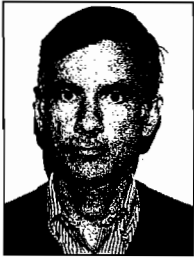


# MATERIALS PROBLEMS AND SOLUTIONS—A METALLURGICAL PERSPECTIVE

by

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## ABSTRACT

Pumps are an essential component of most industrial processes. Reliability is a major concern of pump manufacturers and users, since unexpected shutdowns can have serious and costly implications, including loss of production. Pump manufacturers strive to build rugged and durable equipment. Improvements in design and technology are recognized as major contributors to enhanced reliability. Metallurgical analysis plays an important role in this effort, because it provides insight into the factors that are critical to pump performance and longevity.

Pumps, in common with other types of rotating machinery, will experience gradual degradation of critical components. Clearances will open, bearings will wear, and performance will gradually be reduced, so that it eventually becomes necessary to disassemble and overhaul the pump. This type of maintenance is expected and predictable. With proper planning, it can be handled with minimal impact on production schedules. High performance machines, however, also experience sudden and unexpected failures, either during test or in service, unless they are so over designed as to be noncompetitive. These failures provide a very valuable, albeit costly, source of engineering information. Sharing this information benefits the entire pump community, in that it contributes to improved designs, materials selection, quality control, and service engineering. Most importantly, the knowledge gained will prevent additional failures and improve reliability.

## INTRODUCTION

Pump components can fail by a wide variety of mechanisms. In many cases, the failure is attributed to some form of corrosion, a subject which was covered in some depth in a recent tutorial [1]. The more common types of corrosion were covered in this previous tutorial, and detailed case histories of corrosion in pumps can be found in the literature [2].

Several other materials problems that can occur in pumps, generally categorized as mechanical failure are the focus herein. By

far, the most likely mechanical failure mechanism to be encountered is metal fatigue. These have not received the same level of attention as corrosion failures, and there is only scattered information in the literature on this subject, as specifically related to pumps. That gap is addressed. Several common types of fatigue failures are considered, and metallurgical techniques are employed to identify the root cause for each. Most, it will be shown, are attributable to some deficiency in manufacture, or misuse of the pump in service. A thorough understanding of the cause for failure is necessary before the appropriate corrective actions can be taken to prevent a recurrence. By following the approach outlined herein, the incidence of mechanical failures can be reduced and reliability increased, resulting in significant savings for plant operators.

Another important category of materials problem limiting the life of pumps is cavitation damage. Metallurgical studies of the effect of cavitation damage on material structure have led to an improved understanding of the mechanism, and the development of new alloys with exceptional cavitation resistance. Much of this work is recent, having been done within the past 10 years. It has direct application to pumps and offers the possibility to eliminate chronic cavitation problems simply by upgrading materials. These important advances in the understanding of cavitation damage, and materials response are covered, and information is presented on the development and use of the new, highly resistant alloys.

## FATIGUE FAILURES

### *Description*

Practically all mechanical systems, and especially rotating machinery, are subjected to repeated load applications throughout their life. These loads may occur as tension, bending, or torsion. The stresses caused by such loads are usually far below the static fracture strength of the material. Nevertheless, when such loads are cyclic in nature, and exceed a critical threshold value, the component will have finite cyclic life. That is, after a number of load cycles, varying from the tens to the millions, a crack will develop and propagate. Catastrophic failure will occur when this fatigue crack reduces the cross sectional area to the extent that the structure can no longer support the static load.

Except at high temperatures, where other factors interact, fatigue is cyclic rather than time related. Failure can occur after only minutes, or after years of operation. The time to failure is dependent on both the magnitude and rate of cyclic load application.

Metal fatigue can be defined as the progressive fracture of a component under the application of repeated or cyclic loads. The stress level necessary to initiate and propagate fatigue fracture is much lower than that required to cause yielding or fracture under a single load application.

One may wonder why fatigue failures continue to occur in pumps and a variety of other industrial products. There are several reasons. There are always uncertainties about the loads and environment a part will experience in service. Another is that scatter in fatigue properties is greater than that of most other metal properties. The predominant reason, however, is that complex metal

components may contain hidden or unrecognized areas of stress concentration, or "stress raisers." The majority of fatigue failures initiate at some form of "stress raiser."

As the name implies, a stress raiser is an irregularity in shape, section, or surface, which causes the peak stress at or near the irregularity to be higher than the average stress in the surrounding area.

Stress raisers can be either mechanical or metallurgical. Mechanical stress raisers involve actual discontinuities or separations in the metal, such as notches and cracks. Metallurgical stress raisers result from localized differences in properties, such as hard and soft spots. Most stress raisers can also be classified by their origin:

- Those resulting from design requirements, such as holes, corners, keyways, threads
- Those caused inadvertently during fabrication, such as: laps, seams, tears, cracks
- Those carried over from the refining process, such as: pipe, inclusions, segregation
- Those incurred as a result of the operating or maintenance environment, such as: corrosion, stress corrosion, stress rupture, foreign object damage.

A large part of fatigue failure analysis involves the detection and identification of stress raisers at the fracture origin. Conveniently for material engineers, fatigue fractures generally have a distinctive appearance, which, in most metals, permits not only identification of the fracture mechanism, but location of the fracture origin. The characteristic features of the fatigue zone are usually:

- Smooth, polished fracture surfaces.
- The absence of significant plastic deformation.
- Concentric rings or stop marks that focus back to the origin.
- Lines or shallow ridges that appear to radiate outward from the origin.

The fracture appearance will be greatly influenced by the load spectrum and the metal properties.

The root causes of fatigue failures in pumps are best understood by a review of actual case studies. This requires that one observe the actual metallurgical conditions that led to failure in pump components. Metallic components cannot be made that are completely free of impurities, inhomogeneities and imperfections, because the complex processes of metal refining, metal treating, and metal fabrication are themselves not perfect. Terms such as purity and accuracy are relative and depend on the end use of the component, expected loads in service, and the life expectancy of the pump. In addition, the best designs often can not foresee all the environmental hazards a component may be exposed to during service and maintenance.

#### Examples

Assembled in the following case studies are some of the more common problems that have resulted in fatigue failure of pump components. These can generally be associated with manufacture, use, or maintenance of the pump. Surprisingly, few can be attributed to poor design. A better understanding of the factors leading to fatigue failure will enable manufacturers and users alike to enhance reliability and reduce costs associated with emergency repair and maintenance.

#### Shafts

Abusive grinding of hardenable steels is a common cause for fatigue failure. A 5.5 in diameter shaft from a large, relatively slow

moving sewage pump failed after about one year of service. The fracture occurred at a 0.06 in radius between a smaller and a larger diameter. The fracture surface is shown in Figure 1. It should be noted that this is a relatively short stubby shaft, not subject to excessive bending and with no history of fatigue failures. The material is 1045, a medium carbon steel. The microstructure consists of pearlite with a network of grain boundary ferrite, which suggests that the material probably received a normalizing heat treatment. Metallographic examination at the radius, where cracking initiated, disclosed fine branched transgranular cracks adjacent and parallel to the main fracture surface. These cracks are shown in Figures 2 (unetched), and Figure 3, etched to show that the cracks are independent of structure, that is, they traverse both the harder pearlite and softer ferrite phases.

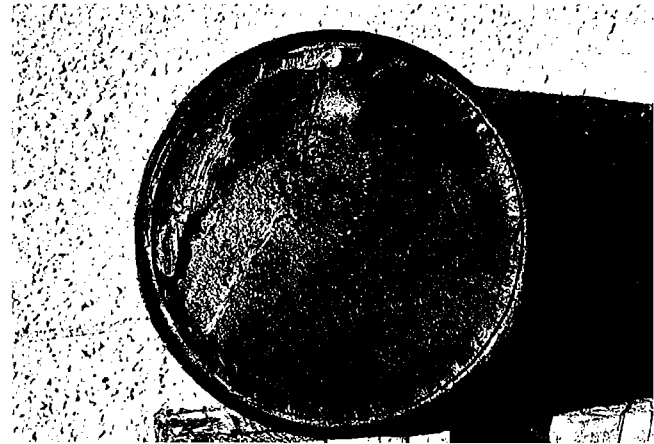


Figure 1. Fracture Surface, Steel Sewage Pump Shaft. Crack propagated, by low stress high cycle mechanism through almost entire cross section before failure.



Figure 2. Fine Cracks in Shaft Radius, Adjacent to Fracture Surface.

There are a very few conditions that will cause this type of cracking in normalized medium carbon steel. The evidence indicated localized overheating during manufacture. The final sizing operation would have had to be grinding in order to hold tolerance on the diameter. It appears that excessive grinding resulted in overheating, transformation at the surface to austenite, which cooled rapidly to form brittle crack prone untempered martensite. The fine

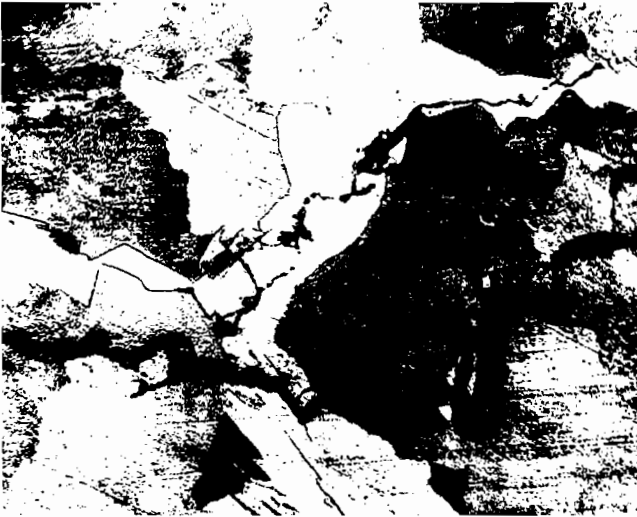


Figure 3. Etched Microstructure, Showing Cracks Are Transgranular, Traversing Ferrite and Pearlite Phases.

cracks that formed increased the stress concentration in the radius sufficiently to allow fatigue cracks to initiate and propagate. This example highlights the need for adequate controls on the final grinding of pump shafts. Adequate cooling is important, as is the instruction of shop personnel who may have some incentive to finish the job quickly and not appreciate the danger associated with abusive grinding.

Another common cause of fatigue failures in pump shafts is improper chrome plating. This process is frequently used in the pump industry, especially by maintenance shops, to repair scored or worn shafts, and restore dimensions. It is not always recognized that chrome plating significantly reduces fatigue resistance. This effect is shown in Figure 4. It is good practice to shot peen prior to chrome and electroless nickel plating to counteract the harmful effects of plating on fatigue life. Shot peening is effective, because it introduces a compressive stress into the surface layer of the base metal. This compressive stress inhibits the propagation of cracks that form in the plating. Shot peening prior to plating is recommended on cyclically loaded parts. It is a requirement of several government specifications for dynamically loaded parts where service requires unlimited life. Shot peening should be specified for pump shafts that will be chrome plated.

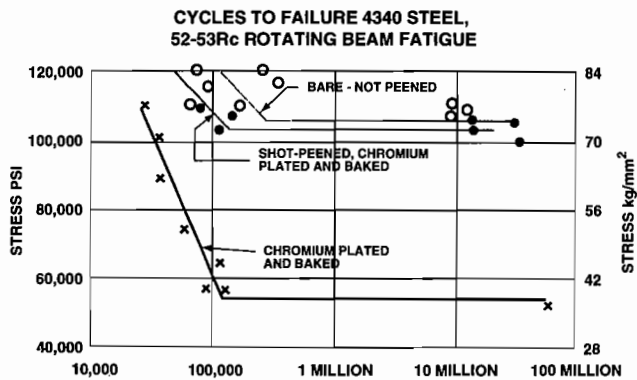


Figure 4. Effect of Chrome Plating on Fatigue Characteristics of Low Alloy Steel.

A large boiler feed pump shaft, in service for many years, failed in fatigue. The fracture surface is shown in Figure 5. Crack initiation appears to have been at several points on the periphery of the

shaft and propagated in a single plane perpendicular to the central axis. At low magnification, the several origins appear to be small pre-existing cracks. The crack front propagated through the entire thickness of the shaft before fracture occurred. Visual examination indicated the shaft was coated, presumably with hard chromium. This was apparently done during overhaul some years back when the pump was converted from packing to a mechanical seal. Fatigue occurred under the mechanical seal sleeve. Fatigue occurred at a location where it would not normally be anticipated, since there is no change in section, keyway or other stress raiser. Metallographic examination showed radial cracks, entirely through the thickness of the chrome plate. These, shown in Figure 6, are very significant stress raisers. Also, lack of deformation of the base metal surface indicates that the shot peening was not performed. This example demonstrates that chrome plating, applied without prior shot peening, is capable of inducing eventual cracking even in locations subject to low nominal cyclic stress.



Figure 5. Fracture Surface of Chrome Plated Boiler Feed Pump Shaft.

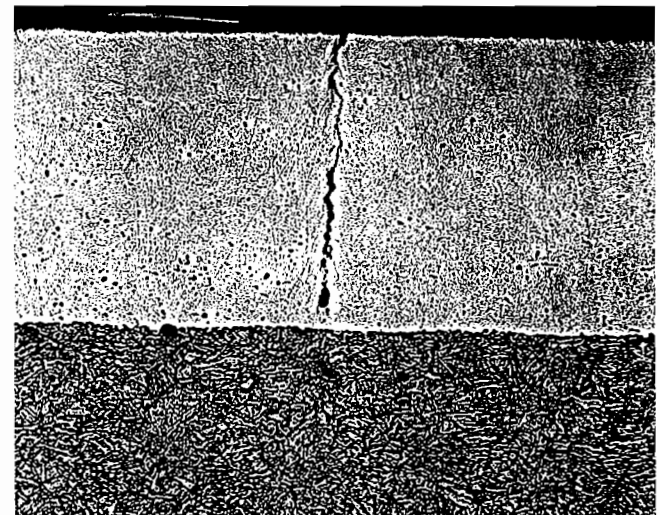


Figure 6. Radial Cracks Through Thickness of Chrome Plate Adjacent to Fracture Surface.

In another instance, a steel shaft experienced fatigue cracking in an area that had been chrome plated. This area had been ground at overhaul to remove a scored surface. Following grinding, the chrome plate had been applied. It appeared initially that the fatigue strength reducing effect of the chrome plate was responsible for the failure. Metallographic analysis, Figure 7, showed a rehardened

zone containing many small cracks under the plate. Chrome plate evident in some of the cracks (Figure 8) proved that these were present prior to plating. Grinding cracks and burns, such as these, can be readily detected by magnetic particle inspection and etching after grinding and prior to plating.

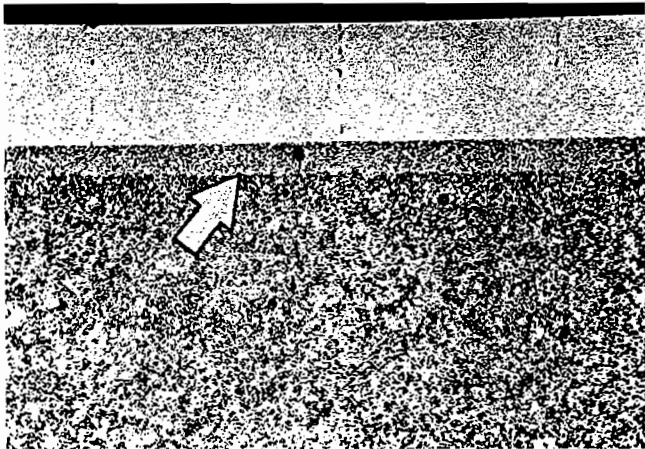


Figure 7. Rehardened Zone under Chrome Plate in Failed Shaft.



Figure 8. Chrome Plate in Pre-existing Crack.

One of several fatigue crack origins in a chrome plated shaft is shown in Figure 9. Failure was attributed to hydrogen embrittlement that took place when the shaft was chrome plated. The material was susceptible to hydrogen embrittlement in a localized area that had been hardened after heat treatment. The only explanation for the presence of the localized hardened area is that the shaft had been straightened by heating during manufacture.

There were numerous intergranular cracks in the hardened area (Figure 10), that were caused by hydrogen embrittlement. Several of these progressed into fatigue cracks during operation. Hardened or high strength steels are susceptible to hydrogen embrittlement during electroplating. Hydrogen is absorbed into the surface, and must be removed by a subsequent thermal treatment. Steels that are fully hard, or hardened and not tempered, are especially susceptible to embrittlement. The hardened area of the failed shaft had a hardness of Rc 46, which is the maximum hardness obtainable in this grade of steel.

Martensitic stainless steels, especially Type 410, are popular shaft materials for boiler feed pumps and other large multistage

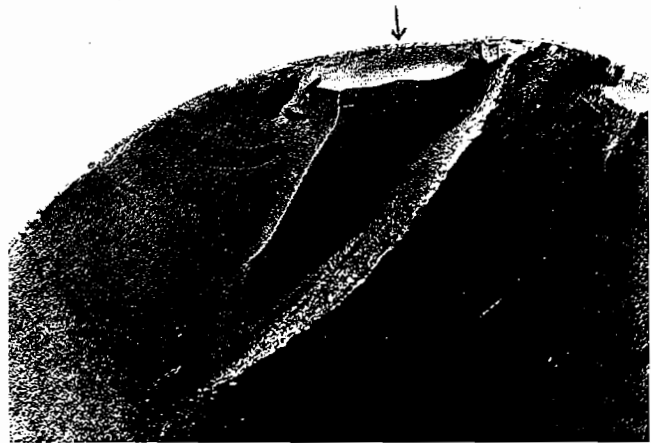


Figure 9. Fatigue Crack Origin in Chrome Plated Shaft.

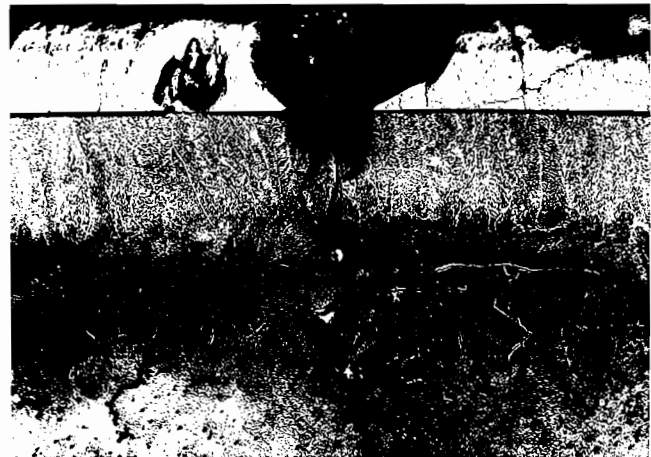


Figure 10. Intergranular Cracks in Localized Hardened Area.

pumps. These materials require a normalize, or quench and temper heat treatment to achieve the specified mechanical properties. Commonly used specifications, such as ASTM A276, do not adequately address heat treat parameters. Consequently, there have been failures, including one that was presented at a recent ASME conference [3], attributable to inadequate heat treatment resulting in deficient material properties.

The fractured shaft shown in Figure 11 is typical of this class of failures. Failure occurred after only 2.5 months of service in a five stage boiler feed pump operating at 3580 rpm, 230°F, and 1100 psi discharge pressure. In the previous 30 years that the pump had been installed, there were no reported incidents of premature shaft failure. Metallurgical analysis was conducted and it was determined that the failed shaft met requirements of the applicable material specification and had no significant flaws or defects. It was fabricated to drawing requirements and apparently not subject to misuse in service. Failure initiated in the keyway at some superficial scratches that occurred when the key was inserted, Figure 12. Root cause was found to be improper heat treatment that embrittled the material, making it highly susceptible to crack initiation and propagation. This was determined by Charpy impact testing, which showed the material to have absorbed energy of 6 ft lb, lateral expansion of 2 mils, and zero percent shear at 70°F. These results are very low, but within the wide range possible, as shown in Figure 13 for 410 stainless that exhibits tremendous variation in the ductile to brittle transition temperature as a function of slight variation in heat treatment parameters.

employed during outages reveals that shafting may experience severe loading at much lower temperatures. Charpy testing is a good indicator of material embrittled by heat treatment, a condition that is not easily detected in any other way. Type 410 stainless must be tempered at 1100°F minimum to avoid potential embrittlement and susceptibility to cracking.

Another metallurgical condition that influences fatigue cracking is grain size. Steels with fine grain size, produced by proper heat treatment, have superior fatigue strength to those with coarse grain size. A shaft failed in fatigue at a change in section adjacent to the keyway. Failure had initiated in this sharp corner, which had been machined with an insufficient radius and acted as a stress raiser. Metallurgical examination also showed that, contrary to specification requirements, this medium carbon steel had a coarse grain structure (Figure 14). Heat treatment of a portion of the fractured shaft demonstrated that the desired fine grain size could be obtained (Figure 15).



Figure 11. Fracture Surface—Type 410 Stainless Boiler Feed Pump Shaft.

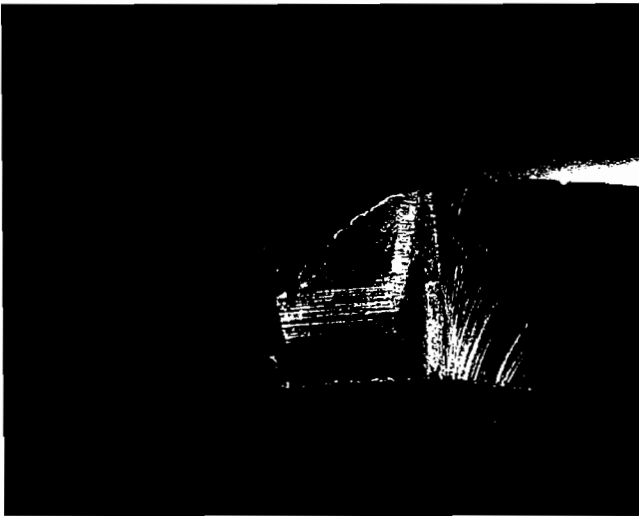


Figure 12. Superficial Scratches in Keyway Were Initiation Site for Fatigue Cracks.

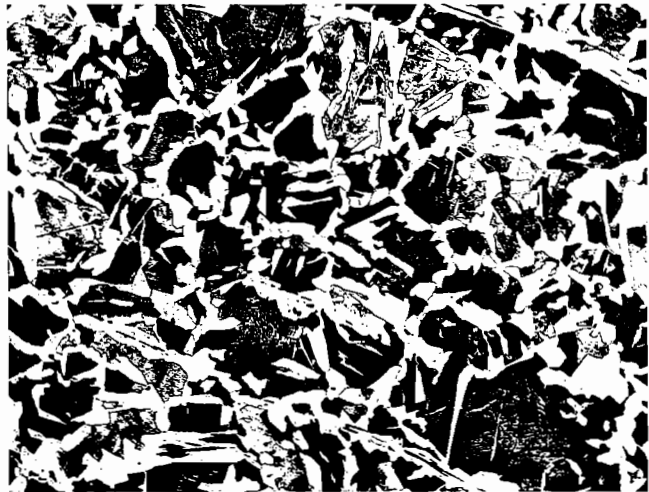


Figure 14. Coarse Grain Structure Has Poor Fatigue Resistance.

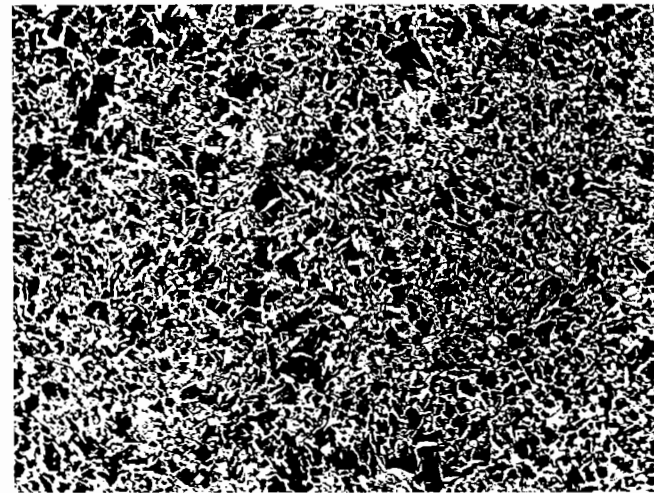


Figure 15. Heat Treatment Produces Fine Grain Structure with Much Improved Fatigue Resistance.

RAVENSWOOD CHARPY IMPACT TESTS

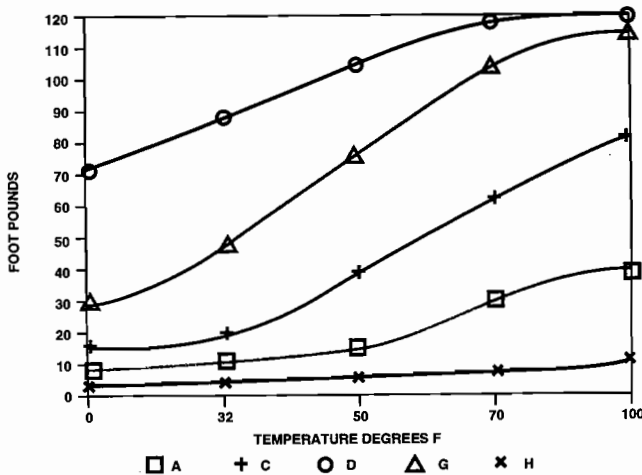


Figure 13. Energy Absorbed, as a Function of Temperature for 410 Stainless Steel with Minor Variations in Heat Treatments.

Charpy impact properties usually are not a requirement for pump materials that will be operated at ambient or higher temperatures. Nevertheless, consideration of maintenance practices

Fatigue strength of steels commonly used for shafting can be reduced by a condition known as banding. This refers to a segregated and inhomogeneous structure of nearly parallel bands aligned in the direction of working. It is caused by insufficient hot working and can occur in material that meets minimum mechanical properties (Figure 16).





Figure 16. Banded Structure in Medium Carbon Steel Shaft, Attributable to Inadequate Hot Work.

A banded structure is shown in Figure 16 in a medium carbon steel shaft that failed in fatigue after about one year of service handling a brine solution. Failure was attributed to the banded structure, tool marks that acted as stress risers, and corrosion.

Banding can also occur in martensitic 13 percent chrome steels. A heavily banded structure in a 400 stainless shaft that failed in bending fatigue at a sharp keyway is shown in Figure 17. The reduction in fatigue strength associated with banding is not well defined.

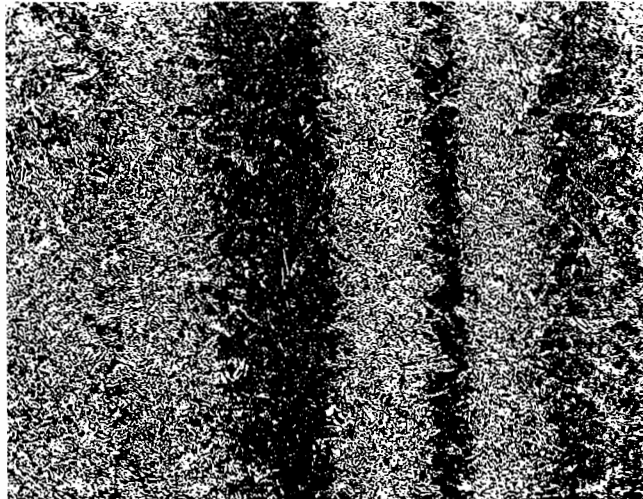


Figure 17. Banded Structure in Martensitic Stainless Shaft That Failed in Fatigue.

Nevertheless, this condition is clearly undesirable in bar stock intended for pump shafting, and should be cause for rejection.

#### OTHER COMPONENTS

While fatigue failures most often occur in shafts, other pump components, including stationary components, are also subject to fatigue cracking. Fluctuations in hydraulic pressure can provide the cyclic stress necessary to initiate and propagate a crack.

The large crack shown in Figure 18 was found in an austenitic stainless forging that served as the liquid cylinder in a reciprocating pump handling demineralized water. Cracking initiated at a small gouge left by the tooling used to drill the large vertical bore

(Figure 19). The gouge corresponds precisely to the center of the bore, and was made by the leading edge, or tip, of the machine tool insert, which was not sufficiently rigid and slipped or chattered as it came within 1/16 inch of the deeper bore. There was some evidence of hand grinding, in an effort to eliminate the defect and provide a radius between the larger and smaller bores.

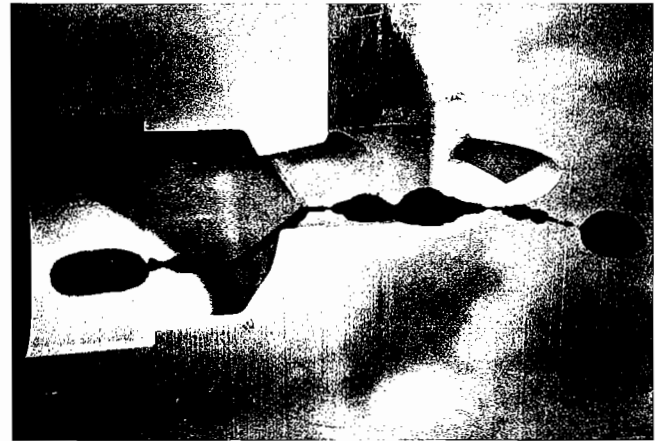


Figure 18. Liquid Penetrant Developer Delineates Large Fatigue Crack in Reciprocating Pump Forging.



Figure 19. Tool Mark Acted as Stress Riser and Initiated Fatigue Crack.

The drawing for this forging specified a 63 rms finish in internal bores, with intersections rounded to a 0.12 inch radius. Clearly this was not done, and cracking initiated at an irregularly shaped tool mark which was only partially eliminated. The site of crack initiation does not correspond with the region of maximum stress by design. The tool mark acted as a stress raiser. In addition, hand grinding probably introduced residual stress, thereby increasing the total stress at this location. This failure can be attributed to manufacturing error.

Fatigue failures in pump components are often associated with welds. The inducer shown in Figure 20 consists of a central hub with three spiral shaped blades welded to it. The welding process employs a GTAW root pass for the fillet weld on both sides of each blade, followed by a SMAW top pass. After manufacture, the inducer is dynamically balanced. The reverse side of this blade, after removal of the cracked portion by saw cutting, is shown in Figure 21. A poor quality repair weld, with considerable porosity, was made on the lower fillet. This weld was made in a direction opposite to that of the original fillet weld. Lack of access appears to have contributed to the poor quality of this weld.

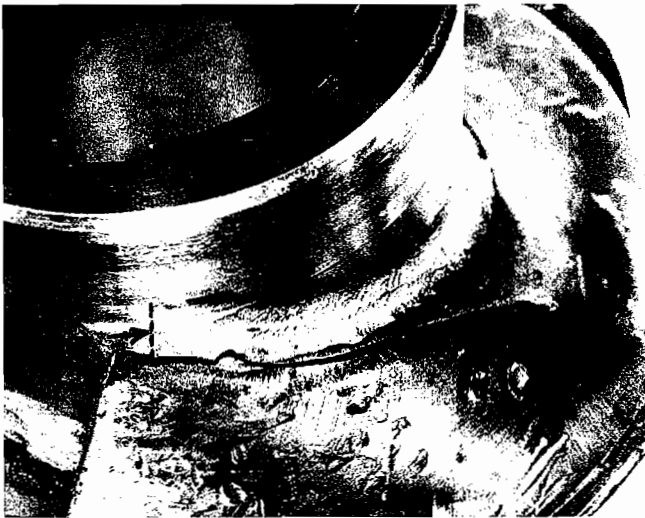


Figure 20. Inducer, with Large Crack Initiating at Blade to Hub Weld.



Figure 21. Crack Initiation Is Associated with Poor Quality Repair Weld.

The primary fatigue crack originates at the blade trailing edge, from the bottom, or repaired side of the blade. A second fatigue crack has initiated at the repair weld (Figure 21). It is known that the inducer was field welded to repair cavitation damage. The weld shown in Figure 21 is believed to have been made in an effort to restore dynamic balance. However, the combination of multiple repairs, poor weld quality, and heavy grinding combined to introduce residual stresses that promote fatigue cracking. Dynamic imbalance resulting from the field repairs produced the high frequency cyclic stress needed to initiate a crack.

Repair welding is commonly employed to salvage worn or damaged pump components. Weld defects will act as mechanical stress raisers to promote fatigue cracking. Frequently, these result from efforts to make repairs in difficult, almost inaccessible locations.

Intermittent cracks were found (Figure 22) around the circumference of a large forged carbon steel barrel at the edge of a stainless steel weld overlay. The pump handles boiler feedwater and had been in service for some 25 years. Metallurgical evaluation revealed the cracks were fatigue, propagating transgranularly along the carbon steel-heat affected zone interface. They were caused by service induced cyclic thermal stress generated by the

difference in coefficient of thermal expansion between the carbon steel barrel and the austenitic stainless steel pressure face weld overlay.

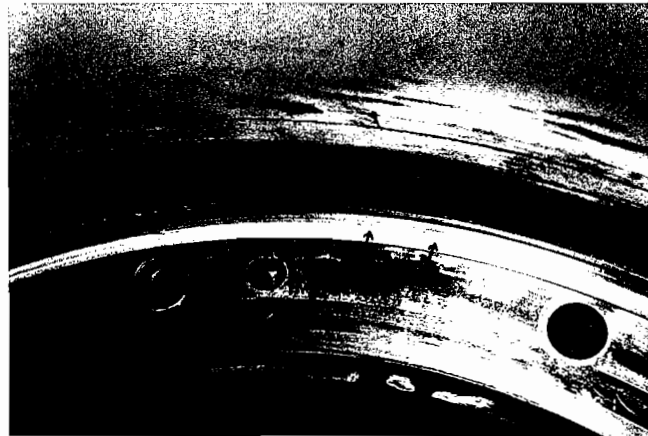


Figure 22. Circumferential Cracking at Weld-base Metal Interface in Forged Barrel.

Thermally induced fatigue cracking is not uncommon in older pumps that operate at elevated temperature and have experienced many thermal cycles. Although this particular failure was caused by stresses associated with differences in coefficient of thermal expansion, others initiate at casting or welding defects. Most of these castings were not examined by radiography when new and invariably contain some degree of internal shrinkage or porosity. With the current emphasis on life extension for old equipment, there is an increasing incidence of thermally induced fatigue cracking in pump components, especially castings and weldments.

Many pumps, especially those used in utility and hydrocarbon processing applications, employ 12 percent chrome martensitic steels. These grades require heat treatment after welding to temper newly formed martensite in the weld and heat affected zone. This is often not possible with finish machined castings because thermally induced distortion would cause warpage exceeding dimensional tolerance limits. Repairs are often made using austenitic grades of filler metal and no postweld heat treatment. While this approach is often successful with minor repairs in low stress areas, it has led to fatigue cracking in diffusers, impellers, and other components.

A diffuser from a large barrel pump is shown in Figure 23 with a section broken out of the casting. The diffuser fractured after some twenty-five years of service. After cleaning, a large austenitic repair weld was found at the site of crack initiation. This was one of several austenitic welds, evidently made at some previous time to repair cracks. Cracking propagated, by a fatigue mechanism, along the fusion line between austenitic weld and martensitic base metal (Figure 24), eventually causing fracture. These welds produce hard brittle heat affected zones, which act as notches and can induce fatigue cracks in components that are cyclically stressed. This approach to repair should be discouraged in most instances, in favor of repair with a matching filler metal followed by postweld heat treatment. Although this may involve additional welding and remachining to accommodate dimensional changes, it is the preferred method for making a sound and durable repair.

## CONCLUSIONS

The examples presented herein were taken from a voluminous file of pump failure analyses developed over many years. They illustrate some of the more common problems that can initiate and propagate fatigue cracks. Efforts to avoid metallurgical and mechanical stress raisers, most of which occur during material

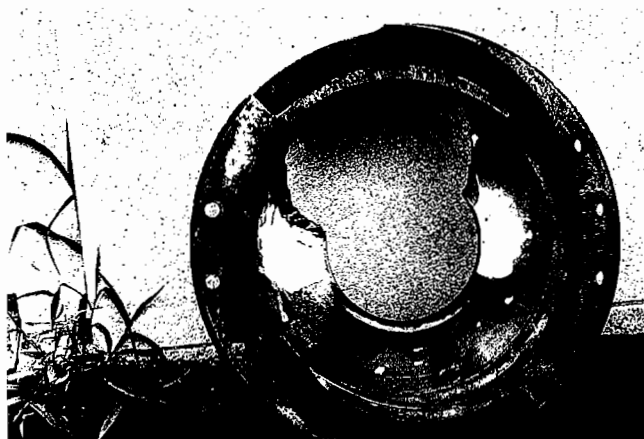


Figure 23. Diffuser, Fractured Due to Fatigue Cracking after Long Service.



Figure 24. Crack Propagation along Fusion Line in 13 Percent Chrome Diffuser Weld Repaired with Austenitic Filler Metal.

processing or fabrication, will contribute to enhanced reliability and fewer unexpected failures.

## CAVITATION DAMAGE

After fatigue failure, cavitation damage is one of the most common forms of mechanical deterioration observed in pumps. Cavitation damage usually manifests itself as a concentrated localized pitted or spongy appearance. It is sometimes mistaken for corrosion, but is strictly a mechanical phenomenon. Cavitation occurs in a pump when the local pressure of the fluid is reduced to the vapor pressure. A great many bubbles may form and collapse in a small area, producing pulses of high kinetic energy and consequent impact pressure of 13.8 to 20.7 MPa (2000 to 3000 psi). This occurs in a time frame of microseconds and generates repetitive impact loading on the metal surface, which causes local stresses and strains approaching the tensile strength of the material. The cumulative effect leads to fatigue damage on a micro scale, which eventually leaves the metal surface in a spongy porous condition.

Until the early 1980s, it was thought that cavitation resistance of metals was a function only of hardness. Investigators [4] using standard vibratory cavitation tests, had demonstrated that damage rate, expressed as mean depth of penetration, varies inversely as the square of the Brinell hardness. This relationship was established for martensitic stainless steels and has been extended to

other materials. It has been the focus of research efforts aimed at developing more cavitation resistant materials. Representative of this approach was the development of a precipitation hardening variant of Alloy CA-15, which is frequently used for boiler feed and a variety of other pump applications.

Attempts to correlate cavitation resistance with hardness were not entirely satisfactory. The slopes and position of hardness vs erosion resistance curves differ appreciably for different materials or alloy types. Cobalt base alloys, in particular, frequently show exceptional erosion resistance at moderate hardness levels. Metallurgical studies demonstrated, about 1970, that cobalt alloys undergo a stress induced phase transformation during cavitation erosion. There is a close association between the progress of cavitation erosion and the surface transformation. Metallographic studies reported by Woodward [5] in 1972 introduced the concept of stacking fault energy as a predictor of cavitation resistance. Stacking fault energy is a measure of the resistance to dislocation motion on a microscopic scale and directly related to the ability to work harden. Lower stacking fault energy alloys will require a greater number of cycles to nucleate a crack in high cycle fatigue. These findings were reinforced some ten years later when researchers at B.C. Hydro [6] showed that stress induced martensite formation controls the cavitation erosion of austenitic stainless steels, and that the rate of transformation is quantitatively linked to alloy composition.

These advances in understanding the relationship between microstructure, chemistry, and resistance to cavitation erosion, led to a major breakthrough in the development of cavitation resistant alloys. Simoneau [7], in 1986, determined that high cavitation resistance in austenitic stainlesses is associated with minimal plastic deformation needed to transform the austenite phase to martensite. Transmission electron microscope studies of the cavitation damage mechanism were used to show that low stacking fault energy is essential for high strain hardening. The key feature for high cavitation resistance of austenitic stainless steels was concluded to be the proper mixture of elements for lowering the stacking fault energy, such as cobalt, manganese, silicon, carbon, and nitrogen.

This enhanced metallurgical understanding contributed to the development of a new cavitation resistant stainless alloy having 9.0 percent of both cobalt and manganese substituted for nickel. Initially, the new alloy was used as a welding consumable to repair cavitation damage in hydraulic turbines. By the late 1980s, efforts were underway to cast the alloy, in order to make pump impellers. These efforts were successful. The first installation, in a boiler feed pump, dates from 1991. Comprehensive information concerning alloy development, foundry techniques, and the initial field application were presented in early 1993 [8]. A number of other impellers are now also in service in a variety of pump applications. Field performance appears to confirm laboratory test results, which indicate the material has cavitation resistance nearly equivalent to cobalt base alloys, and at least five times better than that of conventional stainless steels.

Despite the encouraging field performance, several shortcomings were identified. Difficulties were experienced casting the material into complex shapes, such as double suction impellers. A tendency for cracking persisted, particularly at changes in section, such as the vane to shroud transition. Acceptable surface finish, particularly in impeller vanes, was also difficult to obtain. For these reasons, materials research was pursued to obtain an improved, more easily castable alloy with the same superior cavitation resistance. A new alloy was developed, in 1993, which overcomes the shortcomings of the predecessor material. The new material is an austenitic stainless containing about 16 percent manganese, but little nickel and no cobalt. Details concerning development and application of this alloy were first presented in Europe in 1995 [9]. The cavitation resistance of this new alloy is



shown in Figure 25 as measured in the standard vibratory cavitation test, compared with conventional pump alloys.

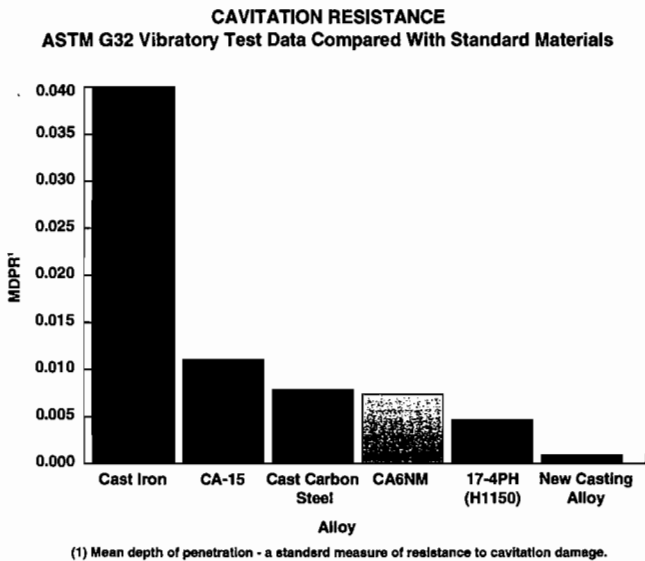


Figure 25. Cavitation Resistance of New Alloy and Standard Pump Materials.

## CONCLUSIONS

There have been major advances in materials technology over the past 10 to 25 years, owing to an enhanced metallurgical understanding of the cavitation process. The technology to produce impellers and other complex castings in advanced highly cavitation resistant alloys offers pump designers and manufacturers the opportunity to significantly extend life in a variety of demanding applications. This can be done with a relatively inexpensive stainless alloy with performance close to that of cobalt base materials.

New cavitation resistant alloys meet a long standing need in the pump industry. This development comes at a time when users are particularly sensitive to the need for efficient, reliable, and cost effective operation. By significantly extending life between shutdown and overhaul, the new materials contribute to improved reliability and reduced maintenance costs. The persistent problem of cavitation damage can now often be solved simply by upgrading to an advanced, highly resistant alloy.

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