an investigator uses the relative size of each fatigue crack stage to determine the magnitude of the loads acting on the component. The identification of the crack origin is also of prime concern in conducting a failure analysis. The crack origin is important to determine if the fatigue crack initiated from a flaw in the material or a notch produced in service or during manufacturing.

Corrosion, often the primary cause of pump material damage, can increase the likelihood of fatigue cracking. *Corrosion-assisted fatigue* is the name given to this special type of cracking. Corrosion damage can change the surface texture and significantly increase the local stresses acting on the pump component. If the corrosion damage is severe enough to produce a sharp notch in a region of high cyclic loading, then fatigue cracking of the component is inevitable. In some cases, the propagation phase is also influenced by oxidation, which can mask the telltale features of the fatigue mechanism. Corrosion oxides, which form along the crack face, can produce a wedging effect, which mechanically increases the local tensile forces acting on the crack tip. This increases the crack propagation rate.

An example of corrosion-assisted fatigue at two locations in the front shroud wall of an impeller is shown in Figures 19 and 20. The evidence of corrosion pitting on the surface indicates a strong possibility that corrosion influenced the fracture mode. Further investigation shows that both shroud wall fatigue fractures were initiated at corrosion pits located in highly stressed areas of the impeller. The fluid pulsations acting on the exit vane tip result in alternating loading.

Corrosion is not the only mechanism of surface degradation that can promote this form of cracking. Surface disruptions through fretting or wear can also provide sites for fatigue crack initiation. Sharp radii and defects at the material surface such as porosity and poor machining act as stress concentrations.

Once the mechanism of fatigue cracking has been identified, suitable corrective actions can be implemented. These include the following:



**FIGURE 19** Overall view of a CF-3M impeller that has two corrosion-assisted fatigue fractures in the front shroud wall



**FIGURE 20** A higher magnification of one of the fatigue fractures that originated at a corrosion pit at the exit vane tip and shroud intersection. Additional corrosion pitting can be seen on the impeller in this figure.

- **Higher strength materials** A good approximation for the endurance limit of a metal is 50% of the material's tensile strength. This is for high-cycle fatigue where no macro plastic loading is experienced. A graph published in *Deformation & Fracture of Engineering Materials*<sup>10</sup> shows this rule of thumb.
- **Design modification** The stress acting upon a component can be reduced with an increased section size. Reducing the stress on a component will increase its life. The design criteria for mean stress in an alternating loading environment can be determined using several analytical models. Since components are subjected to a range of loading (not a constant amplitude), a fluctuating mean stress is encountered. The anticipated load history can aid in the design process to avoid fatigue fractures. The prediction of potential component life can be based upon a fluctuating mean stress design criterion, referred to as the *Pamgren-Miner cumulative damage law*.<sup>10</sup>
- **Surface treatments** The introduction of compressive stresses to the surface of a part increases the fatigue life of a component. This is usually performed at crack-sensitive regions such as sharp corners or notches. If compressive stresses are introduced into the surface of a material, cyclic tensile stresses in excess of the compressive stress value are needed to cancel their effect before fatigue damage can occur. Therefore, any form of compressive stress will benefit a component with respect to fatigue cracking. Compressive stresses can be introduced by (1) cold working, (2) shot peening, or (3) a local heat treatment that introduces beneficial, compressive residual stresses (such as laser hardening or induction hardening).
- **Increased corrosion-resistant materials** The use of more highly corrosion-resistant materials is beneficial in cases where corrosion has decreased a component's life by degradation of its surface condition.

## **MATERIALS OF CONSTRUCTION**

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**Impellers** The pump designer needs to consider several criteria when selecting the material for the impeller:

- Corrosion resistance
- Abrasive wear resistance
- Cavitation resistance
- Casting and machining properties
- Weldability (for repair)
- Cost

For many water and other noncorrosive services, bronze satisfies these criteria and, as a result, is the most widely used impeller material for these services. Bronze impellers should not be used for pumping temperatures in excess of 250°F (120°C). This is a limitation imposed primarily because of the differential rate of expansion between the bronze impeller and the steel shaft. Above 250°F (120°C), the differential rate of expansion between bronze and steel will produce an unacceptable clearance between the impeller and the shaft. The result will be a loose impeller on the shaft.

Leaded bronzes have been used extensively in the past as impellers, especially in less demanding applications. The lead addition to bronze enhances its castability and machinability. In recent years, environmental concerns associated with lead have caused many nonferrous foundries to stop producing these alloys and pump manufacturers are increasing their use of nonleaded bronzes for impeller applications.

It should be noted that bronzes have velocity limitations above which they will suffer accelerated erosion corrosion. The maximum velocity, which will correspond with the periphery of the impeller, is higher in fresh water than in salt water. The most resistant bronzes, able to tolerate the highest velocities, are the nickel aluminum bronzes. These

alloys are often used as impellers in salt water applications because they combine high mechanical properties, good corrosion resistance, and the capability to be weld-repaired. A nickel aluminum bronze impeller can be designed for a higher speed than any other bronze impeller alloy.

Cast-iron impellers are used to a limited extent in small, low-cost pumps. Cast iron is inferior to bronze in corrosion, erosion, and cavitation resistance. It also cannot be welded to repair damage due to wear or erosion. For these reasons, a low initial cost is usually the only justification for selecting a cast-iron impeller.

Martensitic stainless steel impellers are widely used where bronze will not satisfy the requirements for corrosion, erosion, or cavitation resistance. The alloys most commonly used are CA-15 and CA-6NM. These alloys can be used for pumping temperatures above 250°F (120°C), as the differential expansion problem no longer exists with a steel impeller on a steel shaft. Martensitic stainless steel impellers are used in a wide range of applications, including boiler feed water, many cooling waters, and a variety of hydrocarbon applications. It does not have sufficient resistance to pitting corrosion for use in sea water.

Martensitic stainless steels are heat-treatable alloys. The specified mechanical properties are developed through a quench and temper heat treatment. Quenching can be in oil or, as is more common, in air. The cooling rate in air is sufficiently rapid that the high temperature austenitic structure will transform to the metastable martensitic structure, which can subsequently be tempered to the desired hardness. The designer should specify that tempering be done at a minimum temperature of 1100°F (600°C) in order to assure that the casting has adequate toughness. It is also important that these alloys be heat-treated after weld repairs. This can present a problem in the case of a finish machined casting, which would suffer distortion if heat-treated. Welding techniques have been developed, however, that do not require a post-weld heat treatment, but these are, in most cases, unsuitable for use on martensitic stainless impellers.

Oil and refining industry applications often involve exposure to hydrogen sulfide, which may be present as a trace contaminant in hydrocarbon fluids. Martensitic stainless steels are susceptible to a form of SCC in this environment and should be specified with a special double-temper heat treatment designed to limit hardness and thereby prevent cracking.

Austenitic stainless steels are used for impellers in applications requiring a higher level of corrosion resistance than can be obtained from the martensitic grades. A number of different alloys make up this group. The most widely used are CF-8M and CF-3M, which are the cast versions of the well-known 316 and 316L wrought materials. The cast alloys have a slightly different chemistry than the wrought grades. This difference accounts for the presence of 5 to 15% ferrite in the castings, which makes them slightly magnetic. The ferrite also enhances the resistance to SCC and hot shortness, a casting problem associated with fully austenitic cast grades. These alloys provide corrosion resistance over a wide range of pH and have reasonably good resistance to pitting and crevice corrosion in aqueous chlorides.

Higher alloyed austenitic cast grades are also available for applications requiring a greater degree of corrosion resistance. Alloy 20 contains about 30% nickel and was developed for sulfuric acid applications. The high nickel makes the alloy fully austenitic (without ferrite). Consequently, it is difficult to cast and suffers from hot shortness, which may manifest itself as fine cracking at the intersection between the vane and the shroud in an impeller. The high nickel content also makes Alloy 20 very resistant to SCC.

Austenitic grades containing 6% molybdenum have been developed for use in salt water and other high-chloride applications such as acidic brines used in oil field waterflood injection. The high level of molybdenum makes these alloys fully resistant to pitting in stagnant seawater, which will be present when a pump is not in operation. The 6% molybdenum grades are more expensive and therefore not frequently used for most applications. These alloys are usually considered only for critical, demanding applications where a high level of corrosion resistance is needed.

Austenitic stainless steels with unique properties have been developed for specific applications. A chrome-manganese alloy, discussed in the section on cavitation erosion, can be employed to mitigate or entirely eliminate cavitation damage in problem applications.

A high-strength austenitic stainless grade, CF10SMnN, can be used where the mechanical properties of CF-8M are inadequate. Some pump manufacturers also offer nitrogen-enriched austenitic grades that have corrosion resistance and mechanical properties better than CF-8M.

Duplex stainless steels offer a combination of higher mechanical properties and better corrosion resistance than the standard austenitic grades. The original duplex casting grade, CD4MCu, was developed in the 1950s. Use of this material was limited by problems with castability and weldability. Improved steelmaking technologies now enable the addition of precise amounts of nitrogen to duplex stainless steel. The nitrogen addition improves castability, weldability, and also corrosion resistance. Numerous duplex stainless grades have been developed in recent years, all having a specified nitrogen addition. These duplex grades all outperform the old CD4MCu grade, which did not have a nitrogen addition. Many foundries now make CD4MCu with nitrogen.

Duplex stainless impellers are extensively used in mining, flue gas desulfurization, and similar applications that require a combination of resistance to corrosion and abrasion. Duplex stainless steels also have better corrosion resistance than the standard austenitic grades and are used in a variety of applications in the chemical industry, the pulp and paper industry, and the marine industry. Duplex stainless pumps are standard for offshore high-pressure water injection pumps in the oil industry. Published corrosion data indicates that, for acceptable resistance to seawater, a duplex stainless should contain a minimum of 25% chrome, 3% molybdenum, and 0.15% nitrogen.

**Casings** The following criteria should be considered when selecting material for centrifugal pump casings:

- Strength
- Corrosion resistance
- Abrasive-wear resistance
- Casting and machining properties
- Weldability (for repair)
- Cost

For many pumping applications, cast iron is the preferred material for pump casings when evaluated on the basis of cost. For single-stage pumps, cast iron usually has sufficient strength for the pressures developed. For corrosive or hazardous petroleum products, it may be necessary to specify cast steel or cast stainless steel. The concern with cast iron when handling hazardous fluids is that the material is inherently brittle and could fail suddenly in a catastrophic manner with no prior indication of distress.

Cast-iron casings for multistage pumps are limited to approximately 1000 lb/in<sup>2</sup> (6.9 MPa) discharge pressure and 350°F (177°C). For temperatures above 350°F (177°C) and pressures up to 2000 lb/in<sup>2</sup> (13.8 MPa) discharge pressure, a cast steel is usually specified for split-case, multi-stage pumps. For pressures higher than 2000 lb/in<sup>2</sup> (13.8 MPa), a cast or forged steel barrel-type casing is usually required.

In any evaluation of cast iron versus steel casings, consideration should be given to the problem of casing erosion during operation. Erosion can occur either from abrasive particles in the fluid or from wire drawing across the flange of a split-case pump. Although the initial cost of a steel casing is higher than that of a cast-iron casing, a steel casing can often be salvaged by welding the eroded portions and remachining. Salvaging a cast-iron casing by welding is much more difficult, and the casting usually must be replaced.

The ductile irons are useful casing materials for pressure and temperature ratings between cast irons and steels. Although the modulus of elasticity for the ductile irons is essentially the same as that for cast iron, the tensile strength of the former is approximately double that of the latter. In any evaluation of the ductile irons as a substitute for the steels in the intermediate pressure and temperature range, it should be remembered that ductile iron casings cannot be effectively repair-welded.

Austenitic irons, commonly known by the tradename *Ni-Resist*, are used for pump casings in applications where gray and ductile irons have insufficient corrosion resistance. Austenitic irons typically contain 15 to 20% nickel. They are frequently used in brackish and salt water applications where they are considerably more resistant to both corrosion and erosion than unalloyed gray iron. A preferred combination for this service is a Ni-Resist casing and stainless internals. The stainless steel is galvanically protected from pitting when the pump is made idle by the more anodic Ni-Resist casing.

The traditional Ni-Resist alloys have poor weldability in common with other types of cast iron. In recent years, a new and more readily weldable Ni-Resist grade has been developed. This grade, designated *D2W*, contains a small columbium addition that enhances weldability. This new D2W grade is gaining popularity as the preferred grade for pump casings.

Bronzes are also used for pump casings in many water applications. Several bronzes are used, with the choice depending upon the specific application. Leaded bronzes, specifically leaded red brass, are used for small low-pressure pumps. This material is the least costly and easiest to cast of the bronzes. Tin bronzes, with or without lead, are used for larger centrifugal pump casings. The lead contributes to the pressure tightness of the casting. Unleaded bronzes often have to be impregnated in order to obtain adequate pressure tightness. Unleaded tin bronze can be weld-repaired, whereas the leaded version is not weldable. Nickel aluminum bronze has the highest mechanical properties and the best corrosion resistance of the bronze alloys normally considered for pump casings. It can also be repaired by welding. Nickel aluminum bronze casings are expensive and usually not competitive on a cost basis with NiResist or other alternatives.

Stainless steels are selected for pump casings when required due to corrosion considerations. Martensitic stainless steels are commonly used to handle boiler feed waters as well as many hydrocarbon applications. These materials have good mechanical properties and are suited for high-pressure applications. Their corrosion resistance is less than that of other categories of stainless steel and for this reason, they are unsuited for more aggressive waters or other fluids.

The austenitic stainless steels, particularly CF-8M and CF-3M, are frequently used for pump casings in chemical applications and other corrosive services. These materials can handle a wide range of pH. They are resistant to erosions by high velocity and can be field-weld-repaired with relative ease.

Duplex stainless steels (stainless steels having a metallurgical structure that is approximately 50 percent ferrite and 50 percent austenite) are used for pump casings in some applications that require a combination of corrosion resistance and mechanical properties superior to that of the standard austenitic grades. These materials have become the preferred choice for high-pressure, offshore injection pumps handling sea water. The higher mechanical properties permit the design of thinner wall, lighter pumps. The weight savings is an important factor in this application.

**Shafts** The following criteria should be considered in the selection of material for a centrifugal pump shaft:

- Endurance limit
- Corrosion resistance
- Notch sensitivity

The endurance limit is the stress below which the shaft will withstand an infinite number of stress reversals without failure. Since one stress reversal occurs for each revolution of the shaft, this means that ideally the shaft will never fail if the maximum bending stress in the shaft is less than the endurance limit of the shaft material.

In practice, however, the endurance limit is substantially reduced because of corrosion and stress raisers, such as threads, keyways, and shoulders on the shaft. In selecting the shaft material, consideration must be given to the corrosion resistance of the material being pumped as well as to its notch sensitivity. Corrosion will substantially lower the fatigue limit of the material. Fatigue cracks will initiate at corrosion pits or other surface discontinuities that act as stress risers.

In the absence of corrosion, an approximate relationship exist between fatigue endurance limits and mechanical properties. The endurance limit is equal to roughly half the tensile strength of the material. Depending upon the application, the pump designer will usually select the least expensive shaft material that will satisfy the three criteria noted previously. Carbon steel is used when corrosion resistance is not required, and relative low mechanical properties can be tolerated. A low alloy steel, often AISI 4140, is used when the mechanical properties of carbon steel are not adequate. Martensitic stainless steels, usually type 410, are a common choice when some measure of corrosion resistance, combined with reasonably good mechanical properties, is required. The resistance of type 410 stainless to fatigue crack initiation is related to the toughness of the material, which can vary over a wide range in commercial bar stock. The best measure of material toughness is the Charpy impact test, which is not a requirement of most relevant material specifications. In order to ensure the optimum toughness and resistance to fatigue cracking, type 410 stainless should be tempered at a temperature of 1100°F (593°C) minimum.

Stainless steels offering improved corrosion resistance and mechanical properties are also used in pump shafting. These include Nitronic 50, an austenitic grade, and 17-4PH, a precipitation hardening grade.

Several manufacturing issues related to the creation of pump shafts also need to be considered. Difficulty has frequently been experienced when maintaining the stringent tolerances for straightness required for long, thin shafts that are used in multi-stage pumps. This may necessitate intermediate stress relief during the machining process. The shaft may be stress-relieved in the vertical position or, if horizontal, with supports every few feet. Type 410 pump shafting can be specially heat-treated to eliminate residual stress and maintain straightness tolerances during pump operation.

Shafts can be plated or coated in specific areas for an improved resistance to wear or corrosion. Chrome plating is commonly used in this manner. The designer needs to be aware that plating reduces the fatigue endurance limit because of the fine micro-cracking associated with this process. An improvement in fatigue life can be achieved on plated surfaces if the substrate is shot peened. Normally, this reduction in endurance limits is not critical, because it is the flat surfaces, rather than the shoulders or keyways, that are being plated. Consequently, the largest stress raisers are elsewhere in the shaft. There is also the potential for the plating process to cause hydrogen embrittlement cracks in high-strength steels. To avoid this problem, the steel should be baked at 300 to 400°F (150 to 200°C) after the plating process.

Finally, the manufacturing process needs to be carefully controlled to avoid the inadvertent introduction of stress raisers, which could shorten the life of the shaft. Abusive grinding has been identified as the root cause of some shaft fatigue failures. Heavy grinding will heat the surface and cause hardenable steels to form a thin layer of untempered martensite. This is a brittle structure and likely to develop fine cracks. These are stress raisers that can be propagated by a fatigue mechanism once the pump is placed in service. This type of problem is avoided by proper controls on the manufacturing process.

**Wear Rings** The following criteria should be considered in the selection of the material for the wear rings:

- Corrosion resistance
- Abrasive wear resistance
- Galling characteristics
- Casting and machining properties
- Suitability for coating

A centrifugal pump will often have both case and impeller wear rings. The impeller wear ring rotates within the bore of the stationary or case wear ring. These rings provide a close running clearance to minimize leakage from the discharge to the suction of the impeller. As the rings wear with use, leakage will gradually increase, affecting the head, capacity, and efficiency of the pump. In multistage (flexible rotor) pumps, increased wear ring clearance may also affect rotor stiffness.

To reduce the rate of wear of the wear rings, and thereby increase the life of the pump, special considerations must be given to the corrosion and abrasive wear characteristics of the ring material. Since the impeller and case rings may occasionally touch one another, the combination should also be selected to have anti-galling characteristics.

Bronze is a widely used material for wear rings because it exhibits good corrosion resistance for a wide range of water services. In addition, bronze exhibits good wear characteristics in clear liquids but tends to wear rapidly when abrasive particles are present. The bronzes also have a relatively good resistance to galling. The leaded bronzes offer excellent galling resistance but use of these grades has been reduced due to environmental concerns associated with lead. The casting and machining properties of most grades of bronze are excellent.

In applications where bronze is not suitable because of either corrosion or abrasive wear limitations, or where pumping temperatures exceed 250°F (120°C), stainless steel rings are used. Unlike bronze, the stainless steels of the 300 and 400 series have poor galling resistance. Several options are available to minimize the possibility of galling between stainless steel rings. The clearance between the rings can be increased, serrations can be machined into one of the rings, or a minimum hardness differential of 50 to 100 Brinell points can be established between the rings, if made from a hardenable grade of stainless, such as the martensitic grades. If both rings are hardened to above 400 BHN, it is not necessary to maintain a hardness differential.

Martensitic stainless steel rings are usually hardened in a furnace. A laser hardening process is also available that involves heating only the surface of the material, which is rapidly quenched by the base metal, resulting in a precisely controlled surface hardness and a soft ductile core. Rings hardened in this manner are more resistant to cracking in some environments and provide increased wear resistance because of increased surface hardness (50-55  $R_c$ ). A summary of adhesive wear test results can be found in Table 3.

Increasing the clearance between rings is the least costly method for reducing the risk of galling or seizures. However, increasing the clearance will reduce the output and efficiency of the pump. In large, low-head pumps, the loss in efficiency is less than one percent, but in small, high-head pumps, the loss in efficiency can be significant. Serrated rings

**TABLE 3** Calculated wear factor

Material (Ring/Block)	Hardness DPH (Ring/Block)	Wear Factor K
In Distilled Water Specific Gravity 1.0		
Leaded Bronze/ASTM A48 Class 30 CI	80/205	$0.17 \times 10^{-4}$
Ni-Resist/Ni-Resist	120/120	$0.41 \times 10^{-4}$
Nitronic 50/Nitronic 60	195/190	$0.76 \times 10^{-4}$
90-10 CuNi/ASTM A48 Class 30	87/210	$1.14 \times 10^{-4}$
Stellite 12/Stellite 6	440/395	$1.71 \times 10^{-4}$
Ampco 18/Ampco 18	155/155	$2.40 \times 10^{-4}$
AISI 410/ASTM A743-CA6NM	300/270	$2.45 \times 10^{-4}$
AISI 410/AISI 416	290/430	$2.97 \times 10^{-4}$
AISI 416/AISI 416	430/360	$3.57 \times 10^{-4}$
In Alcohol Specific Gravity 0.87		
Nitronic 50/Nitronic 60	195/190	$0.62 \times 10^{-4}$
Leaded Bronze/ASTM A48 Class 30	80/205	$1.54 \times 10^{-4}$
AISI 410/AISI 416	290/430	$7.38 \times 10^{-4}$
In Iso-octane Specific Gravity 0.69		
Leaded Bronze/ASTM A48 Class 30 CI	80/205	$0.41 \times 10^{-4}$
Nitronic 50/Nitronic 60	195/190	$0.69 \times 10^{-4}$

can be used on smaller pumps to help maintain the efficiency level, but only at an increase in manufacturing costs.

For cast-iron, bronze, hardened 11- to 13% chromium steels, and materials with similar low-galling tendencies, the recommended minimum running clearances between rings are given in API Standard 610, "Centrifugal Pumps for Petroleum, Heavy Duty Chemical, and Gas Industry Services." For materials with higher galling tendencies, such as austenitic stainless steels and for all materials operating at temperatures above 500°F (260°C), it is suggested that 0.005 in (0.125 mm) be added to the recommended minimum diametrical clearances.

Several anti-galling material combinations have been used that do not compromise either wear or corrosion resistance. Nitronic 60 is a nonstandard austenitic grade that contains both manganese and nitrogen. This alloy has been developed for antigalling characteristics and will resist galling when mated with standard 300-series grades, Nitronic 50, and other alloys having poor galling resistance. Nitronic 60 is available in both wrought and cast forms. A cast nickel base alloy, Waukesha 88, offers equally good antigalling characteristics and can be used in brine and other corrosive environments. A summary of galling thresholds for commonly used material combinations is shown in Tables 4 and 5.

Colmonoy- or Stellite-coated rings are used in some critical applications and provide a high degree of resistance to abrasive wear, corrosion, and galling. These coatings are applied by welding, which can produce unacceptable distortion in rings, especially in larger diameters. The pump designer needs to exercise caution in specifying rings having a weld overlay because of potential manufacturing problems, which can involve cracking of the weld overlay or distortion of the ring. Some large rings for sewage pumps have performed well with tungsten carbide coatings applied using a high-velocity plasma spray process. The advantage of this process is that it does not heat the substrate, thereby avoiding distortion. Tungsten carbide is used for its high hardness and resistance to abrasion.

## SELECTION OF MATERIALS OF CONSTRUCTION

The selection of materials for pumps is often not a simple and straightforward matter because of the weight assigned to various technical and economic factors by different

**TABLE 4** Galling resistance of alloys

Metals in Contact			Threshold Galling Stress (ksi)	Threshold Galling Stress (mPa)	
Silicon Bronze	BHN 200	vs. Silicon Bronze	BHN 200	4	27.6
Silicon Bronze	BHN 200	vs. Type 304	BHN 140	44	303
Waukesha 88	BHN 141	vs. Type 303	BHN 180	50+	345+
Waukesha 88	BHN 141	vs. Type 316	BHN 200	50+	345+
Waukesha 88	BHN 141	vs. S17400	BHN 405	50+	345+
Type 410	BHN 322	vs. Type 420	BHN 472	3	20.7
Type 416	BHN 342	vs. Type 316	BHN 372	13	89.6
Type 416	BHN 372	vs. Type 410	BHN 322	4	27.6
Type 440C	BHN 560	vs. Type 440C	BHN 604	11	75.8
S17400	BHN 311	vs. Type 304	BHN 140	2	13.8
S17400	BHN 435	vs. Type 304	BHN 140	2	13.8
Nitronic 50	BHN 205	vs. Nitronic 50	BHN 205	2	13.8
Nitronic 60	BHN 213	vs. S17400	BHN 313	50+	345+
Nitronic 60	BHN 205	vs. Nitronic 50	BHN 205	50+	345+
Nitronic 60	BHN 205	vs. Stellite 6B	BHN 415	50+	345+

**TABLE 5** Galling resistance of alloys

Metals in Contact				Threshold Galling Stress (ksi)
Class 30 Cast Iron	(BHN 159-172)	vs. UNS C93200—Leaded Tin Bronze	(RB 41-43)	14.3
ASTM A487 CA6NM	(RC 29-31)	vs. Type 416	(BHN 352-415)	5.9
ASTM A487 CA6NM	(RC 29-31)	vs. Type 410	(BHN 353-415)	2.1
ASTM A487 CA6NM	(RC 29-31)	vs. Type 420—Laser Hardened	(RC 53-55)	1.7
Laser hardened Type 420	(RC 50-51)	vs. Type 420—Laser Hardened	(RC 53-55)	15.9
Type 420	(RC 50-55)	vs. Type 420	(RC 50-55)	21.1
Type 420	(RC 48-49)	vs. As-received nodular iron	(RC 24-26)	2.5
Type 420	(RC 48-49)	vs. Nitrided nodular iron	(RC 45)	10.9
Type 420	(RC 48-49)	vs. Laser glazed nodular iron	(RC 57-60)	11.3
Type 420	(RC 48-49)	vs. Laser hardened nodular iron	(RC 57-60)	6.8
Type 420	(RC 48-49)	vs. CA15	(RC 44-45)	1.8
Type 420	(RC 48-49)	vs. Zirconia	(R45N 74-79)	25*
Type 420	(RC 48-49)	vs. TDC on AISI 4140	(RC 70-80)	5.1
Type 420	(RC 48-49)	vs. Electroless nickel on nodular iron	(RC 45-49)	5.1
Type 420	(RC 48-49)	vs. Graphalloy bronze	(45-50 Schleroscope)	4.3
Type 420F	(BHN 262-302)	vs. Type 420F	(RC 50-55)	3.8
Type 410	(BHN 262-302)	vs. Type 410	(BHN 353-415)	1.2
Type 416	(BHN 262-302)	vs. Type 416	(BHN 352-415)	2.7
Nodular iron	(RC 27)	vs. Graphalloy bronze	(45-50 Schleroscope)	3.6
Nodular iron	(RC 27)	vs. Graphalloy nickel	(45-50 Schleroscope)	
Nitrided nodular iron	(RC 45)	vs. Graphalloy bronze	(45-50 Schleroscope)	2.0
Nitrided nodular iron	(RC 45)	vs. Graphalloy nickel	(45-50 Schleroscope)	3.6
Laser glazed nodular iron	(RC 57-60)	vs. Graphalloy bronze	(45-50 Schleroscope)	3.6
Laser glazed nodular iron	(RC 57-60)	vs. Graphalloy nickel	(45-50 Schleroscope)	3.6
Laser hardened nodular iron	(RC 57-60)	vs. Graphalloy bronze	(45-50 Schleroscope)	5.0

(continues)

**Table 5** Continued.

Metals in Contact				Threshold Galling Stress (ksi)
Laser hardened nodular iron	(RC 57-60)	vs. Graphalloy nickel	(45-50 Schleroscope)	7.0
CA15	(RC 44-45)	vs. Graphalloy bronze	(45-50 Schleroscope)	2.0
CA15	(RC 44-45)	vs. Graphalloy nickel	(45-50 Schleroscope)	3.6
TDC on AISI 4140	(RC 70-80)	vs. Graphalloy bronze	(45-50 Schleroscope)	3.8
Electroless nickel on nodular iron	(RC 45-49)	vs. Graphalloy bronze	(45-50 Schleroscope)	2.5
Graphalloy bronze	(45-50 Schleroscope)	vs. Graphalloy bronze	(45-50 Schleroscope)	3.6**
TDC on AISI 4140	(RC 70-80)	vs. Graphalloy nickel	(45-50 Schleroscope)	5.0
Electroless nickel on nodular iron	(RC 45-49)	vs. Graphalloy nickel	(45-50 Schleroscope)	3.8
Graphalloy bronze	(45-50 Schleroscope)	vs. Graphalloy nickel	(45-50 Schleroscope)	3.6**
Nodular iron	(RC 24-26)	vs. Zirconia	(R45N 74-79)	12.7*
Nitrided nodular iron	(RC 45)	vs. Zirconia	(R45N 74-79)	14.0
Laser glazed nodular iron	(RC 57-60)	vs. Zirconia	(R45N 74-79)	25.5*
Laser hardened nodular iron	(RC 57-60)	vs. Zirconia	(R45N 74-79)	25.5*
CA15	(RC 44-45)	vs. Zirconia	(R45N 74-79)	15.3*
Nodular iron	(RC 24-26)	vs. TDC on AISI 4140	(RC 70-80)	1.8
Nitrided nodular iron	(RC 45)	vs. TDC on AISI 4140	(RC 70-80)	11.5
Laser glazed nodular iron	(RC 57-60)	vs. TDC on AISI 4140	(RC 70-80)	15.3***
Laser hardened nodular iron	(RC 57-60)	vs. TDC on AISI 4140	(RC 70-80)	20*
CA15	(RC 44-45)	vs. TDC on AISI 4140	(RC 70-80)	5.1
Nodular iron	(RC 24-26)	vs. Electroless nickel on nodular iron	(RC 45-49)	3.8
Nitrided nodular iron	(RC 45)	vs. Electroless nickel on nodular iron	(RC 45-49)	2.5
Laser glazed nodular iron	(RC 57-60)	vs. Electroless nickel on nodular iron	(RC 45-49)	5.1
Laser hardened nodular iron	(RC 57-60)	vs. Electroless nickel on nodular iron	(RC 45-49)	5.1
CA15	(RC 44-45)	vs. Electroless nickel on nodular iron	(RC 45-49)	5.1

\* No galling at this stress. Testing is limited by torque capabilities.

\*\* No severe damage

\*\*\* Inconsistent results

Note: All stress values in ksi (1 ksi = 6.894759 mPa)

users. A final selection may involve a compromise between the manufacturing cost and the anticipated maintenance costs. This is particularly true for fluids like sea water, for which a wide range of materials have been used, from cast iron pumps with bronze internals to 6% molybdenum austenitic stainless steels. Despite the fact that economic factors unique to a particular application may influence the choice of materials for that application, some general guidelines can be used for some of the more common fluids.

**Boiler Feed Water/Condensate** High purity water at a high temperature can be very corrosive to cast iron and carbon steel despite the fact that it usually has a low oxygen content. These materials will suffer erosion corrosion, sometimes within months, if incorrectly applied. High purity water is defined as that having a conductivity of 20 micromhos/cm or less, which is equal to a dissolved solids content of 10 ppm or less. At these low levels, carbon steel and cast iron are incapable of developing surface films such as magnetite that minimize erosion corrosion. The precise mechanism is not well defined, but the relationships between conductivity, oxygen content, pH, temperature, and the influence of these variables on erosion corrosion were established by pioneering work conducted at the Detroit Edison Power Plants in the 1950s.

The purity of feedwaters has increased over the years as water treatments have become more effective in removing dissolved solids to meet the demands of modern boilers. As a consequence, these waters have also become more corrosive. The early work at Detroit Edison showed that chromium additions to carbon steel dramatically enhance the resistance to erosion corrosion in high purity water. Chrome additions of 1–1.25% are sufficient in most boiler feedwaters to impart acceptable corrosion resistance. Pump manufacturers initially used 5% chromium alloy steels for these applications. Difficulties in casting and welding five-percent chromium steels led to the more recent use of 12–13% chrome steels, notably CA-15 and CA-6NM. These are now commonly used in boiler feed pumps, condensate pumps, and others that handle high purity waters.

Water purity is often reported in the fluid's conductivity. Units of micromhos or microsiemens are used for this purpose. It has been determined that for high-temperature, boiler feed water services greater than 200°F (greater than 93°C), care in selecting materials is important for ultra pure waters. For waters greater than 200°F (93°C) with a conductivity less than 20  $\mu$ mho and alloys with greater than 3% chrome, an addition is required to avoid corrosion erosion at high-velocity areas. Figure 21 shows a carbon steel shaft that was severely damaged in ultra pure water. The proper selection of materials can be achieved by using Figure 22 as a guideline.

Some applications still remain in which cast iron, bronze, and other less costly materials can be used. Materials are selected based on water chemistry, which is divided specifically into four parameters: pH, temperature, conductivity, and dissolved oxygen. Table 6



**FIGURE 21** The corrosion erosion of a carbon steel shaft that was damaged in an ultra-pure water service after approximately six months

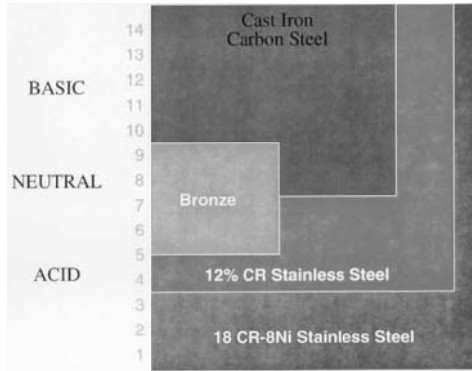


FIGURE 22 A graph indicating the proper materials selection in specific pH ranges for boiler feed services

TABLE 6 Materials for Boiler Feed Water Services

pH range	Feedwater Parameters				
	0–14	4.5–14	6–9	6–14	9–14
Temperature ≤ 200°F (93°C)	S	G-S	B*-J* H-G-S	H-G-S	C*-L*-DR* H-G-S
Temperature > 200°F (93°C) Conductivity < 20 μmho/cm Dissolved Oxygen > 0.04 ppm	S	G-S			
Temperature > 200°F (93°C) Conductivity < 20 μmho/cm Dissolved Oxygen < 0.04 ppm	S	G-S		NM-G-S	
Temperature > 200°F (93°C) Conductivity > 20 μmho/cm Dissolved Oxygen < 0.04 ppm	S	G-S	B*-J* H-G-S	H-G-S	C*-L*-DR*

\* Head must be less than 600 ft/stage (180 m/stage)

Materials:

B—Cast iron casing—bronze impeller—cast iron/bronze rings

C—All cast iron

DR—Carbon steel casing—cast iron impellers

G—All 12% chrome (CA-15 or CA-6NM)

H—Carbon steel case—12% chrome impellers (CA-15 or CA-6NM)

J—Cast iron case—bronze impellers—bronze rings

L—All cast iron with 12% chrome rings

NM—1- or 2-chrome barrels—12% chrome impeller (CA-15 or CA-6NM)

S—All 316 stainless (CF-3M)

represents an industry consensus on the recommended materials choices for the full range of high purity waters.

**Saline Water** Saline waters have been defined as those that are sufficiently electrically conductive to enable an appropriate pump casing material to galvanically protect the pump internals when the pump is shut down. This corresponds to waters with more than

about 1000 ppm chloride. Many pump applications involve saline waters. Among the more common saline water applications are the following:

- **Tidal river water** The chloride level here can fluctuate significantly with the season and the ingress of salt water from a bay or estuary.
- **Groundwater** The chloride level and corrosivity can vary over a wide range. Some groundwaters, which are injected by high-pressure pumps into oil formations to enhance output, are very corrosive, due to low pH and very high chloride levels.
- **Geothermal water** This type may contain high levels of hydrogen sulfide, carbon dioxide, and other gases in addition to chlorides.
- **Oilfield brines** These are often deaerated, greatly reducing their corrosivity. Less corrosion-resistant pump materials may be used but are susceptible to corrosion during shutdown periods when oxygen cannot be effectively excluded from the water.
- **Sea water** The chemical composition of seawater is relatively uniform throughout the world. Other factors, including temperature, microbiological activity, and the presence of pollutants can alter the corrosivity of the seawater to pump materials of construction.

For each of the saline waters, a variety of materials has been used for pumps. The choice of materials for a particular application will depend on the water chemistry and other factors including the expected life of the pump, whether it will operate continuously or sit idle for long periods, and user preferences based on previous experiences. Some general considerations will influence material selections.

The materials for saline water pumps must resist erosion corrosion. Ni-Resist and copper base alloys are frequently specified but have velocity limits, above which the protective oxide film is stripped off and accelerated corrosion occurs. Among copper base alloys, nickel aluminum bronze can tolerate the highest velocity. The pump designer needs to be aware of these limitations and use bronze and Ni-Resist only for components when the velocity limits of the materials will not be exceeded.

Stainless steels develop a more tenacious oxide film than bronzes and can tolerate velocities much higher than those seen in pumps without suffering erosion corrosion. However, stainless steels are susceptible to pitting and crevice corrosion in stagnant seawater. These problems are exacerbated if marine biofouling occurs. Several methods exist for handling this problem. The stainless internals of a pump can be effectively protected by galvanic coupling with Ni-Resist. The combination of a Ni-Resist case and stainless steel internals is widely used because of this favorable galvanic relationship.

To avoid localized corrosion during shutdown in an all-stainless pump, some form of cathodic protection is required. This can be either sacrificial anodes or an impressed current system. It is also possible to construct the pump of stainless grades that are highly alloyed and develop adequate corrosion resistance. This approach requires either 6% molybdenum austenitic grades or 25%, 3% molybdenum duplex grades. These materials are considerably more expensive than standard 300-series austenitic stainlesses and see limited use in critical applications. Higher alloyed duplex grades have become the universal standard for high-pressure injection pumps, especially those used in offshore locations. The high mechanical properties enable the design of lighter, smaller pumps. The weight saving is an important factor in offshore applications.

Many large sea water pumps are constructed of cast iron with bronze internals. Provided the velocities are not too high, this combination of materials has been known to provide approximately 20 years of service in some large vertical pumps. Nickel aluminum bronze is preferred over tin bronze for the impeller because it is stronger, has better resistance to high velocity, and is more easily weld-repaired.

Monel shafting is no longer commonly specified for sea water pumping applications. This material is expensive and will develop pitting in stagnant water. Several grades of stainless steel will provide a combination of strength and corrosion resistance equivalent to Monel at a significantly lower cost. These include Nitronic 50 and several of the higher alloyed duplex grades, such as Ferralium.

When specifying materials for sea water pumps, the designer should also consider whether the water will be chlorinated, and, if so, where the chlorine is to be added. Chlorine is added to cooling waters to kill marine organisms that cause biofouling. The chlorine may be added continuously at low levels or as a shock treatment at periodic intervals. Chlorination at normal levels of up to 2 ppm does not appear to be detrimental to alloys commonly used in saline water pumps. However, an injection should be made far enough upstream of the pump intake so that the dilution occurs ahead of the pump. When an injection is made at or near the pump intake, copper alloys, stainless steels, and Ni-Resist may suffer accelerated corrosion. Recent work has shown that the corrosion rate of stainless steels will begin to increase at chlorine levels of about 5 ppm.

Galvanic considerations will also play a role in the material selection for saline water pumps. In general, the pump internals should be cathodic to the pump case. Coatings should be avoided, especially on the anodic component. Flaws or defects in a coating will expose a small area of base metal. Corrosion will then proceed at a high rate due to the extremely unfavorable area ratio. It is also inadvisable to use carbon or graphite bearings in sea water pumps. These are at the noble end of the galvanic series and are likely to cause a galvanic corrosion of stainless steels or other alloys with which they come in contact.

Table 7 indicates a number of material combinations commonly specified for seawater pumps.

**Hydrocarbons** Pure hydrocarbons are not corrosive, but they frequently contain small amounts of water or other substances that make them corrosive. The material selection guidelines for a variety of hydrocarbon services have been developed by the American Petroleum Institute and are reproduced in Tables 8 and 9. These tables give general guide-

**TABLE 7** Materials for saline water pumps

	Component	Reference	Alternative	Non-ferrous
Vertical Pumps	Column/Head	Ni-Resist <sup>1</sup>	316L	C614 <sup>4</sup>
	Diffuser	Ni-Resist <sup>1</sup>	CF-8M/CF-3M <sup>2</sup>	C952 <sup>4</sup>
	Bowl	CF-8M/CF-3M <sup>2</sup>	Ni-Resist <sup>3</sup>	C952 <sup>(4)</sup>
	Inlet Ball	Ni-Resist	Ni-Resist	C952 <sup>4</sup>
	Impeller	CF-8M/CF-3M <sup>2</sup>	CF-8M/CF-3M <sup>2</sup>	C958 <sup>4</sup>
Centrifugal Pumps	Case	Ni-Resist	CF-3M/CF-8M <sup>5</sup>	C952 <sup>4</sup> G/M Bronze
	Impeller	CF-3M/CF-8M <sup>2</sup> CD4MCu <sup>4</sup>	CF-3M/CF-8M <sup>2</sup> CD4MCu <sup>4</sup>	C958 <sup>4</sup> Monel
	Component	Deaerated Brine	Low pH Brine – H <sub>2</sub> S	
High Pressure Multistage —Oilfield Brines	Case	Duplex <sup>6</sup> C952 <sup>4</sup>	5-6% Mo Alloy <sup>7</sup> CF-8M	
	Impeller	Duplex <sup>6</sup> CF-8M C952 <sup>4</sup>	5-6% Mo Alloy <sup>7</sup>	

<sup>1</sup>Furnace stress relieved

<sup>2</sup>CF-8M should be postweld heat treated

<sup>3</sup>Erosion – corrosion may be high

<sup>4</sup>Postweld heat treat required

<sup>5</sup>Galvanic protection desirable to prevent crevice corrosion

<sup>6</sup>High alloy grade with 25 Cr, 5-6 Ni, 3 Mo, and N

<sup>7</sup>20 Cr, 19-25 Ni, 5-6 Mo, and N

**TABLE 8** Material classes for centrifugal pump services (Courtesy of the American Petroleum Institute, Reference 16)

CAUTION: This table is intended as a general guide. It should not be used without a knowledgeable review of the specific services involved.

Service	On-Plot Process Plant	Off-Plot Transfer & Loading	Temperature Range		Pressure Range	Material Class (see Tble 9)	See Reference Note
			Deg C	Deg F			
Fresh water, condensate, cooling-tower water	X	X	< 100	< 212	All	I-1 or I-2	
Boiling water and process water	X	X	< 120	< 250	All	I-1 or I-2	5
	X	X	120–175	250–350	All	S-5	5
	X	X	> 175	> 350	All	C-6	5
Boiler feed water							
Axially split	X	X	>95	>200	All	C-6	
Double casing (barrel)	X	X	>95	>200	All	S-6	
Boiler circulator	X	X	>95	>200	All	C-6	
Foul water, reflux drum water, water draw, and hydrocarbons containing these waters, including reflux streams	X	X	< 175	< 350	All	S-3 or S-6	6
Propane, butane, liquefied petroleum gas, and ammonia (NH <sub>3</sub> )	X	X	< 230	< 450	All	S-1	
Diesel oil; gasoline, naphtha; kerosene; gas oils; light, medium, and heavy lube oils; fuel oil; residuum;	X	X	< 230	<450	All	S-1	
crude oil; asphalt; synthetic crude bottoms	X		230–370	450–700	All	S-6	6, 7
Noncorrosive hydrocarbons, e.g., catalytic reformate, isomaxate, desulfurized oils	X	X	> 370	> 700	All	C-6	6
Xylene, toluene, acetone, benzene, furfural, MEK, cumene	X	X	230–370	450–700	All	S-4	7
Sodium carbonate, doctor solution	X	X	<175	<350	All	I-1	
Caustic (sodium hydroxide) concentration of $\leq 20\%$	X	X	<100	<210	All	S-1	8
			$\geq 100$	$\geq 200$	All		9
Sea water	X	X	< 95	< 200	All	—	10

(continues)

TABLE 8 Continued.

Service	On-Plot Process Plant	Off-Plot Transfer & Loading	Temperature Range		Pressure Range	Material Class (see Table 9)	See Reference Note
			Deg C	Deg F			
Sour water	X	X	<260	<470	All	D-1	
Sulfur (liquid state)	X	X	All	All	All	S-1	
FCC slurry	X	X	<370	<700	All	C-6	
Potassium carbonate	X	X	<175	<350	All	C-6	
	X	X	<370	<700	All	A-8	
MEA, DEA, TEA-stock solutions	X	X	<120	<250	All	S-1	
DEA, TEA-lean solutions	X	X	<120	<250	All	S-1	8
MEA-lean solution (CO <sub>2</sub> only)	X	X	80–150	175–300	All	S-9	8
MEA-lean solution (CO <sub>2</sub> and H <sub>2</sub> S)	X	X	80–150	175–300	All		8, 11
MEA, DEA, TEA, rich solutions	X	X	<80	<175	All	S-1	8
Sulfuric acid concentration >85%	X	X	<38	<100	All	S-1	6
85%–< 1%	X	X	<230	<450	All	A-8	6
Hydrofluoric acid concentration of > 96%	X	X	<38	<100	All	S-9	6

1. The materials for pump parts for each material class are given in Table 9.
2. Separate materials recommendations should be obtained for services not clearly identified by the service descriptions listed in this table.
3. Cast iron casings, where recommended for chemical services, are for nonhazardous locations only. Steel casings (S-1 or I-1) should be used for pumps in services located near process plants or in any location where released vapor from a failure could create a hazardous situation or where pumps could be subjected to hydraulic shock, for example, in loading services.
4. Mechanical seal materials: For streams containing chlorides, all springs and other metal parts should be Alloy 20 or better. Buna-N and Neoprene should not be used in any service containing aromatics. Viton should be used in services containing aromatics above 200°F (95°C).
5. Oxygen content and buffering of water should be considered in the section of material.
6. The corrosiveness of foul waters, hydrocarbons over 450°F (230°C), acids and acid sludges may vary widely. A materials recommendation should be obtained for each service. The material class previously indicated will be satisfactory for many of these services but must be verified.
7. If production corrosivity is low, Class S-4 materials may be used for services at 451–700°F (231–370°C). A separate materials recommendation should be obtained in each instance.
8. All welds shall be stress relieved.
9. Alloy 20 or Monel pump material and double mechanical seals should be used with a pressurized seal oil system.
10. For seawater service, the purchaser and the vendor should agree on the construction materials that best suit the intended use.
11. Class A-7 materials should be used, except for carbon steel casings.

**TABLE 9** Materials for pump parts (Courtesy of the American Petroleum Institute, Reference 16)

		Material Class and Material Abbreviations <sup>a</sup>													
Part	Full <sup>b</sup> Compliance Material?	I-1	I-2	S-1	S-3	S-4	S-5	S-6	S-8	S-9	C-6	A-7	A-8	D-1	
		Cl	Cl	STL	STL	STL	STL	STL	STL	STL	STL	12% CHR	AUS	316 AUS	DUPLEX
		Cl	BRZ	Cl	NI-RESIST	STL	STL 12% CHR	12% CHR	316 AUS	MONEL	12% CHR	AUS <sup>1,2</sup>	316 AUS <sup>1,2</sup>	DUPLEX	
Pressure casing	Yes	Cast iron	Cast iron	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon Steel	Carbon steel	Carbon steel	12% CHR	AUS	316 AUS	Duplex	
Inner case parts (bowls, diffusers, diaphragms)	No	Cast iron	Bronze	Cast iron	Ni-Resist	Cast iron	Carbon steel	12% CHR	316 AUS	Monel	12% CHR	AUS	316 AUS	Duplex	
Impeller	Yes	Cast iron	Bronze	Cast iron	Ni-Resist	Carbon steel	Carbon steel	12% CHR	316 AUS	Monel	12% CHR	AUS	316 AUS	Duplex	
Case wear rings	No	Cast iron	Bronze	Cast iron	Ni-Resist	Cast iron	12% CHR hardened	12% CHR hardened	Hard faced 316 AUS <sup>3</sup>	Monel	12% CHR hardened	Hard faced AUS <sup>3</sup>	Hard faced 316 AUS <sup>3</sup>	Duplex <sup>3</sup>	
5.41 Impeller wear rings	No	Cast iron	Bronze	Cast iron	Ni-Resist	Cast iron	125 CHR hardened	12% CHR hardened	Hard faced 316 AUS <sup>3</sup>	Monel	12% CHR hardened	Hard faced AUS <sup>3</sup>	Hard faced 316 AUS <sup>3</sup>	Duplex <sup>3</sup>	
	Yes	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon steel	AISI 4140	AISI 4140 <sup>4</sup>	316 AUS	K-Monel	12% CHR	AUS	316 AUS	Duplex	
Shaft sleeves, packed pumps	No	12% CHR hardened	Hard Bronze	12% CHR hardened	12% CHR hardened or hard faced	12% CHR hardened or hard faced	12% CHR hardened or hard faced	12% CHR hardened or hard faced	Hard faced 316 AUS <sup>3</sup>	K-Monel, hardened	12% CHR hardened or hard faced	Hard faced AUS <sup>3</sup>	Hard faced 316 AUS <sup>3</sup>	Duplex <sup>3</sup>	
Shaft sleeves, mechanical seals	No	AUS or 12% CHR	AUS or 12% CHR	AUS or 12% CHR	AUS or 12% CHR	AUS or 12% CHR	AUS or 12% CHR	AUS or 12% CHR	AUS or 12% CHR	K-Monel, hardened	AUS or 12% CHR	AUS	316 AUS	Duplex	
Throat bushings	No	Cast iron	Bronze	Cast iron	Ni-Resist	Cast iron	12% CHR	12% CHR	316 AUS	Monel	12% CHR hardened	AUS	316 AUS	Duplex	
Interstage sleeves	No	Cast iron	Bronze	Cast iron	Ni-Resist	Cast iron	12% CHR hardened	12% CHR hardened	Hard faced 316 AUS <sup>3</sup>	K-Monel, hardened	12% CHR hardened	Hard faced AUS <sup>3</sup>	Hard faced 16 AUS <sup>3</sup>	Duplex <sup>3</sup>	
Interstage bushings	No	Cast iron	Bronze	Cast iron	Ni-Resist	Cast iron	12% CHR hardened	12% CHR hardened	Hard faced 316 AUS <sup>3</sup>	K-Monel, hardened	12% CHR hardened	Hard faced AUS <sup>3</sup>	Hard faced 316 AUS <sup>3</sup>	Duplex <sup>3</sup>	

(continues)

TABLE 9 Continued.

		Material Class and Material Abbreviations <sup>a</sup>													
Part	Full <sup>b</sup> Compliance Material?	I-1	I-2	S-1	S-3	S-4	S-5	S-6	S-8	S-9	C-6	A-7	A-8	D-1	
		CI	CI	STL	STL	STL	STL	STL	STL	STL	STL	12% CHR	AUS	316 AUS	DUPLEX
		CI	BRZ	CI	NI-RESIST	STL	STL 12% CHR	12% CHR	316 AUS	MONEL	12% CHR	AUS <sup>1,2</sup>	316 AUS <sup>1,2</sup>	DUPLEX	
Seal gland	Yes	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	Monel	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	316 AUS <sup>5</sup>	Duplex <sup>5</sup>	
Case and gland studs	Yes	Carbon steel	Carbon steel	AISI 4140 steel	AISI 4140 steel	AISI 4140 steel	AISI 4140 steel	AISI 4140 steel	AISI 4140 steel	K-Monel, hardened <sup>3</sup>	AISI 4140 steel	AISI 4140 steel	AISI 4140 steel	Duplex <sup>8</sup>	
Case gasket	No	AUS, spiral wound <sup>6</sup>	AUS, spiral wound <sup>6</sup>	AUS, spiral wound <sup>6</sup>	AUS, spiral wound <sup>6</sup>	AUS, spiral wound <sup>6</sup>	AUS, spiral wound <sup>6</sup>	AUS, spiral wound <sup>6</sup>	316 AUS, spiral wound <sup>6</sup>	PTFE filled <sup>5</sup>	AUS, spiral wound <sup>6</sup>	AUS, spiral wound <sup>6</sup>	316 AUS, spiral wound <sup>6</sup>	Duplex SS spiral wound <sup>6</sup>	
Discharge head/suction can	Yes	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon steel	AUS	AUS	316 AUS	Duplex	
Column/bowl shaft bushings	No	Nitrile <sup>7</sup>	Bronze	Filled carbon	Nitrile <sup>7</sup>	Filled carbon	Filled carbon	Filled carbon	Filled carbon	Filled carbon	Filled carbon	Filled carbon	Filled carbon	Filled carbon	
Wetted fasteners (bolts)	Yes	Carbon steel	Carbon steel	Carbon steel	Carbon steel	Carbon steel	316 AUS	316 AUS	316 AUS	K-Monel	316 AUS	316 AUS	316 AUS	Duplex	

The abbreviation above the diagonal line indicates the case material; the abbreviation below the diagonal line indicates trim material.

Abbreviations are as follows: BRZ = bronze, STEL = steel, 12% CHR = 12% chrome, AUS = austenitic stainless steel, CI = cast iron, 316 AUS = Type 316 austenitic stainless steel.

Parts designated as *full compliance* materials shall meet all the requirements of the industry specification listed for the material. Parts not designated as *full compliance* materials shall be made of materials with applicable chemical composition but need not meet the other requirements of the listed industry specification.

<sup>1</sup>Austenitic stainless steels include ISO Types 683-13-10/19 (AISI Standard Types 302, 303, 304, 316, and 347). If a particular type is desired, the purchaser will so state.

<sup>2</sup>For vertically suspended pumps with shafts exposed to liquid and running in bushings, the shaft shall be 12 percent chrome, except for Classes S-9, A-7, A-8, and D-1. Cantilever (Type VS5, API 610) pumps may utilize AISI 4140 where the service liquid will allow.

<sup>3</sup>Unless otherwise specified, the need for hard-facing and the specific hard-facing material for each application shall be determined by the vendor and described in the proposal. Alternatives to hard-facing may include opening running clearances or the use of non-galling materials, such as Nitronic 60 and Waukesha 88, depending on the corrosiveness of the pumped liquid.

<sup>4</sup>For Class S-6, the shaft shall be 12 percent chrome if the temperature exceeds 350°F (175°C) or if used for boiler feed service (refer to Table 8).

<sup>5</sup>The gland shall be furnished with a non-sparking floating throttle bushing of a material such as carbon graphite or glass-filled PTFE. Unless otherwise specified, the throttle bushing shall be premium carbon graphite.

<sup>6</sup>If pumps with axially split casings are furnished, a sheet gasket suitable for the service is acceptable. Spiral-wound gaskets should contain a filler material suitable for the service.

<sup>7</sup>Alternate materials may be substituted for liquid temperatures greater than 110°F (45°C) or for other special services.

<sup>8</sup>Unless otherwise specified, APSI 4140 steel may be used for non-wetted case and gland studs.

lines that do not necessarily apply to every situation. In many hydrocarbons, hydrogen sulfide is present as a contaminant.

Hydrogen sulfide causes a form of stress corrosion cracking in hardenable steels and other alloys. Additional precautions must be taken when hydrogen sulfide is present, consisting of special heat treatments to limit hardness. Details concerning the requirements for specific materials can be found in NACE standard MR-01-75.

Naphthenic acid is an organic acid that is found in many crude oils. It causes corrosion problems at temperatures in excess of 450°F (232°C). Austenitic stainless steels containing molybdenum, either 316 or 317, are required for effective resistance against naphthenic acids.

Amine solutions have caused cracking in welded carbon steel components that have not been post-weld heat treated. Although repairs to carbon steel casings may not require post-weld heat treatment, it is prudent to specify this for welds made to rotating components or piping welds to a casing.

## **MATERIALS FOR SLURRY AND ABRASIVE SERVICES**

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The construction materials for pumps that handle high concentrations of suspended solids are often based upon high bulk hardness. In many applications, coatings, hard liners, and weld overlays are used to specifically increase the surface hardness of the internal wetted portions within the pump. However, many of the slurry applications use non-metallics that do not have high bulk hardness because of their unique qualities.

**Nonmetallics** Contrary to “harder is better,” a good number of slurry pumps use non-metallic materials, such as rubber, that absorb the kinetic energy of the solid particles through a large elastic deformation of the surface. Natural rubber is the most commonly used material since it provides good wear resistance with abrasive particles less than approximately 0.25 to 0.38 in (6 to 9 mm). Rubber linings pose a problem in the bonding of this outer shell to a metallic substrate. This is particularly true for cut water areas of a casing and, of course, attachment to metal skeletons of an impeller. Care must be taken also in considering the liquid phase of the slurry and the temperature of the application, both of which can degrade the rubber.

Other factors to consider when using elastomeric liners include pressure in the flow passage versus the pressure between the liner and the wall, and temperature, since rubber softens around 240°F (115°C). It is also important to consider the size of the particles greater than 0.2 in (5 mm) if they are dull or greater than 0.08 in (2 mm) if they are sharp, and the head per stage.

**Metals** In mildly abrasive services, carburized steels are sometimes used to increase the wear life of components. Carbon is diffused into the surface of carbon steel, which, after a hardening heat treatment, can achieve a surface hardness of 60 *R<sub>c</sub>*. This gas diffusion heat treatment can produce high hardness layers that penetrate the outside surface of the pump component to a depth of approximately 0.080 to 0.090 in (2.0 to 2.3 mm). However, after carburization, the materials are impossible to weld-repair without cracking. Using a special process, usually a vacuum furnace, carburizing has been employed in the surface hardening of the 12% chromium stainless steels, such as CA15, for abrasive services where mild corrosion is expected.

The most commonly used materials for severe slurry services are the abrasion-resistant cast irons found in ASTM A532. Essentially, three main classes and several types of alloys are covered in this specification. The most widely employed material in slurry applications is the Class III hard irons. A brief description of this class of abrasion-resistant iron is as follows:

ASTM A532 Grade	Composition (Cr, Ni, and Mo)	Hardness (BHN)
Class I: Type A (Ni-Hard)	1–11% Cr, 3–7% Ni	500–600
Class II: Type A, B, C, D, E	11–23% Cr, 0.5–3.5% Mo	450 (annealed for machining) 600 (hardened)
Class III: Type A (26% chrome iron, original trade name of HC-250)	23–28% Cr	400–600 depending on desired properties

All three classes contain a martensitic matrix with secondary hard phases of chrome and iron carbides that increase the wear resistance. The molybdenum in class II increases the material's hardenability for thicker cross sections.

In general, it should be stressed that machining and welding these three classes of material is impossible. Another important consideration is the role of carbon content on corrosion, erosion, and fracture resistance. High-carbon contents reduce corrosion resistance because any chromium tied up as chrome carbide is no longer available to form a protective chrome oxide layer. Although beneficial with regard to erosion and abrasion resistance, high-carbon content increases the susceptibility to breakage by thermal and mechanical shocks.

To counteract this problem, a number of precautionary measures must be adopted to enhance the serviceability of this class of material. First, slow warm-up cycles must be instituted, typically around 100 to 150°F per hour.<sup>14</sup> Another strategy is to lower the hardness from about 600 to 400 Brinell by a partial anneal. This measure reduces brittleness, but at the expense of erosion resistance.

***Linings, Inserts, and Coatings*** The low ductility and toughness of A532 cast irons do not permit their usage with primary pressure boundaries according to ASME code and API regulations. This restricts the use of hard irons to internal wetted parts. Therefore, it is necessary to use steel pressure casings with hard materials as liners. A common slurry pump consists of ASTM A532, Class III, Type A (HC-250) impellers and replaceable HC-250 wear liners for the volute and for both the inlet and outlet ends of the pump casing.

Since pump erosion is often quite localized, in some instances it is more practical to install replaceable, mechanically attached inserts at high wear areas, such as the cut water. These are typically made of sintered tungsten carbide or some other hard material. Newer materials, such as ceramic composites and toughened ceramics, should perform better than the "cermets" used in the past.

Several problems, however, can occur with mechanically attached inserts. One problem is protecting the fastening device against erosive wear. Another problem is the insert's tendency to act as a turbulence riser due to an imperfect fit or erosion-induced crevices and offsets. Limited success has been achieved with weld-applied overlays of Stellite and other hardfacing materials. Weld overlays are extensively utilized, but several problems may occur. These include a propensity for cracking, debonding resulting from preferential corrosion of the bond line, dilution of the hardfacing material with the substrate, and potential uneven thickening after machining.

Thermal spray coatings as well as diffusion surface treatments have been used in pump applications for fluids containing high concentrations of suspended solids. Spray coatings are restricted to areas within the pump, accessible by the line of sight. Diffusion-produced coatings are not limited by this constraint. A disadvantage of diffusion processes is that they are performed at high temperatures that can negatively influence the base material properties. Diffusion coatings can range from traditional gas carburizing to the diffusion of high chromium alloys. These coatings increase the sur-

face hardness of the component and, depending upon the process, can increase the material's surface hardness to values in excess of  $60 R_c$ . Diffusion layers can be produced to a depth of approximately 0.100 in (2.54 mm). One item of caution: these coatings usually render the material unweldable after application. For this reason, steps must be taken to protect areas of anticipated welding, such as attachment piping. Future weld repairs are not possible unless the coating is completely worn off or removed.

Through the years, developments in thermal spray equipment have enhanced the acceptability of this surface modification process. Thermal spray processes employ the transfer of a material onto another by raising the temperature of the hard-facing material, usually in powder form, and projecting it against the component that requires the additional erosion resistance. The bond strength between the hard-faced material and the substrate material is directly influenced by the maximum velocity that the particles of molten material achieve in a given thermal spray process. The greatest bond strength is achieved by the highest velocity process. The typical thermally sprayed materials used in pumps to resist solid particle erosion damage are as follows:

- Nickel chromium boride coatings
- Cobalt-based hardfacing coatings
- Tungsten carbide coatings
- Solid particle tungsten carbide loaded (1) or (2)

The processes used to apply the above hardfacing materials are as follows:<sup>15</sup>

Process	Typical Particle Velocity
Flame spray	100 ft/s (30.5 m/s)
Plasma spray	800 ft/s (244 m/s)
D-Gun (Union Carbide tradename for detonation gun process)	800 ft/s (244 m/s)
HVOF (high velocity oxy-fuel)	3000 ft/s (915 m/s)

The severity of the service usually dictates the process. In the past, thermal spray coatings, for the most part, were tungsten carbide and the diffusion coatings were high in borides. It was found that for spray coatings an increased performance could be achieved by applying them over erosion-resistant substrates. This is a challenge because the high-chromium, carbon, abrasion-resistant materials are thermal-crack-sensitive. Overlay coatings, if applied several times, are thicker but are more prone to cracking, chipping, and spalling. An alternative is to use carburized carbon steel or 12% chromium stainless steel centrifugal pump components for mildly corrosive environments. Coatings are frequently used to increase the life of plungers in reciprocating pumps for slurry services.

Another process for applying hard-faced materials is by laser consolidation. This process can be accomplished in two different ways. The first case is one in which a laser beam is used to melt a thermally sprayed coating applied upon a substrate. The other process is to simultaneously melt the substrate while applying a hard-faced material. In either case, the principle is to use the hard-faced material as a consumable in a laser-welding operation. Since laser welding is a rapid process, very little dilution of the hard facing material is produced. This allows for much thinner coatings that are less prone to thermally induced cracking during an operation. In addition, since there is little dilution, the hardness and chemistry of the coating are very consistent. This provides for uniform erosion resistance throughout the entire coating thickness.

**SUMMARY**

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It should be clear from the discussion of materials for saline waters and hydrocarbon applications that the selection of materials for a pump is a complicated exercise, requiring knowledge of the engineering properties of the material, its fabrication characteristics, and corrosion and erosion resistances. An in-depth discussion of the considerations governing material selections for other pump applications, such as the chemical industry, mining industry, and others, is beyond the scope of this section, but a number of references are included to provide additional guidance. Past experience is often helpful, but it is recommended that the materials selections be reviewed by a metallurgist or corrosion engineer with experience in this area, especially for critical applications or those applications with which you are not familiar.

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