# SELECTION OF MATERIALS AND MATERIAL RELATED PROCESSES FOR CENTRIFUGAL COMPRESSORS AND STEAM TURBINES IN THE OIL AND PETROCHEMICAL INDUSTRY

**by**

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## ABSTRACT

In today's marketplace the selection of materials for the various components for centrifugal compressors and steam turbines is very competitive and an important factor in the overall cost and delivery of the product. This paper reviews the material selection for major components for compressors and steam turbines such as shafts, impellers, blading, bolting, seals, etc. This paper is not intended to cover reciprocating, screw compressors, and high temperature hot gas expanders. Various material properties are discussed for the manufacture and service exposure of major components such as impellers, shafts, bolts, blades, and casings. Due to the various aggressive corrosive, fouling, and erosive environments in which both compressors and steam turbines are operated in, coatings must frequently be used to prolong the life of the machine. The application of various coating systems will be reviewed and how effective the coating system is with respect to withstanding the particular environment. Also discussed are the repairs for long lead time components such as rotors and the application of design proven repair procedures utilizing a design for fitness for service approach.

## INTRODUCTION

Over the past 15 years a great deal of progress has been made with respect to the application of materials and related processes applied to various components for centrifugal compressors and industrial steam turbines. This paper will review how materials are specified for the various components and which material properties/factors one must consider for the application. Both rotating and nonrotating components of centrifugal compressors and steam turbines will be reviewed for material selection.

Due to the very competitive market, material selection has moved beyond simply finding the material with the most ideal properties. Material cost and delivery can be one of the most important factors in the overall cost and delivery of the product, and therefore have become major drivers when selecting materials. Most original equipment manufacturers (OEMs) are continuously reviewing new ways whether by material changes or processes to reduce costs or delivery in order to remain competitive. This becomes even more important with the prevalence of outsourcing and inventory concepts such as "just in time." OEMs are now competing not only for sales, but also as customers in places like casting and forging shops. At the same time, the environments the components are exposed to are increasing in severity, leading to the need for more specialized materials. The use of these typically more costly materials may be avoided by selection of various coatings that are resistant to the aggressive environment under consideration. As stated previously, the paper will review materials selections for:

- Centrifugal compressors—both rotating and stationary components.
- Industrial steam turbines—rotating and stationary components.
- Application of coatings for protection against corrosion, erosion, and fouling environments.

## CENTRIFUGAL COMPRESSORS

The choice of materials for rotating and stationary components of centrifugal compressors requires selection based on a number of design and environmental factors. The design factors that require consideration are the properties of the materials together with the operating requirements of the unit. For example, operating a machine intermittently or with variations is usually considered a much more severe service relative to constant, long-duration service, and must be designed accordingly. The properties of materials that can be utilized for use in the design are as stated by Cameron and Danowski (1973) and listed in Table 1. Long time, high temperature properties such as creep or creep rupture are rarely encountered in centrifugal compressors and, therefore, are not considered in this selection process. However, in cases where the temperature of operation is determined to be significantly different from room temperature, temperature is an important factor, since the following properties are temperature dependent: strength of material, corrosion rate, coefficient of thermal expansion, and fracture toughness.

*Table 1. List of Material Properties Used in Design of Centrifugal Compressors.*

| Material Properties | |
|---|---|
| Tensile/Yield Strength, $\sigma_{UTS}$, $\sigma_{YS}$ | Specific Heat, $C_p$ |
| Modulus of Elasticity, E | Hardenability |
| Coefficient of Thermal Expansion, $\alpha$ | Weldability |
| Fracture Toughness, $K_{IC}$ | Coefficient of Friction, $\mu$ |
| Dampening | Corrosion Resistance |
| Fatigue Strength | Erosion Resistance |
| Thermal Conductivity, k | Non-metallic Material Degradation |

From an OEM perspective, receiving quality information with respect to the anticipated operating parameters is vital to producing a compressor that meets the customer's expectations. API Standard 617 (2002) provides some guidelines as to what information should be shared by both the OEM and the purchaser. For instance, paragraph 2.2.1.3 requires the purchaser to specify any corrosive agents that may be present. As an example of why this is important, there is a substantial difference between the materials that are used in an air compressor when compared to an application that may contain wet chlorine.

NACE MR0175 (2003) and MR0103 (2005) define which ferrous and nonferrous alloys can be used in wet hydrogen sulfide service to resist sulfide stress corrosion cracking. The alloys allowed by these specifications must also be heat treated in accordance with the specifications and meet a maximum hardness limit. NACE MR0175 (2003) is labeled "Metals for Sulfide Stress Corrosion Cracking and Stress Corrosion Cracking Resistance in Sour Oilfield Environments," which applies to a component or machinery used for petroleum production, drilling, flow lines, and field processing facilities exposed to wet hydrogen sulfide service. NACE MR0103 (2005) is titled "Materials Resistant to Sulfide Stress Corrosion Cracking in Petroleum Refining Environments," and is thus more specific to compressor components. Compressors with wet hydrogen sulfide present in the process gas are usually required to meet one or both of these NACE specifications to avoid stress corrosion cracking during service.

*Rotating Components*

The heart of a centrifugal compressor is the rotor, which consists of a series of impellers and a shaft. The impellers are designed to accelerate the process gas, which causes it to be compressed in the proceeding diaphragm, while the shaft provides the support and rotation to the impellers.

*Impellers*

Given the importance of the impellers, a great deal of attention is given to their manufacture. Generally, centrifugal compressor impellers are fully shrouded, consisting of a solid hub and cover separated by radial equally spaced blades. The attachment of the blades to the impeller hub and cover can be either done by welding, integral cast, brazing, riveting, electrodischarge machining, integrally machined to the hub and/or cover, or a combination of these methods. A fully shrouded impeller is shown in Figure 1. Today, for most impellers, the blades are integrally machined to the impeller hub or cover and then welded to the nonmachined blade hub or cover.

*Figure 1. Photograph of a Fully Shrouded Centrifugal Compressor Impeller.*

Throughout the compressor industry selection of impeller materials can vary depending upon service operating conditions. Since operating conditions govern the material selection requirements, a number of mechanical and chemical properties such as yield and tensile stresses, low temperature properties, corrosion resistance, hydrogen sulphide resistance, weldability, and machinability must be considered. For over 50 years, OEMs have utilized impeller materials such as AISI 4330/4340, 4130/4140, AISI 410/17-4PH and 13Cr4Ni and nickel (Ni) base alloy.

Impellers for centrifugal compressors are typically made from low alloy steels or stainless steels, and both NACE MR0175 (2003) and MR0103 (2005) have identical requirements for common impeller materials. Impellers made from AISI 4140 or 4130 steel have to meet a maximum hardness requirement of 22 HRC in the base metal, weld metal, and heat-affected zone (HAZ). In order to achieve the necessary hardness requirement, AISI 4140 impellers have to be austenitized, quenched, and tempered after welding to eliminate the HAZ. UNS G43200 and modified versions of G43200 with higher carbon contents are acceptable for compressor impellers by both NACE MR0175 (2003) and MR0103 (2005), provided that they are heat treated per the NACE standards. These UNS G43200 have a maximum yield strength requirement of 90 ksi, but there is no hardness limitation given per the NACE standards. AISI 410 stainless steel meets both applicable NACE standards if it is austenitized and double tempered with the second temper being performed at a lower temperature than the first temper. Both NACE MR0103 (2005) and MR0175 (2003) allow the use of low carbon stainless steel CA6NM (13%Cr-4%Ni) for impellers at a maximum hardness of 23 HRC after the material has been austenitized and double tempered at the temperature ranges defined in the NACE specifications. Precipitation hardenable stainless steels UNS 17400 (17-4PH) and UNS15500 (15-5PH) also meet both NACE specifications at a maximum hardness of 33 HRC after it has been through a solution annealing followed by a double aging treatment.

Since the maximum hardness requirement is 33 HRC for these steels, they are often used when impellers with higher yield strengths are necessary in hydrogen sulfide service environments.

Although other manufacturing techniques have been utilized in the past 20 years, most impellers are welded using various weld processes. Other manufacturing techniques that have been utilized are:

- Cast impellers.
- Electrodischarge machining to shape the gas passage of impellers.
- Riveted impellers.
- Brazing impellers.
- Electron beam welding.
- Combination of electron beam welding and brazing.
- One piece machine impellers.

Early on, shielded metal arc was the welding process utilized for joining the sections of impellers, whether it would be milled blades to cover/hub to the unmilled section or joining preformed blades to a machined hub and cover. This welding process is still used today. In the 1980s several manufacturers started to utilize automation with other welding processes such as gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and submerged arc welding (SAW). Generally, these processes were applied to simple two-dimensional (2D) configuration impellers with 2D curved blades. Special torches were designed for both open bladed and closed configuration welding.

Due to technological advances in five axis milling, two-piece three-dimensional (3D) geometric compressor impellers with various types of three-dimensional curved blades were being designed and manufactured. These impellers were designed to increase performance of the wheel. Since the impellers are two-piece designed, that is, either the blades are milled to the hub or cover, material selection becomes more important for consideration of manufacturability.

Brazing of impellers has been used since the 1950s but in the recent years its popularity has increased. Early brazed impellers were done in a dry hydrogen atmosphere. More recently, however, impellers are done in a vacuum furnace, which produces more acceptable results and consistency. The inspection of the braze joints has also improved over the years with the application of C-scan immersion ultrasonic testing. The author's company utilizes a special calibration block to represent the impeller braze joint. This special block was utilized for the application of C-scan ultrasonic immersion equipment. The Figure 2 shown is a printout of an acceptable C-scan ultrasonic immersion test. Brazed impellers are also fluorescent penetrant inspected to validate the soundness of the braze joint.

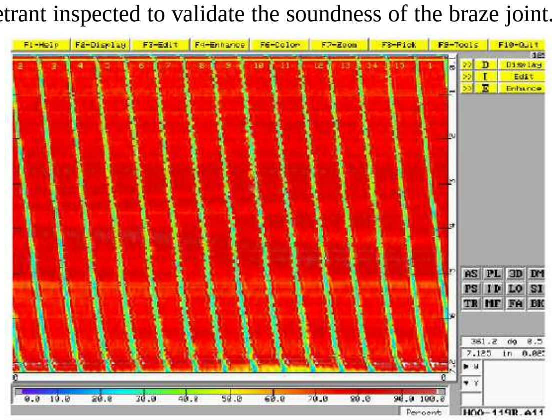

*Figure 2. Immersion C-Scan Ultrasonic Results from a Brazed Impeller Joint.*

Materials such as low alloy steels have limited hardenability. Hardenability also becomes an issue as the diameter of the impeller increases. This is illustrated in Figure 3, which shows the hardenability curve for various section diameters of AISI 4140. To understand why material mechanical properties such as AISI 4140, 4340, and 4330 diminish from the surface to the center of the material, one must review the continuous cooling transformation diagram (CCT) for that particular alloy and an elementary understanding of heat transfer. Figure 4 shows the CCT for AISI 4140 (Atkins, 1980). Depending on the rate of cooling, whether by air, oil, polymer, or water, for various thicknesses of material, certain microstructure phases such as ferrite, pearlite, bainite, and martensite are formed. Each one of these phases has an effect on the strength, ductility, and toughness of the material. Table 2 (Cameron, 1989) shows mechanical properties of impeller materials. Consequently, special consideration must be applied when selecting these low alloy steels in heavy forgings from which the blades are milled. For example, during austenitizing treatment to a fabricated impeller followed by a rapid quench, special attention must be made to changes in section thickness, such as that which occurs where the blades are welded to either the hub or cover in order to minimize the risk of quench cracking at the blade to hub/cover location. In some cases, quenching by forced air-cooling or salt bath may be required to avoid the quench cracking phenomenon. Other high alloy materials such as AISI 410, 17-4PH, and 13Cr4Ni have good hardenability with less drastic cooling rates; requiring only air or forced air cooling to achieve the desired mechanical properties. Figures 5 (Atkins, 1980) and 6 (Arlt, et al., 1988) show the CCT diagrams for AISI 410 and 13Cr4Ni, respectively.

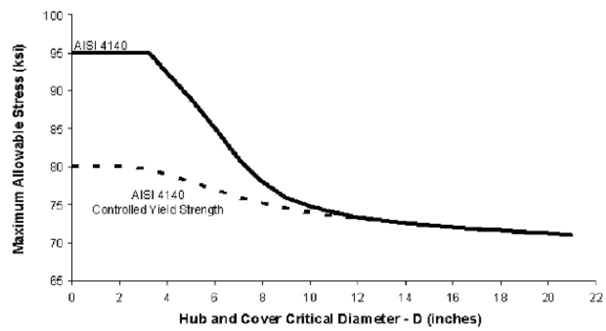


*Figure 3. Hardenability Curves for Standard and Controlled Yield Strength AISI 4140.*

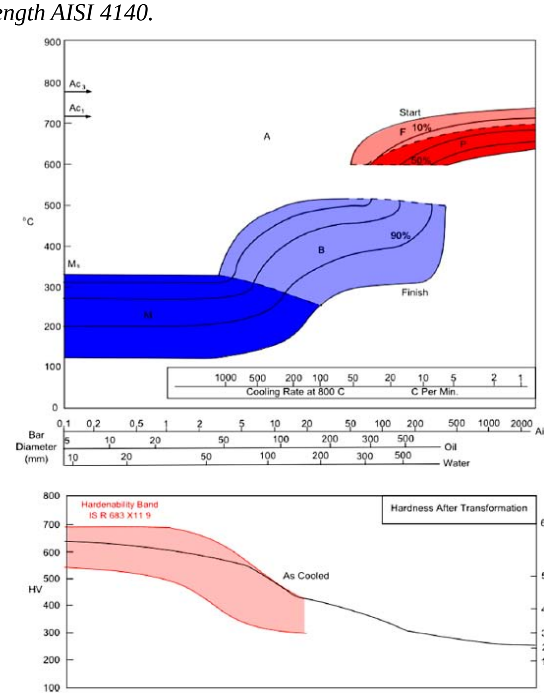


*Figure 4. CCT Curves for AISI 4140.*

*Table 2. Mechanical Properties of Impeller Materials.*

| Material | Tensile Strength (ksi) | Yield Strength (ksi) | Elongation (%) | Reduction of Area (%) | Brinell Hardness |
|---|---|---|---|---|---|
| AISI 4140 | 100-120 | 80-95 | 16 | 45 | 212-321 |
| AISI 4340 | 125-140 | 110-125 | 15 | 40 | 369-341 |
| 13Cr-4Ni (UNS S424000) | 100-136 | 80-125 | 14-17 | 40-50 | 212-341 |
| 12%Cr Steels | 95-110 | 75-90 | 14 | 40 | 212-255 |
| Ppt'n Hardening | 130-150 | 100-120 | 15 | 45 | 269-341 |
| AISI 304 | 75 | 30 | 40 | 50 | 200 |
| Monel K500 | 130 | 85 | 20 | | 255 |
| Ti (unalloyed) | 65 | 40 | 17 | 30 | 200 |
| Ti 6Al 4V | 130 | 110 | 10 | 20 | HRC 36-39 |
| Al C355 | 45 | 33 | 3 | | 100 |
| Al 2025T6 | 52 | 33 | 12 | | 125 |
| Al 7050T73 | 74 | 65 | 5 | | 142 |

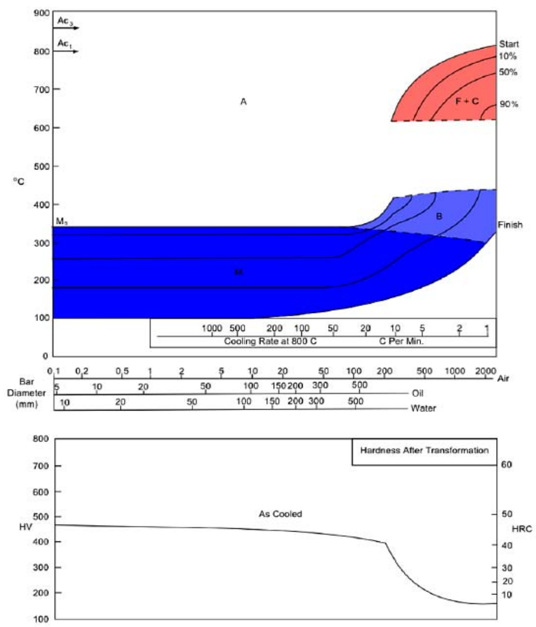


*Figure 5. CCT Diagram for AISI 410.*

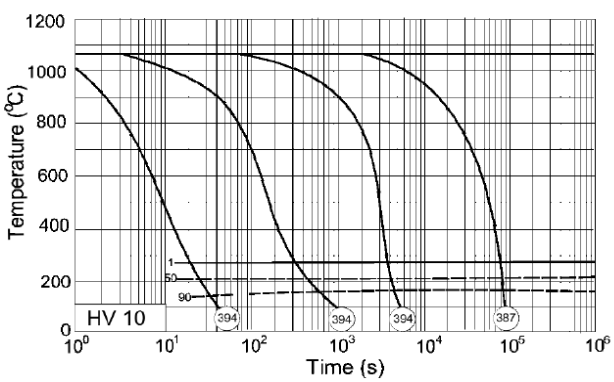


*Figure 6. CCT Diagram for 13Cr4Ni.*

The material 13Cr4Ni (UNS S42400) has been utilized for manufacturing impellers to meet a wide range of requirements such as high strength, controlled hardness $H_2S$, low temperature, and good corrosion resistance. For low temperature applications using 13Cr4Ni, controlling the volume fraction of austenite in the structure increases the material toughness. This increase in toughness also can lead to a reduction in hardness. Dowson (2002) also substantiated the application of a two-stage tempering treatment to obtain the maximum requirement of HRC 23 maximum. For welding, matching welding consumables are always applied to higher alloy steels. The author's company has formulated a patented chemistry for the welding consumables of 13Cr4Ni to be applied for impellers. This patent chemistry enabled HRC 23 maximum hardness to be achieved consistently for $H_2S$ controlled hardness environments. Procedures were developed using 13Cr4Ni for the various operating conditions utilizing the various welding processes and brazing application. These procedures were developed for welding and brazing applications requiring high strength, qualification to meet NACE MR0175-200 (2003) (metallic sulfide stress cracking resistant materials), and low temperature (down to −166°F (−110°C) applications. The Figures 7 and 8 show the properties that can be achieved using the 13Cr4Ni material (Dowson, 2002).

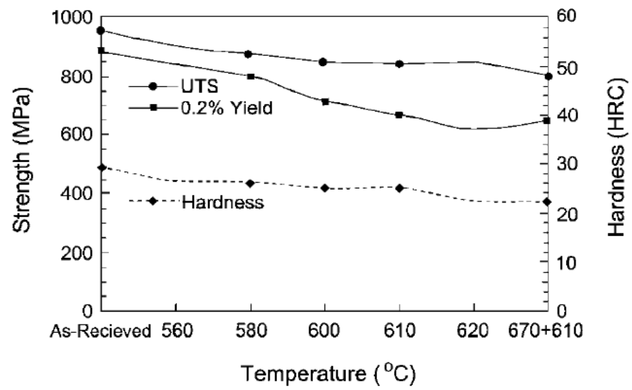


*Figure 7. Plot of Strength and Hardness Versus Tempering Temperature (4 Hour Hold) for 13Cr4Ni.*

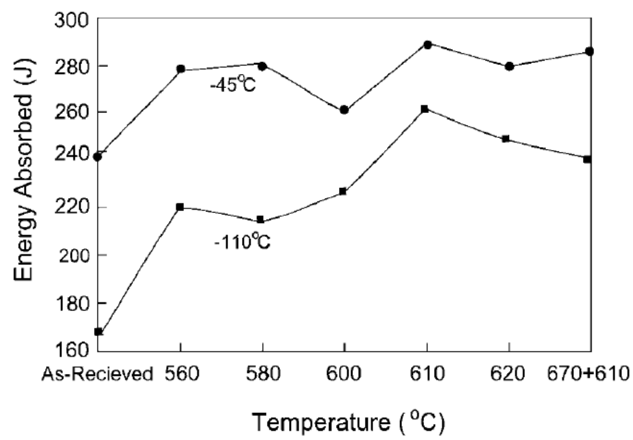


*Figure 8. Plot of Charpy Impact Energy Versus Tempering Temperature (4 Hour Hold) for 13Cr4Ni.*

The precipitation grades such as Armco 17-4PH, Armco 15-5PH, and Carpenter Custom 450 obtain their mechanical properties by solution treatment and precipitation treatments. By varying the precipitation treatments, one can obtain a range of tensile strengths. In comparing the Armco 17-4PH with Armco 15-5, whose chemistries overlap, 17-4PH is more prone to form delta ferrite than 15-5PH, which may result in a loss of ductility/toughness. The precipitation treatments for these grades are usually in the range of 1050°F to 1175°F. For application in hydrogen and hydrogen sulfide environments, 17-4 or 15-5PH material is given a double precipitation treatment at approximately 1150°F to obtain the necessary maximum hardness of HRC 33 maximum for $H_2S$ environments and 120 ksi maximum yield strength for hydrogen environments.

*Special Impeller Materials*

There are other special materials that are utilized in certain specialized applications. In moist halogen machines, such as a chlorine machine, Monel® K500 has been successfully used for impellers. Monel® K500 was also used in oxygen machines, because of its resistance to sparking. Special welding procedures were developed to obtain good quality fabricated Monel® K500 impellers. Titanium and titanium alloys have been used for wet chlorine and in special cases where low density makes the material attractive. Precipitation hardenable nickel base alloys such as UNS

N0 7716 and UNS NO 7725 have been applied to aggressive coal gasification applications with a great deal of success. For temperatures down to −320°F, the 9%Ni steel has widely been accepted for impellers in compressors for boil off gas from liquid methane due to its high fracture toughness at these low temperatures. Special processing of these grades is required to obtain the required mechanical properties. For some applications, aluminum alloys have also been used successfully especially in connection with liquefied natural gas projects.

*Rotor Shafts*

Generally, shafts are manufactured from either rolled bars or forgings. In the size range where both are acceptable by API 617 (2002) (currently ≤ 8 inches finished machined), the choice between rolled bar or a forging should be dependent on cost and availability, as there is little difference in the end result, if manufactured to relevant American Society for Testing and Materials (ASTM) procedures. Tolerances on rolled bar can be more tightly controlled, which results in less machining required than for forgings and have a slight advantage in terms of thermal stability. Conversely, depending on availability of the particular material and size, selecting rolled bar may require the purchase of an entire length of bar or an entire heat, while forged shafts are "made to order." Shafts with a finished diameter greater than 8 inches are generally made from forgings.

For shaft materials the standard AISI 4330 and 4340 can be heat treated to give the required mechanical strength and toughness values. Due to these materials having higher strength values, the lateral expansion parameter is utilized for ASME Boiler and Pressure Vessel Code Section VIII Division I (2007). The requirement is 15 mils, which was proposed by Gross and Stout (1957). These materials have been used successfully down to −150°F with the tensile strength at 110 ksi minimum and yield strength of 90 ksi minimum. For temperatures lower than −150°F, ASTM A470 Class 7 has been used with a great deal of success.

Shafts that are used in $H_2S$ environment cannot be limited to the NACE requirements due to the need for the higher strength required at the drive end of the shaft. Consequently, the applied stress in the main body of the shaft, which comes in contact with the gas, is low (<10 ksi). This value is below the threshold stress value for sulfide cracking as a function of hardness (Figure 9) (Warren and Beckman 1957).

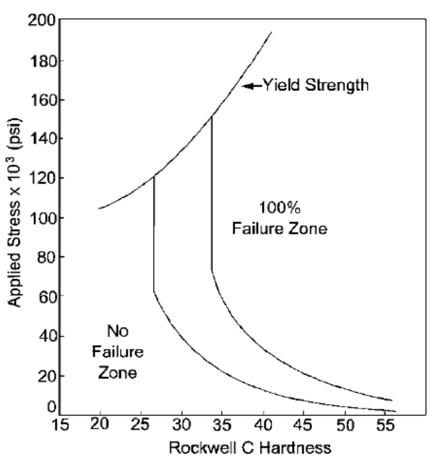


*Figure 9. Threshold Stress for Sulfide Cracking as a Function of Hardness.*

The selection of shaft materials is also important to prevent certain types of failures, in particular, wire wooling. Wire wooling is an infrequent, but devastating, failure mechanism that occurs during startup (not necessarily the initial startup) in the bearing and seal area shafts. Areas where oil films are thin and loads are high, such as at the thrust bearing, are most susceptible to this type of failure. The process of wire wooling begins when a small particle of foreign material enters the bearing or seal. Through a series of localized temperature increases, due to high coefficient of friction between particle and rotor, material transfers from the rotor to the particle, and by hardening mechanisms, the particle becomes a hard, black scab that is able to cut and spin material from the shaft. Shaft material also continues to transfer to the scab as the cutting is occurring, allowing the scab to grow and propagate the failure. The result is a deeply grooved shaft. The material cut from the shaft often has the appearance of wire wool. Figure 10 shows damage to the journal and thrust collar due to wire wooling and the corresponding black scab on the journal bearing. For a more detailed description of the mechanism, the reader is directed to Fidler (1971).

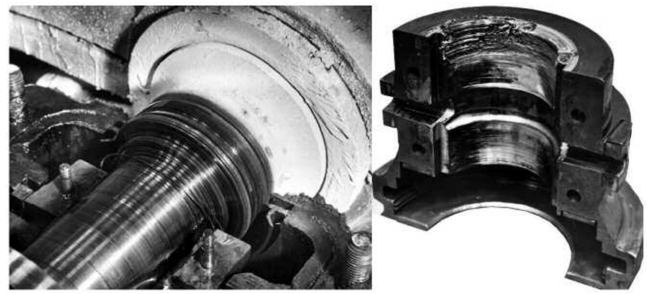

*Figure 10. Photographs Showing Wire Wooling Failure of a Journal and Thrust Collar and the Corresponding Black Scab on the Journal Bearing.*

For reasons that are not clearly understood, shaft materials with higher Cr contents are more susceptible to wire wooling. The critical Cr content proposed by Fidler (1971) is 1.8 percent. Because of this, shafts should be made of 4140 or 4340 wherever possible. If a higher Cr content material must be used, steps must be taken to reduce the risk of wire wooling. Altering the surface of the shaft or increasing clearances are ways that can be used to reduce the risk. One way to alter the surface of the shaft is to harden it by nitriding or hardfacing with hard chrome or carbide coatings. Sleeving with a wire wooling resistant material, such as 4140, can also work. Increasing the clearances reduces risk by increasing the size of particle able to initiate the failure. All of these have their pros and cons, which must be evaluated when deciding which method yields the best overall results.

*Stationary Parts*

The bulk of the centrifugal compressor consists of stationary parts. The most obvious is the casing, which is the pressure containing shell that surrounds the rotor. Diaphragms are responsible for slowing down the gas after it is accelerated by the impellers, causing it to be compressed. Bolts are used to fasten the parts together. Split line seals fit between the casing pieces to maintain the overall pressure. Abradable and rub tolerant seals maintain the pressure between each individual stage. Piping is used for gas path connections.

*Casings*

Nearly all multistage centrifugal compressor casings are made from carbon or a low alloy material that is either cast or fabricated from castings, forgings, plate, or a combination of these. Occasionally higher alloy steels are required for aggressive corrosion conditions or to achieve the desired toughness for extreme low temperature (−320°F) operating conditions, such as those for boil off gas compressors in liquified natural gas service. For low temperature application down to −175°F, low alloy steels such as shown in Table 3 are applied in propane and ethylene compressors. The table must be used with some caution and understanding of the effect chemical makeup will have on the ability to achieve the desired toughness.

*Table 3. Minimum Temperature for Low Temperature Application of Low Alloy Steels.*

| ASTM | Trade name | Min. Temperature (°F) |
|---|---|---|
| *Wrought* | Carbon Steel | -50 |
| A516 Gr.60 | Carbon-Manganese | -75 |
| A537 C1.1 | 2.25% Nickel | -100 |
| A203 Gr.A | 3.50% Nickel | -150 |
| A203 Gr.E | 3.50% Nickel | -160 |
| A353/A553 | 9% Nickel | -320 |
| *Cast* | | |
| A216 Gr.WRB | Carbon Steel | -20 |
| A352 Gr.LCB | Carbon Steel | -50 |
| A352 Gr.LC2 | 2.25% Nickel | -100 |
| A352 Gr.LC3 | 3.50% Nickel | -150 |
| A352 Gr.LC4 | 4.50% Nickel | -175 |
| A571 | Aust. Nickel Duct. Iron | -320 |

Compressor casings are typically manufactured from carbon steel castings or carbon steel plate that is formed and welded. NACE MR0103 (2005) limits the hardness of carbon steel castings and plate to 200 HBW maximum and NACE MR0175 (2003) limits the hardness to 22 HRC (237 HBW). Under both specifications, carbon steel castings are acceptable in the normalized and normalized and tempered conditions, and carbon steel plate is acceptable in the hot-rolled condition as long as the material meets the maximum hardness requirement. The hardness of the carbon steel is largely controlled by the carbon content, so keeping the carbon content low is essential to meeting the maximum hardness requirement. Welding of the carbon steel plates under NACE MR0103 (2005) is controlled by NACE MR0472 (2005) which also limits the maximum hardness in the base metal and the weld metal to 200 HBW while limiting the hardness of the HAZ to 248 HV 10. The maximum hardness of 22 HRC is required in the base metal, weld metal, and HAZ under MR0175 (2003). The chemical composition of the filler metal used during welding must be similar or identical to the base metal composition. The hardness may be verified by the welding procedure qualification when all of the welding parameters and filler metal composition defined by the procedure qualification are controlled and followed. A post weld heat treatment (PWHT) may be performed to ensure that the hardness values meet the required specifications. NACE MR0103 (2005) has a lower maximum hardness limit than MR0175 (2003) to compensate for nonhomogeneity of some weld deposits and normal variations in production hardness testing using a portable Brinell tester.

During the last 15 years, compressor casings have become larger with increases in pressure rating. This has also been applied to applications where the compressor casings are subjected to low temperatures. Design engineers now require thicker sections due to the higher pressure ratings to prevent gas leakage at the various joints connections. For the thicker sections, special controlled chemistry and heat treatments are required to achieve the desired toughness for low temperature application. For low alloy nickel steels, the elements C, S, and P are controlled to ensure good toughness is attained. Table 4 shows results of chemistries and their corresponding toughness results. These chemistries not only apply for steel plate but also for forgings and castings. Since the application of argon oxygen decarburization (AOD) and calcium-argon injection, cleaner steels, with sulfur as low as 0.005 percent, are attainable. Because of the addition of calcium compounds, the inclusions that remain resist elongation during rolling; remaining spherical. Consequently, inclusion shape control steel plates show improved ultrasonic quality, macrocleanliness, and mechanical properties as can be observed in Figures 11, 12, and 13 (Lukens Fineline Steels).

*Table 4. Results of Chemistries and Their Corresponding Toughness Results.*

| Chemistry (wt%) | Plate | Casting |
|---|---|---|
| C | 0.08 | 0.081 |
| Mn | 0.74 | 0.69 |
| P | 0.003 | 0.009 |
| S | 0.002 | 0.009 |
| Cu | 0.05 | 0.1 |
| Si | 0.34 | 0.47 |
| Ni | 3.57 | 3.56 |
| Cr | 0.03 | 0.18 |
| Mo | 0.01 | 0.07 |
| V | 0.001 | 0.004 |
| Nb | 0.003 | --- |

| Impact Toughness (CVN) | Temp. (°F) | Avg. (ft-lbs) |
|---|---|---|
| Plate | -152 | 98 |
| Casting | -150 | 63 |

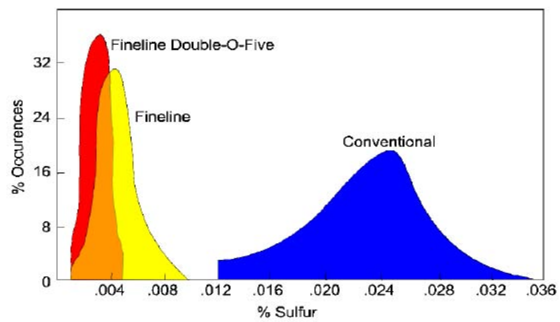


*Figure 11. Comparison of Sulfur Contents of 50 Heats of Conventionally Processed Steel and 50 Heats of Lukens Fineline Double-O Five.*

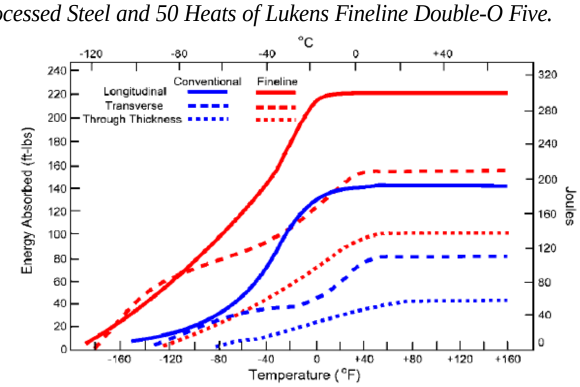


*Figure 12. Comparison of Charpy Impact Energy for Conventional and Fineline ASTM A633C Plate, 4 Inches Thick, Normalized.*

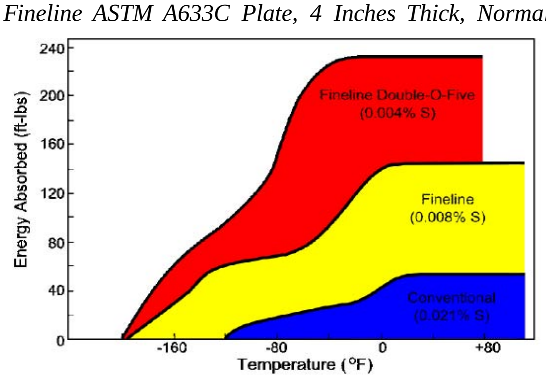


*Figure 13. Comparison of Charpy Impact Energy for ASTM A633C Plates, 1 to 2 Inches Thick, Normalized, Transverse Orientation.*

The introduction of inclusion shape control steel plates has also minimized the susceptibility of lamellar tearing during the fabrication of casings. Generally, this phenomenon can occur in thicknesses greater than 3 to 4 inches. By achieving lower carbon, sulfur, phosphorus, and inclusion shape control structures, excellent toughness properties can be achieved. However, for the larger thicknesses, accelerated quenching during heat treatment using water as the media from the austenitizing temperature is required. To maximize the quench affect of the water, the following is required: control of water temperature 80°F maximum, good agitation of the water, adequate amount of water for the weight of component (2 gallons per pound of metal) and time from furnace to water less than one minute. In some cases movement of the component in the water sideways or up and down is required (Figures 14, 15, 16, and 17) (Metals Handbook, 1981).

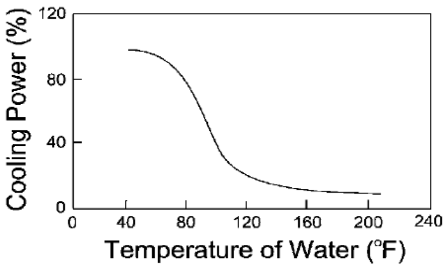


*Figure 14. Surface Cooling Power of Moderately Agitated Water Versus Water Temperature.*

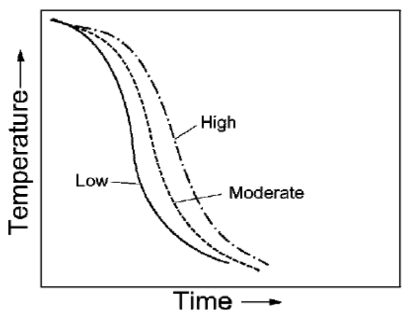


*Figure 15. Effect of Concentration on Cooling Rate.*

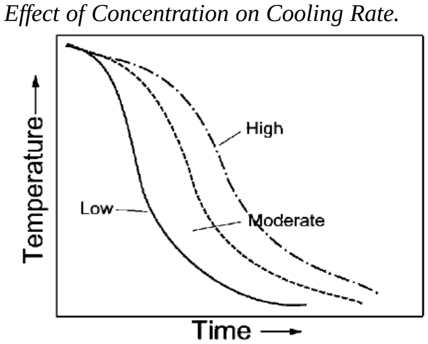


*Figure 16. Effect of Temperature on Cooling Rate.*

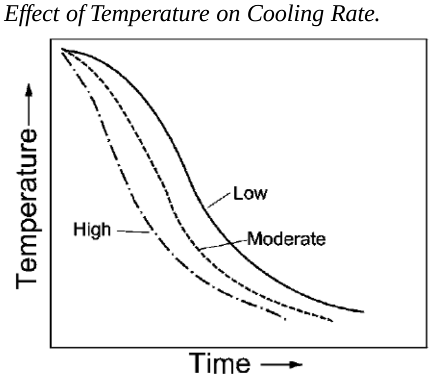


*Figure 17. Effect of Agitation on Cooling Rate.*

In Cameron's (1989) paper, the changes in the 1987 *ASME Boiler and Pressure Vessel Code Section 8 Division I* as required by API 617 (2002) specified the required Charpy V-notch energy absorption values had been made a function of the plate thickness. Refer to *ASME Boiler & Pressure Vessel Code - Section VIII* (2007) to show the values required. Since most of the compressor casings are fabricated, the welding consumables have to satisfy the impact test requirement of the base material. Actual test results of the weldments and surrounding heat-affected zone depend strongly on the preheat, interpass temperature, thickness of individual weld bead, heat input rate, and post weld heat treatment. Manufacturers have developed specific welding consumables, processes, and procedures to obtain the required mechanical properties for the casings. Since the soaking time of post weld heat treatments can affect the toughness of the materials as well as the weldments, simulated PWHT is performed on the materials that are used for low temperature application. Figure 18 shows effect of PWHT time on toughness (Charpy V-notch impact value).

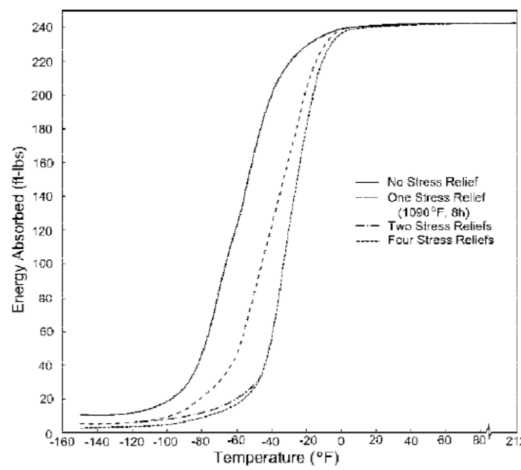


*Figure 18. Impact Energy Versus Temperature for SA516 Grade 60 after Various PWHT.*

*Diaphragms*

In the past, diaphragms were generally constructed from grey cast-iron materials. When higher strength is required, ductile irons or fabricated mild steel is applied. In all cases, the casting or fabrications are heat treated to produce low levels of internal stress and difficulty with instability in service is virtually unknown. In the last 10 years, the choice of diaphragm material has been mild steel with the blades either milled integral or welded and the two-piece construction bolted together. One of the main reasons for the change is that the mild steel materials can be repaired by welding more readily as compared to grey cast-iron. The use of ductile iron that has improved weldability over grey cast-iron can also be selected as a material choice for diaphragms.

*Sulphide Stress Cracking*

There is extensive literature on sulfide cracking in oil well casing materials going back to about 1950. Incidents involving centrifugal compressors, however, have been rare as reported by Kohut and McGuire (1968) and Moller (1968). However, a failure due to sulphide stress cracking (SSC) can be serious; leading to loss of service of a vital link in the production chain of a chemical or petrochemical plant. For SSC to occur, the following conditions must be fulfilled:

- Hydrogen sulfide must be present.
- Water must be present in the liquid state.
- The pH must be acidic.
- A tensile stress must be present.
- Material must be in a susceptible metallurgical condition.

When all the above conditions are present, sulfide cracking can occur with the passage of time.

As stated previously, all manufacturers follow the requirements specified by NACE. In reviewing the work done Treseder and Swanson (1968) showed the effect of pH on sulphide stress cracking, Figure 19 where $S_c$ is an experimental stress value. This $S_c$ value increased substantially as the pH increased from 2 to 5. Other work done by Keller and Cameron (1974) has shown the importance of pH. In their work, quenched and tempered welded AISI 4140 material stressed to 80 percent of yield strength failed at pH 2.5, while at pH 4.2 no specimens failed. The yield strength of the base material was reported to be 126 ksi. From the same paper the material AISI 4140 quenched and tempered with a yield strength of 83 ksi was welded and given a temper treatment of 1100°F. In this case, at pH 2.5 all specimens failed. At pH 4.2, a large percentage of specimens failed, while at 6.5 pH there were no failures in those tests. It is important to note that these are controlled laboratory experiments. In practice, it is difficult to specify a threshold concentration of $H_2S$ in a gas below which sulfide cracking will not occur, because other components of the gas can cause the pH to vary. Chlorides, for example, can lower the pH well below 4.3, while other components may cause an increase.

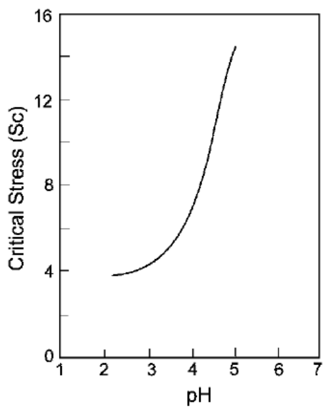


*Figure 19. Critical Stress for Sulfide Cracking as a Function of pH.*

*Bolting*

Bolting for use in hydrogen sulfide service environments is also defined by NACE MR0175 (2003) and MR0103 (2005). Both specifications allow the use of AISI 4140 steel and AISI 410 stainless steel at a maximum hardness of 22 HRC provided the material is quenched and tempered. Both AISI 4140 and AISI 410 bolting is commonly available from bolting suppliers; however, an extra tempering treatment is required to meet 22 HRC maximum hardness requirement and conform to ASTM A193 Grade B7M for the AISI 4140 steel or ASTM A193 Grade B6M for AISI 410 stainless steel. For higher strength bolting materials, UNS 17400 and UNS 15500 stainless steel may be used. NACE MR0175 (2003) allows these alloys to be used at a hardness of 33 HRC while NACE MR0103 (2005) limits the hardness to 29 HRC maximum for pressure-retaining bolting.

*Piping*

The piping of a compressor unit is typically manufactured from carbon steel piping. NACE MR0103 (2005) limits the hardness of carbon steel piping to 200 HBW while NACE MR0175 (2003) allows carbon steel piping up to 22 HRC (237 HBW). The carbon content of the carbon steel pipe has a large influence on the hardness, so the carbon content must be limited to comply with the maximum hardness limit. Under both NACE specifications, the piping must also be thermally stress relieved following any cold deforming by rolling, cold forging, or any other manufacturing process that results in a permanent outer fiber deformation greater than 5 percent. For carbon steel piping welds, NACE MR0103 (2005) defers to NACE RP0472 (2005) which allows a maximum hardness of 248 HV10 in the HAZ and a maximum hardness of 200 HBW in the base metal and weld metal. NACE MR0175 (2003) requires a maximum hardness of 22 HRC at all carbon steel piping weld locations. When matching filler metals are used, a post weld heat treatment is not required if all hardness values meet the maximum hardness requirement. The hardness values may be verified by the welding procedure qualification if all welding parameters and the filler metal composition are defined by the qualification and are followed during production per NACE MR0175 (2003). Under NACE MR0103 (2005), which defers to NACE RP0472 (2005), 5 percent of all production piping butt welds must be hardness tested.

*Splitline Seals/O-Rings*

Turbomachinery casings usually consist of two or more pieces, which are bolted together. With respect to centrifugal compressors, the seam created is sealed using elastomeric materials in the form of O-rings. The choice of material used for this seal is vital to the operation of the compressor, as it is typically the weakest link in the casing in terms of chemical resistance, temperature resistance, mechanical properties, longevity, etc. Due to the wide range of operating parameters encountered in a centrifugal compressor and wide range of reactions to those parameters by the various elastomers, there is not a single, one stop choice. Table 5 is a compatibility chart for some common gases and O-ring materials. In fact, choosing the proper material frequently consists of an evaluation and acceptance of several compromises, particularly in cases with complex process gases. As a simplified example, fluoroelastomers will work well in hydrogen and nitrogen separately up to 300°F. If they are mixed at 250°F, such that a small amount of ammonia can form, the situation is no longer clear cut. The fluoroelastomer is not compatible with ammonia, nitrile has a maximum temperature of 212°F, and silicone is not compatible with hydrogen. Clearly a compromise must be made to accept what shortcoming will occur when the chosen material is exposed to the offending environmental parameter.

*Table 5. Compatibility of Split Line Seal Materials in Various Environments.*

| Max temp °F / Process Gas / Seal Material | 175 Chloroprene | 212 Nitrile | 200 Fluoro elastomer | 300 Fluoro elastomer | 350 Fluoro elastomer | 400 Fluoro elastomer | 450 Silicone | 500 Hi-Temp Silicone | 550 Perfluoro elastomer |
|---|---|---|---|---|---|---|---|---|---|
| Hydrogen & Methane | | X | | X | | X | | | |
| Chlorine (dry), Ethylene, & Propylene | | | X | X | | X | | | |
| Air & Nitrogen | | X | | X | | X | X | X | X |
| Isobutane, Butane, & Propane | | X | | | | X | | | |
| Water, Fluegas, Ethylene, Feed gas, Recycle | | X | | | | X | X | X | X |
| Refinery Feedgas, Benzene, Toluene, Xylene, Coke oven gas, Syn gas | | | | | | X | | | |
| Petroleum Base Lubricants | | X | | | X | | | | |
| Wet Refinery Feedgas | | | | | | X | X | X | X |
| Ammonia (gas) | X | X | | | | | X | X | X |
| Oxygen | | | | X | | | X | | |

*Abradable and Rub Tolerant Seal Materials*

Selection of abradable material for application in centrifugal compressors is very important. There are a number of property factors that need to be considered when selecting the abradable material:

- Abradability and erosion resistance
- Compatibility of the abradable material with the gas
- Temperature limits of the abradable material
- Coefficient of thermal expansion of the material

*Abradability and erosion resistance*—In the paper presented by Dowson, et al., (1991), abradable material mica-filled trifluoroethanol (TFE), nickel graphite, and silicon rubber were found to have good to very good abradability. The abradable silicon aluminum polyester, although not as good as those abradables stated previously, did perform well at lower rates of interaction and higher rubbing velocities. The author's company has applied the silicon aluminum polyester abradable material in various centrifugal compressor applications with great success. Also since the 1991 paper, nickel graphite abradable seals have been used extensively in various applications for centrifugal compressors. However, to achieve optimum abradability and erosion resistance, special control of the hardness needs to be achieved. In the early years of manufacture of these seals, it was found that high heat input spray processes such as plasma could reduce the percent graphite in the coating and thereby reduce the abradability. During testing of an abradable nickel graphite seal the labyrinth rotating teeth were found to gall with the seal causing excessive damage to the impeller seal eye location (Figure 20).

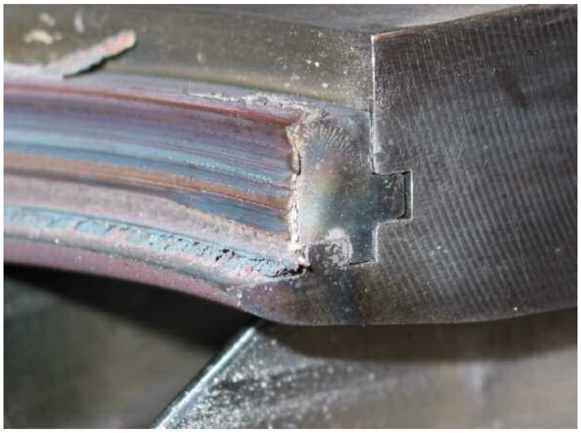

*Figure 20. Damage to Nickel Graphite Impeller Seal.*

*Compatibility of the abradable material with the gas*—The mica-filled TFE is generally impervious to corrosive attack from most gaseous mixtures and would be acceptable with all hydrocarbon gases, sour natural gas, and chlorine gaseous conditions. However, for wet gaseous conditions (water > 2 percent) certain design considerations must be addressed to account for water absorption leading to possible swelling of the seal during service. The aluminum silicone abradables would operate under the same gaseous conditions that are generally applied to conventional aluminum seals. Exposed to extreme sour natural gases and chlorine gaseous conditions, these materials would be attacked severely. The nickel graphite coating could be used for all hydrocarbon gases and most sour natural gases. However, for hydrocarbon gases that contain large quantities of carbon monoxide (CO), a reaction can occur between the base coat of nickel and CO leading to delamination of the nickel graphite abradable seal as shown in Figure 21.

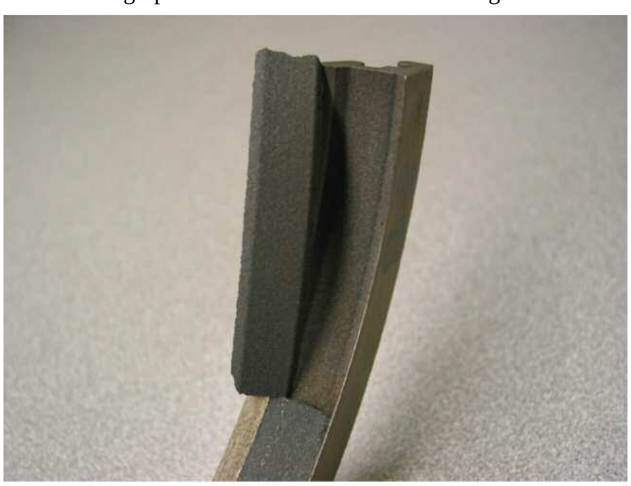

*Figure 21. Delamination of Nickel Graphite Seal Due to Reaction of CO with Ni.*

*Temperature limits of the abradable material*—The temperature limits for the various abradables are shown in Table 6.

*Table 6. Temperature Limits.*

| **Temperature Limits for Various Materials Temperature °F** | | |
|---|---|---|
| Abradable Material | Minimum | Maximum |
| Mica-filled Tetrafluoroethylene | -150 | 350 |
| Nickel Graphite Blended Powder | -320 | 900 |
| Aluminum Powder Alloy Containing Silicon and Polyester Resin | -320 | 650 |
| Silicon Elastomer Containing Hollow Glass Microspheres | -100 | 500 |
| Nickel Chromium Powder with Lucite Polymer | -320 | 1200 |

*Coefficient of thermal expansion of the material*—When designing seals, the coefficient of thermal expansion of the material must be taken into account at the design. The mica-filled TFE material has a coefficient well above that of steel and, therefore, dimensional changes due to temperature must be calculated in the overall design of the compressor. However, since the sprayed abradables are only 0.1 inch thick bonded to a metallic substrate, the coefficient of the substrate would apply for design purposes. For silicon rubber abradable material, the material is flexible/soft and will deform elastically to accommodate any thermal strains caused by the substrate.

*Rub Tolerant Polymer Seals*

Rub tolerant labyrinth polymer seals are seals with reduced clearances and, if contact is made between the stationary seal and smooth rotating member, the stationary teeth will deflect during contact without wear or damage to the rotor or seals.

The rub tolerant plastic seals that are used in centrifugal compressors today are the new thermoplastics, which have better resistance to elevated temperatures. The thermoplastics matrix materials are tougher and offer the potential of improved hot/wet resistance.

Because of their high strains to failure, they are the only matrixes that offer the new intermediate modulus, high strength (and strain) carbon fiber to use their full strain potential in the composite. These materials include such resins as polyetheretherketone (PEEK), which is intended to maintain thermoplastic character in the final composite. Others, such as polyamideimide (PAI), which is originally molded as a thermoplastic and is then postcured in the final composite to produce partial thermosetting characteristics. The partial thermosetting characteristic of the PAI enables an improved subsequent temperature resistance (*Engineered Materials Handbook: Composites,* 1987).

When considering thermoplastic materials in rotating equipment, one has to understand their thermal properties (Table 7). The two thermoplastic materials used exclusively as labyrinth seals in centrifugal compressors are PEEK with additives and PAI. For the PEEK materials as labyrinth seals the temperature limit is dependant on the glass transition temperatures $T_g$ of the material. Addition of additives such as chopped or continuous wound carbon fibers or graphite powder or PTFE will not increase the $T_g$ of the material. The $T_g$ is the temperature at which the crystalline polymer changes to a viscous or rubbery condition. In other words, the material has a dramatic change in properties. Generally, for labyrinth seals from PEEK material, the operation temperature is limited to 290°F.

*Table 7. Properties of Thermoplastics.*

| Properties of Thermoplastics | | | | |
|---|---|---|---|---|
| **Material** | **Tg °F** | **T in °F** | **Tensile Strength ksi** | **Fracture Toughness $G_{IC}$ ft-lbf/ft$^2$** |
| PAI | 530 (275°C) | | 28 | 70 |
| PEEK | 290 (143°C) | 650 (343°C) | -- | 110 |

For PAI materials, since the material is partial crystalline in character with some amorphous features, the $T_g$ of the material is higher. However, when the crystalline character of the polymer is decreased, its resistance to solvents and water decreases also. The higher the degree of crystallinity, the higher the modulus and the higher the resistance to solvents and water. In the case of PAI careful consideration must be given to attack from amines, ammonia, oxidizing acids, and stray bases. Due to its partial crystallinity in character, PAI is prone to moisture absorption. Due to the moisture absorption, dimensional changes can occur that need to be addressed at the design stage and in manufacturing/storage. Generally, thermoplastic resin suppliers provide some information on water absorption after a 24 hour immersion in water. A more severe test is the 24 hour boiling water test.

Due to the high thermal expansion coefficient of both the PEEK and PAI materials, accurate calculations of the growth of the seals with respect to the diaphragms and rotating components need to be done to enable one to calculate the clearances.

Also, in the manufacture processing of PAI or PEEK into a tubular form, there exists a size limitation for polymer labyrinth seals.

- PAI—In tubular bulk form the size limitation is 35 inches. However, larger sizes can be constructed up to 45 inches by segmenting the seals.

- PEEK with chopped carbon fibers—Generally supplied in molded bulk form with a size limitation of 30 inches.

- PEEK with 68 percent continuous wound carbon fiber—Generally supplied in a tubular form and there is no size limitation.

Abradable seals have been used successfully in centrifugal compressors for reducing clearances and improving the efficiency of compressors. The author's company has applied abradable material such as Ni graphite, aluminum silicon polyesters, and fluorosint to numerous labyrinth seal applications with great success.

Careful consideration must be applied to ensure that rub tolerant polymer seals can be utilized in centrifugal compressor labyrinths. The tests that were done at the author's company indicated that the PAI material for labyrinth seals may not be suitable for temperatures greater than 100°F using similar clearances to that of abradables. The PAI material at a temperature of 150°F was found to wear dramatically when it came into contact with the rotating member. Other polymer materials, such as PEEK or carbon wound PEEK, may be more suitable (Dowson, et al., 2004).

## STEAM TURBINES

Steam turbines present some different problems relative to centrifugal compressors. Temperatures are usually higher, which affects the various temperature dependent processes like corrosion rate and degradation mechanisms, such as creep, must now be considered. The key components of a steam turbine are the rotor, blades (buckets), casing, and bolting.

With the exception of 12%Cr blading alloys, low alloy materials have been conventionally used for the major components of steam turbines for many years. For example, 1CrMoV has been used for high temperature rotor forgings and 3½NiCrMoV for low temperature forgings. High temperature pipe work and castings for valve chests and turbine casings utilize 2¼CrMo or CrMoV. These materials were available in the 1950s and 1960s and over the past 30 to 40 years materials development concentrated on optimizing the properties of these materials for their application to larger components, which in turn, increases the reliability of components and their fabrications.

### *Rotors*

Mechanical drive steam turbine rotors are manufactured from low alloy steel forgings. Rotors consist of a shaft and a series of disks, which may be monoblock, in which the disks are integral parts of the shaft (A type), disks shrunk fit onto the shaft (B type), or sections of the rotor may be welded together (C type). Mechanical drive turbines are in general "A" or "B" type rotors, with the majority being "A" type.

For the higher temperature application up to 1025°F, the 1Cr1Mo¼V steels are currently in wide use but are limited to 1025°F. For higher temperatures, the 12%Cr steel forgings have good experience at 1050°F, where they have an excellent combination of creep strength, ductility, and toughness. However, there is a drive to use the most creep resistant version of 12%Cr up to temperatures of 1100°F. In order to provide an additional margin of safety, the allowable creep strength at 1100°F needs to be equivalent to that currently used with 12%Cr steel at 1050°F (Gold and Jaffee, 1984; Armor, et al., 1984). For developing improved alloys, a tentative goal for rupture strength has been established at 14.5 ksi for a rupture life of 100,000 hours at 1100°F. Figure 22 shows a comparison of 100,000 hour rupture strengths for various low alloy steels, 12%Cr and other development rotor steels. The Figure 23 shows the Larson-Miller rupture curves for commercial and developmental 12 percent rotor steel (Newhouse, 1987). Other critical material properties for rotor integrity are toughness, resistance to crack, initiation under creep, thermal fatigue and resistance to subcritical crack propagation in creep and fatigue. Toughness is discussed in more detail below.

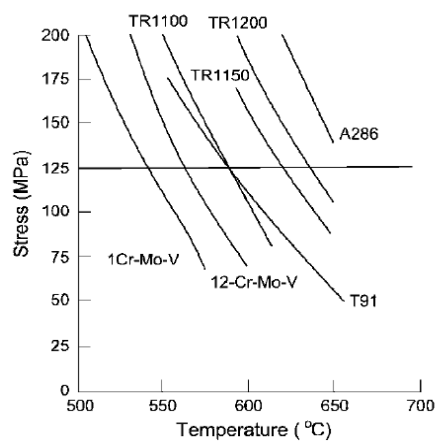


*Figure 22. Plot Showing 100,000 Hour Rupture Strength of Various Rotor Steels.*

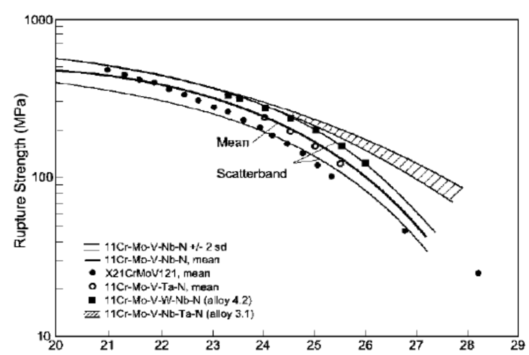


*Figure 23. Larson-Miller Rupture Curves for Commercial and Developmental 12 Percent Rotor Steel.*

*Toughness*

In CrMoV rotors, ASTM A470 Class 8 specification limits the fracture appearance transition temperature (FATT) to 250°F. The FATT values for the base material normally range from 185 to 260°F. Since the advancement of fracture mechanics technology, it has now become possible to characterize toughness in terms of a critical crack size $a_c$. The cold start sequence of a rotor is most critical and the critical flaw size $a_c$ based on analysis of temperature and stress can lead to catastrophic failure (Viswanathan and Jaffee, 1983). For the Gallatin rotor, the temperature at the time of the peak stress 74 ksi was 270°F. The combined crack size reached its lowest value 0.27 inches at this temperature and stress (Figure 24).

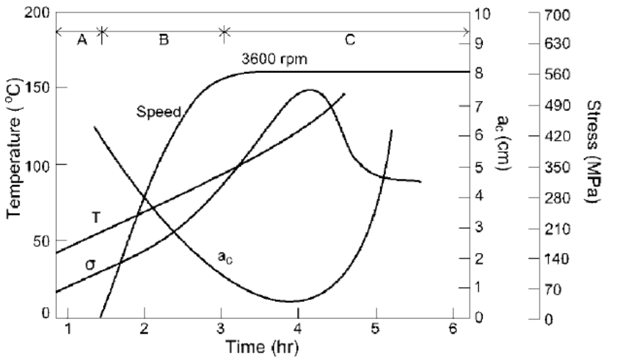


*Figure 24. Illustration of Cold-Start Sequence and Associated Variations in Stress (σ), Temperature (T), and Critical Flaw Size ($a_c$) as Functions of Time from Start.*

Variations in temperature, stress and material in homogeneity throughout the rotor dictate the critical flaw size $a_c$. By using lower scatterband values of $K_{IC}$, the critical flaw size can be converted (Schwant and Timo, 1985). Another method of estimating the lower-bound values of $K_{IC}$ for CrMoV steel is by using the expression (Jones, 1972):

$$K_{IC} = \frac{6600}{60-(T-FATT)} \quad \textbf{(1)}$$

where:
$K_{IC}$ is expressed in MPa $\sqrt{m}$
T is in °C

Although equipment manufacturers have records of the FATT value of the rotor material prior to service, the effect of temper embrittlement during service increases the FATT value and decreases the $K_{IC}$ value (Figure 25) (Viswanathan and Jaffee, 1983).

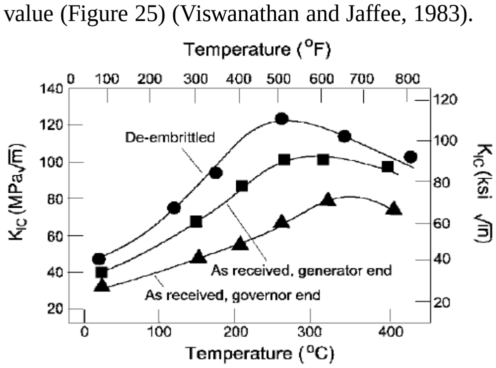


*Figure 25. Effect of Temper Embrittlement on Fracture Toughness of CrMoV Rotor Steel.*

The maximum temper embrittlement occurring at location of the rotor exposed to temperatures from 700°F to 800°F. Consequently, evaluation of FATT (or $K_{IC}$ at the concerned location) in the service exposed condition is critical for damage assessment (Dowson, et al., 2005).

An ASTM special task force on large turbine generator rotors of subcommittee VI of ASTM Committee A-1 on steel has conducted a systematic study of the isothermal embrittlement at 750°F of vacuum carbon deoxidized (VCD) NiCrMoV rotor steels. Elements, such as P, Sn, As, Sb, and Mo were varied in a controlled fashion and the shifts in FATT, (Δ) FATT were measured after 10,000 hours of exposure. From the results, the following correlations were observed in Equation (2):

$$\Delta FATT = 13544P + 12950Sn + 2100As - 93Mo - 810{,}000(P \times Sn) \quad \textbf{(2)}$$

where:
ΔFATT is expressed in degrees Fahrenheit and the correlation of all the elements are expressed in weight percent. According to this correlation, the elements P, Sn, and As increase temper embrittlement of steels, while Mo, P, and Sn interaction decrease the temper embrittlement susceptibility.

All available 10,000 hour embrittlement data are plotted in Figure 26 as a function of calculated ΔFATT using Equation (2) (Newhouse, et al., 1972). A good correlation is observed between calculated and experimental ΔFATT. The scatter for these data is approximately ± 30°F for 750°F exposure and ±15°F for the 650°F exposure.

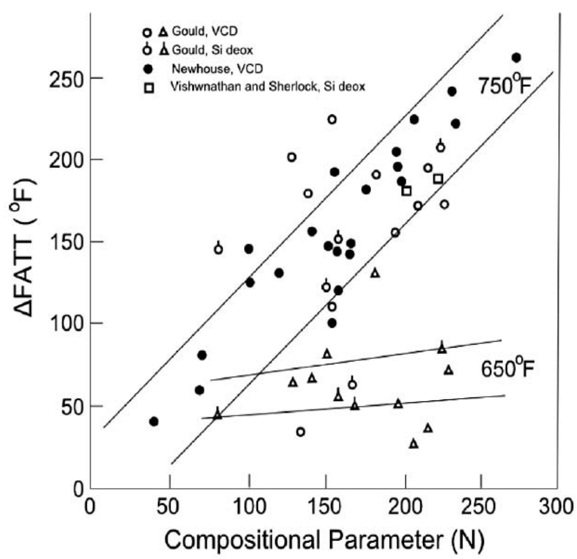


*Figure 26. Correlation Between Compositional Parameter "N" and the Shift in FATT of NiCrMoV Steels Following Exposure at 650°F and 750°F for 8800 Hours.*

Other correlations for determining the temper embrittlement susceptibility of steel, such as the J factor proposed by Watanabe and Murakami (1981) and $\bar{x}$ factor proposed by Bruscato (1970), are widely used. These factors are given by:

$$J = (Si + Mn)(P + Sn)\,10^4 \quad \textbf{(3)}$$

$$\overline{X} = (10P + 5Sb + 4Sn + As)\,10^2 \quad \textbf{(4)}$$

The Figures 27 and 28 show relationship between increase of FATT and J factor and $\bar{x}$ factor at 750.2°F (399°C) for a 3.5%NiCrMoV steel.

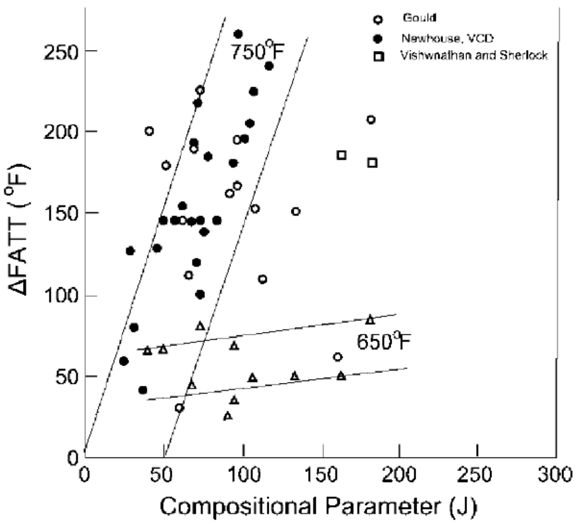


*Figure 27. Correlation Between Compositional Factor "J" and the Shift in FATT of NiCrMoV Steels Following Exposure at 650°F and 750°F for 8800 Hours.*

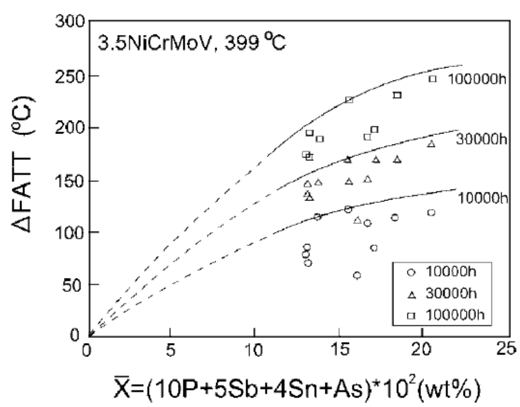


*Figure 28. Relationship Between Increase of FATT and $\bar{x}$.*

In the high temperature regions, creep and creep rupture are a concern. The traditional approach is to use a Larson-Miller plot as shown in Figure 29. The design stresses are generally based on the $10^5$ hours smooth bar creep rupture stress divided by some appropriate safety factors.

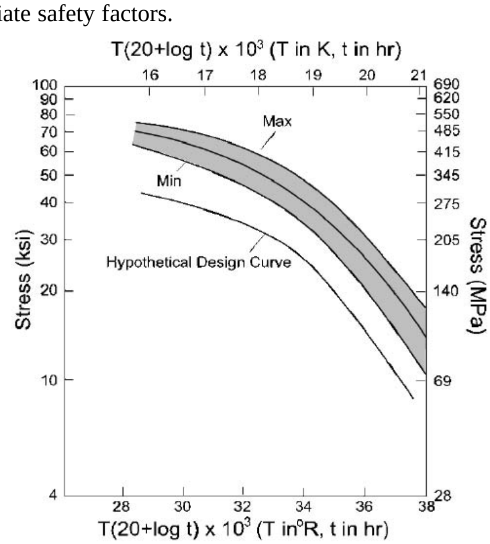


*Figure 29. Larson-Miller Stress Rupture Curve for 1Cr 1Mo ¼V Rotor Steel.*

*Steam Turbine Blades (Buckets)*

There are basically three groups of steam turbine blade material used by turbine manufacturers. These are various grades of 12 to 13 percent chromium (cr) steels with additions of Mo, W, Cb, and V, higher chromium precipitation hardening steels such as 17-4PH and titanium alloys. Table 8 gives a listing of the commercial available materials used in blading (ASTM A1028, 2003). Additional data regarding the heat treatment and mechanical properties can be found in *Aerospace Structural Metals Handbook: Volume 2* (1988), and Briggs and Parker (1965) (Figures 30 and 31).

*Table 8. Composition and Mechanical Properties of Commercial Blading Materials.*

| | Composition % | | | | | |
|---|---|---|---|---|---|---|
| | Grade A | Grade B | Grade C | Grade D | Grade E | Grade F |
| UNS Designation | S41000 | S41005 | S41428 | S42225 | S41041 | S17400 |
| C | 0.15 max | 0.10 - 0.15 | 0.10 - 0.17 | 0.20 - 0.25 | 0.13 - 0.18 | 0.07 max |
| Mn | 1.0 max | 0.25 - 0.80 | 0.65 - 1.05 | 0.5 - 1.0 | 0.4 - 0.6 | 1.0 max |
| P (max) | 0.018 | 0.018 | 0.020 | 0.020 | 0.030 | 0.040 |
| S (max) | 0.015 | 0.015 | 0.015 | 0.010 | 0.030 | 0.030 |
| Si | 0.5 max | 0.5 max | 0.10 - 0.35 | 0.20 - 0.50 | 0.5 max | 1.0 max |
| Ni | 0.75 max | 0.75 max | 2.25 - 3.25 | 0.5 - 1.0 | 0.5 max | 3.0 - 5.0 |
| Cr | 11.5 - 13.0 | 11.5 - 13.0 | 11.25 - 12.75 | 11.0 - 12.5 | 11.5 - 13.0 | 15 - 17.5 |
| Mo | 0.5 max | 0.5 max | 1.5 - 2.0 | 0.9 - 1.25 | 0.20 max | --- |
| V | --- | Report Only | 0.25 - 0.40 | 0.20 - 0.30 | --- | --- |
| W | --- | 0.10 max | 0.10 max | 0.9 - 1.25 | --- | --- |
| N | --- | 0.08 max | 0.02 - 0.045 | Report Only | --- | --- |
| Al | --- | 0.025 max | 0.025 max | 0.25 max | 0.05 max | --- |
| Nb | --- | 0.20 max | --- | 0.05 max | 0.15 - 0.45 | 0.15 - 0.45 |
| Co | --- | --- | --- | 0.20 max | --- | --- |
| Ti | --- | 0.05 max | 0.05 max | 0.025 max | --- | --- |
| Cu | --- | 0.50 max | 0.50 max | 0.15 max | --- | 3.0 - 5.0 |
| Sn | --- | 0.05 max | 0.05 max | 0.02 | --- | --- |

| | Composition % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Grade A | | Grade B | Grade C | | Grade D | | Grade E | | Grade F |
| | Class 1 | Class 2 | Class 1 | Class 1 | Class 2 | Class 1 | Class 2 | Class 1 | Class 2 | Class 1 |
| Tensile Strength, min, ksi | 100 | 110 | 110 | 145 | 160 | 140 | 140 | 115 | 110 | 135 |
| Yield Strength, min, ksi, 0.2% offset | 70 | 80 | 90 | 115 | 120 | 90 | 100 | 75 | 80 | 105 |
| Elongation in 2 in., min, % | 20 | 18 | 18 | 15 | 16 | 13 | 13 | 15 | 18 | 16 |
| Reduction of Area, min, % | 60 | 50 | 50 | 30 | 50 | 30 | 35 | 50 | 55 | 50 |
| Impact Strength, min, av., Cv, Rt, ft-lb | 30 | 25 | 30 | 30 | 40 | 8 | 10 | 20 | 25 | 41 |
| Hardness, max, Brinell | 255 | 269 | 269 | 352 | 375 | 331 | 331 | 277 | 262 | 341 |

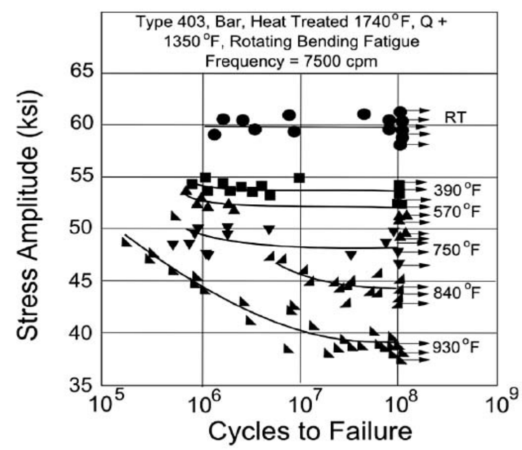


*Figure 30. Rotational Bending Fatigue Behavior of Type 403 at Various Temperatures.*

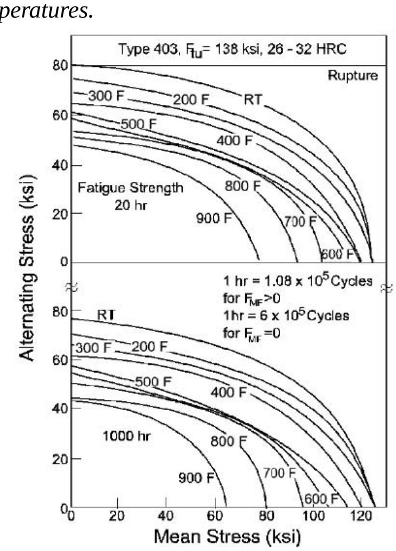


*Figure 31. Stress-Range Diagrams at Various Temperatures for Type 403 Heat Treated to 26-32 HRC.*

In designing blades one must take into account the material properties, the operating conditions, and the quality/purity of the steam. The principal failure mechanisms that occur in blades are high cyclic failure and creep rupture. Blades are designed to prevent creep rupture failures; therefore, it is rare that steam turbine blades fail by this mechanism. In general, most blade failures are due to high cycle fatigue caused by a number of factors. Some of the factors are listed below:

- Dynamic stresses caused by nonsteady steam forces, nozzle wakes, thermal transient per revolution diaphragm harmonics, and flow instabilities
- Strong exciting harmonics of rotational speed such as the nozzle passing frequency
- Steam purity and its effect on corrosion in fatigue and pitting corrosion

Speidel (1981) highlighted the satisfactory corrosion fatigue resistance of X21CrMoV121 steel in a good purity steam (Figure 32). However, the growth of fatigue cracks in 12 percent chromium steels is greatly enhanced by the presence of chloride solutions at low cyclic stress intensities and high mean loads (Figure 33). Speidel (1981) also illustrated how the $\Delta K_{th}$ (threshold stress intensity) is greatly reduced by the presence of certain environments (Figure 34). Other work done by Batte and Murphy (1981) showed similar results on the fatigue strength reduction in various aqueous solutions (Figure 35). With these data, it can be concluded that the most concerning conditions for fatigue crack growth is a high mean stress with superimposed cyclic stresses in the presence of aqueous solutions. These conditions are the service conditions that steam turbine materials are subjected to. It is well known that shot peening enhances the fatigue resistance of metallic materials by introducing compressive stresses at the surface layer of the component. However, in a corrosive environment, pits may penetrate the compressive stress layer, thereby negating the benefit gained by peening (Figure 36). The importance of steam purity and corrosion resistance of the blade material are clear when considering that it is not feasible in most cases to avoid the stress state and exposure to aqueous solutions present in the turbine and that treatments such as peening are not reliable.

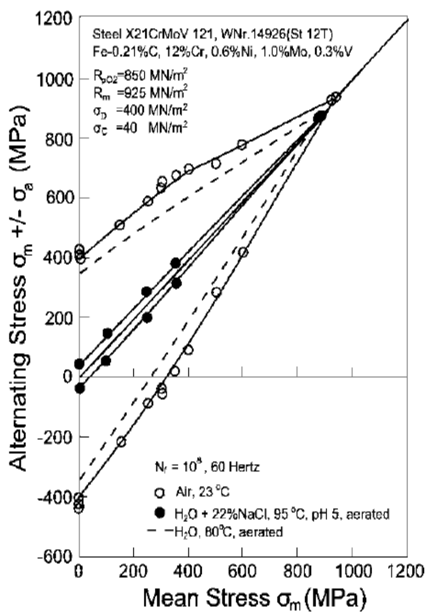


*Figure 32. Fatigue and Corrosion Fatigue of X21CrMoV 121 in Air, Deaerated Water, and Aerated Hot Chloride Solutions.*

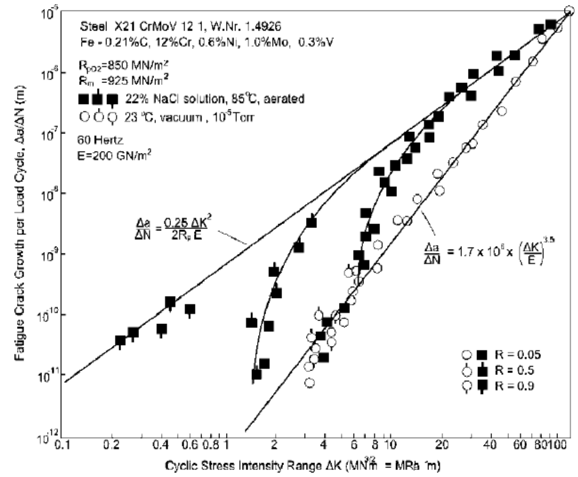


*Figure 33. Effect of Chloride Solutions on the Fatigue Crack Growth Rate of 12%Cr Steels.*

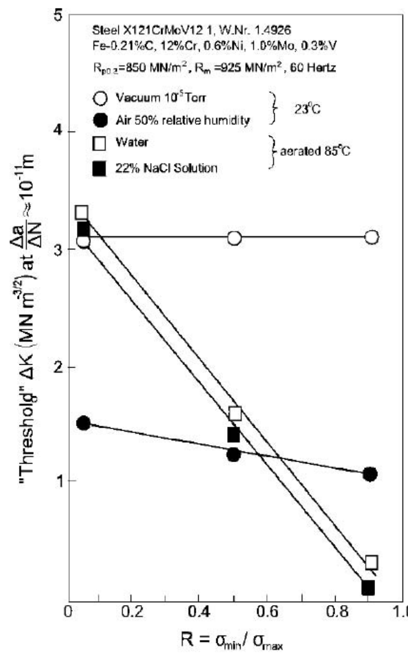


*Figure 34. Effect of Environment on the Threshold Stress Intensity $K_{th}$ of 12%Cr Steels.*

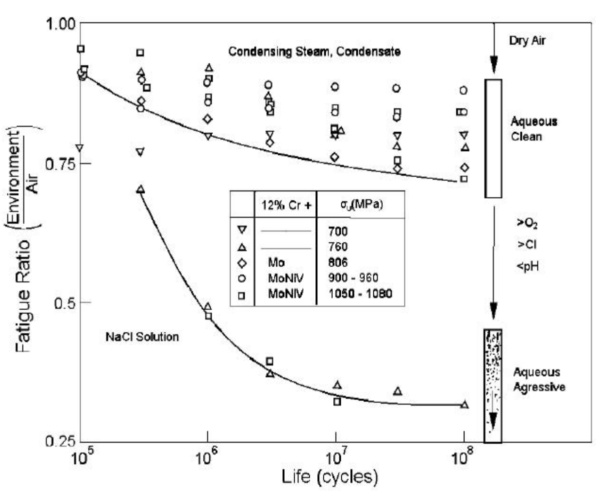


*Figure 35. Effect of Various Aqueous Environments on Fatigue Strength.*

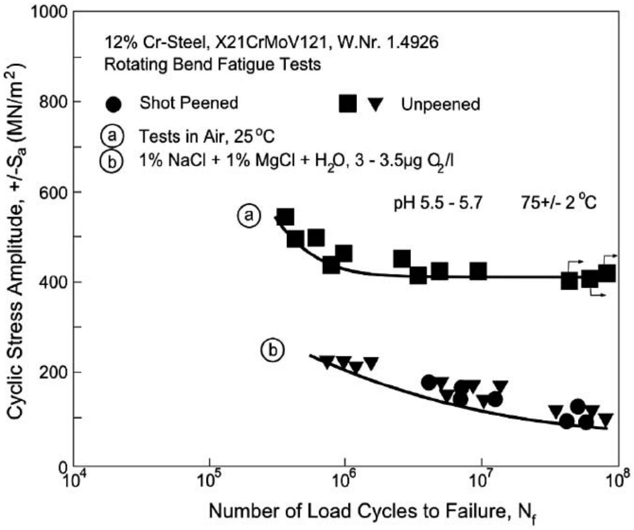


*Figure 36. Effect of Environment on Fatigue Resistance of Shot Peened 12%Cr Steel.*

### *Casings*

The various composition of steels used for turbine casings are shown in Table 9. During the years the drive toward improving creep strength to accommodate the steadily increasing temperatures led to progressive changes in material from the C-½ Mo and 1Cr½Mo to the 1Cr1Mo¼V and 2¼Cr1Mo. In the late 1960s and early 1970s, numerous instances of reheat cracking (stress relief cracking) in the weld heat affected zones occurred in the 1Cr1Mo¼V and the importance of rupture ductility was realized. The material ½Cr½Mo¼V was standardized by some manufacturers who implemented stringent specifications relating to control of residual elements (particularly phosphorus, antimony, tin, copper, aluminum, and sulfur), deoxidation practices, and welding procedures. Casing designs were modified to eliminate manufacturing and in-service reheat cracking. Other manufacturers utilized the 2¼Cr1Mo steel due to its higher creep ductility, higher low cycle fatigue resistance, and better weldability. The current designs use either ½Cr½Mo¼V or the 2¼Cr1Mo steel material. For steam temperatures of 1050°F and above, and up to 1100°F, the 9 to 12%Cr casting grade steels will be utilized.

*Table 9. Various Composition of Steels Used for Turbine Casings.*

| | Composition (wt%) | | | | | | | | | Range of Application |
|---|---|---|---|---|---|---|---|---|---|---|
| Material | C | Si | Mn | Cr | Mo | V | Ni | Nb | N | °F |
| Flake-graphite gray cast iron | 3.00 | 1.80 | 0.70 | --- | --- | --- | --- | --- | --- | 752 max |
| Ferritic SGI | 3.22 | 2.94 | 0.25 | --- | --- | --- | --- | --- | --- | --- |
| Carbon Steel | 0.20 max | 0.50 max | 1.10 max | --- | --- | --- | --- | --- | --- | --- |
| C-1/2Mo | 0.25 max | 0.20-0.50 | 0.50-1.00 | --- | 0.50-0.70 | --- | --- | --- | --- | 896 max |
| Cr-1/2 Mo | 0.15 max | 0.60 max | 0.50-0.80 | 1.00-1.50 | 0.45-0.65 | --- | --- | --- | --- | 977 max |
| 2 1/4Cr-1Mo | 0.15 max | 0.45 max | 0.40-0.80 | 2.00-2.75 | 0.90-1.10 | --- | --- | --- | --- | 1000 max |
| Cr-Mo-V | .015 max | 0.15-0.30 | 0.40-0.60 | 0.70-1.20 | 0.70-1.20 | 0.25-0.35 | --- | --- | --- | 1049 max |
| 1/2Cr-Mo-V | 0.10-0.15 | 0.45 max | 0.40-0.70 | 0.40-0.60 | 0.40-0.60 | 0.22-0.28 | --- | --- | --- | 1049 max |
| T91 | 0.08-0.12 | --- | --- | 8.0-9.5 | 0.85-1.05 | 0.18-0.25 | 0.4 max | 0.04-0.10 | 0.03-0.07 | 1100 max |

The optimization of low alloy materials has taken place over a period of 50 years or more. The development and optimization of the 9 to 12%Cr have only just begun. A lot of work remains to be done to characterize these materials for design lives of up to 250,000 hours and to cast variation in their properties. The development of joints between the modified 9%CrMo and low alloy material has been done in order to optimize selection of welding consumables, welding parameters, and post weld heat treatment. Creep tests on such joints have indicated that in long-term tests, their rupture strength falls near the lower bound of the low alloy parent material's strength. Due to composition gradients, carbon depleted, ferritic zones can form on the low alloy side of the interface between the high and low alloy materials. Consequently, joint locations are designed such that the temperature and stress are lower so that creep and carbon diffusion in service will be very limited.

### *Nozzles and Diaphragms*

In steam turbines, stationary nozzles and diaphragms are selected based upon stress/temperature, oxidation, and corrosion. The blades of nozzles and diaphragms are made from wrought 13%Cr series stainless material. The blade holders are manufactured from mild steel, ductile iron, or low alloy steels. The choice of material depends on the method of construction and the operating design stress at temperature.

During service, erosion due to wet steam can occur on the latter stages of the steam turbine diaphragms. Normally repairs in those areas are done by depositing weld material that has improved water/steam erosion resistance, i.e., AWS E309/ER309 or Inconel® weld consumable. In some instances, a mechanical fix may be performed using an austenitic stainless or nickel base wrought material.

### *High Temperature Bolting*

In a steam turbine, bolts in flange joints operating in the creep range at temperatures up to 1050°F must be able to withstand steam pressures up to 2 ksi or in some cases even higher. The main requirement of bolts in the creep range is to maintain joints without relaxing below the required design stress limit, which may allow leakage. Consequently, the important property for bolts is the stress relaxation characteristics of the material. For a given joint, the load required to exceed the steam load is applied to the flange area by tensile loading of the bolts. During service, creep in bolt causes relaxation of this initial load. The elastic strains produced by initial tightening of the bolts are progressively converted to creep strains; elongating the bolt and thereby, reducing the effective load in the joint. For design, the final relaxation stresses must be in excess of the design stress to keep the joint tight. Depending on the material and duty requirements, bolts are usually tightened to a predefined cold strain, e.g., 0.15 percent from which the initial stress on the bolt can be calculated. Consequently, the bolts need to retain their design stress between each overhaul when the bolts are removed for maintenance of the machine and retightened on reassembly.

Typical composition of bolt steel, their properties, and various national standards are summarized in Tables 10 and 11 (Everson, et al., 1988). For convenience, the Central Electricity Quenching Board of the United Kingdom has classified these compositions into grouping numbered one through eight. Several of these groups of materials show stress relaxation behavior after 30,000 hours as a function of temperature when subjected to a cold prestrain of 0.15 percent (Figure 37) (Branch, et al., 1973). In selection of bolt material, the compatibility of the thermal expansion coefficient of the bolts with respect to the joint materials, as well as its susceptibility to various fracture mechanisms, must be taken into account. When sufficient stress relaxation data are not available, one can apply the useful correlations that exist between the creep rupture data and relaxation stress at 0.15 percent strain (Figure 38).

*Table 10. Various National Bolting Material Specifications.*

| | | Typical Composition (%) | | | | | | RT Tensile Strength | Rupture Stress (ksi), $10^4$ h at temp. (°F) of: | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Specification | Grade | C | Cr | Mo | V | Others | Heat Treatment (°F) | (ksi) | 932 | 1022 | 1112 |
| United States: | B7 | 0.4 | 1 | 0.2 | --- | --- | T ≥ 1100 | ≥115 | NA | NA | NA |
| A193-84a | B7M | 0.4 | 1 | 0.2 | --- | --- | T ≥ 1148 | ≥100 | NA | NA | NA |
| | B16 | 0.4 | 1 | 0.6 | 0.3 | --- | T ≥ 1202 | ≥110 | NA | NA | NA |
| Germany: | 21CrMoV57 | 0.2 | 1.2 | 0.7 | 0.3 | --- | 1706 OQ + 1328 | 102-123 | 39 | 25 | --- |
| DIN 17240 | 40CrMoV47 | 0.4 | 1.2 | 0.6 | 0.3 | --- | 1706 OQ + 1292 | 123-145 | 39 | 25 | --- |
| | X22CrMoV121 | 0.2 | 12 | 1 | 0.3 | 0.5 Ni | 1922 AC + 1256 | 130-152 | 53 | 32 | 16 |
| France: | 25 CD 4 | 0.25 | 1 | 0.2 | --- | --- | 1616 OQ + ≥1112 | 87-109 | 26 | 11 | --- |
| NF A 35 558 | 20 CDV 5.07 | 0.2 | 1.3 | 0.7 | 0.25 | --- | 1706 OQ + ≥1112 | 102-123 | 39 | 25 | --- |
| | Z20 CDNbV11 | 0.2 | 11 | 0.7 | 0.2 | 0.4 Nb | 2048 AC + ≥1238 | 128-149 | 57 | 40 | 23 |
| Russia | 20KhIMIFTR | 0.2 | 1.2 | 1 | 0.9 | Ti, B | 1832 Q + 1292 | NA | NA | NA | NA |
| Australia | Comsteel 029 | 0.2 | 1 | 1 | 0.6 | Ti, B | 1814 OQ + 1292 | 119-145 | NA | NA | NA |

*Table 11. United Kingdom Bolting Material Specifications.*

| Steel Designations | | Nominal Composition (%) | | | | | Typical Heat | RT Tensile | Strength (ksi) Rupture, $10^4$ h | | Relaxation, 0.15% strain | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BS 1506:1986 | CEGB Group | C | Cr | Mo | V | Others | Treatment (°F) | Strength (ksi) | 932 °F | 1022 °F | 932 °F | 1022 °F |
| 631-850 | GP 1 (Cr-Mo) | 0.4 | 1 | 0.5 | --- | --- | | 123-145 | 34 | 14 | 12 | --- |
| 670-850 | GP 2 (Cr-Mo_V) | 0.4 | 1 | 0.5 | 0.25 | --- | | 123-145 | 47 | 22 | 12 | --- |
| --- | GP 3 (3Cr-Mo-V) | 0.3 | 3 | 0.5 | 0.75 | --- | --- | --- | --- | --- | --- | --- |
| --- | GP 4 (Mo-V) | 0.2 | --- | 0.5 | 0.25 | --- | --- | --- | --- | --- | --- | --- |
| --- | GP 5 (1Cr-Mo-V) | 0.2 | 1 | 1 | 0.75 | --- | * | * | * | * | * | * |
| 681-820 | GP 6 (1Cr-Mo-V) | 0.2 | 1 | 1 | 0.75 | Ti, B | | 119-145 | 61 | 41 | 20 | 10 |

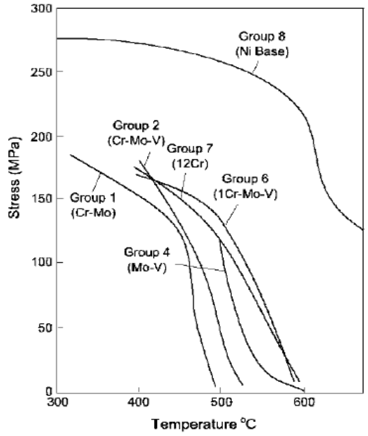


*Figure 37. Comparison of Stress-Relaxation Behavior after 30,000 Hours as a Function of Temperature for Various Bolt Materials Subjected to a Cold Prestrain of 0.15 Percent.*

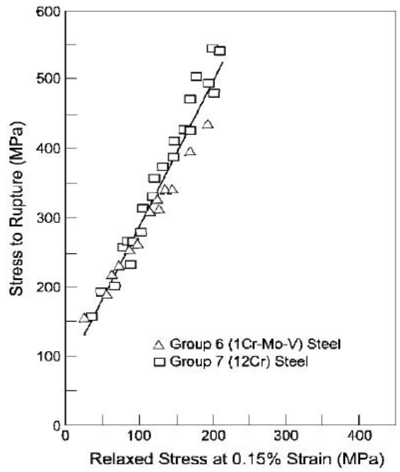


*Figure 38. Relationship Between Relaxed Stress and Rupture Strength at the Same Duration for Times from 1000 to 30,000 Hours and Temperature from 885 to 1110°F (475 to 600°C).*

Fracture of a bolt can occur if the local creep strain reaches the creep ductility of the material from which the bolt was made. Consequently, low rupture ductilities lead to notch sensitive bolt material. Numerous failures of 1Cr-1Mo-V steel bolts were attributed to notch sensitive failures. By reducing the impurity elements of the bolt steel, appreciable improvements have been made to rupture ductility without compromising the creep strength (Figure 39). The residual element content can be reduced by careful scrap selection, avoidance of air melt, and use of double vacuum melting (Figure 40).

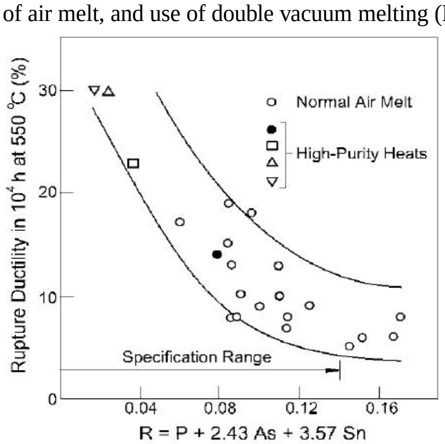


*Figure 39. Relationship Between Residual Element Content and Ductility.*

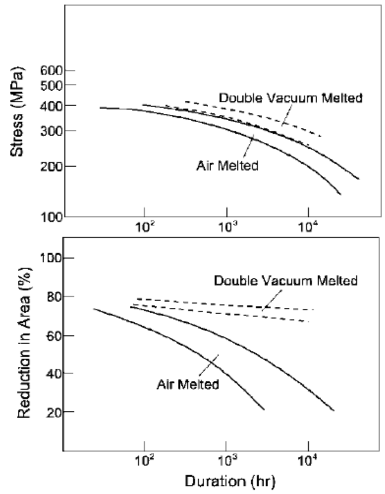


*Figure 40. Effect of Double Vacuum Melting on Stress-Rupture Properties of 1Cr-Mo-V Steels at 1020°F.*

Other improvements in notch ductility were in a new class of CrMoV containing titanium and boron with subsequent grain refinement. Further improvements in the rupture ductility of 1CrMoVTiB steel have been made by reducing the major embrittling elements. The application of very clean steel practices have shown beneficial effects on ductility and notch strength. This material will continue to be used as a very cost-effective option for temperatures up to 1049°F (565°C). Also nickel-based super alloys such as Nimonic 80A and IN901 have been used for some of the high temperature bolts where stress relaxation is an issue.

## REPAIRS

In the rotating equipment industry, service of components requires either replacement with new or refurbishment of the components. The refurbishment can mean restore the component to its original dimension either by welding/mechanical fix or other sprayed/plating processes. All OEMs have developed repair procedures for most of the long lead delivery components, e.g., components such as impeller, shaft, casing, and diaphragms. API RP 687 (2001) specifies the minimum requirements for performing the repairs to rotors.

Throughout the last 20 years hundreds of rotors and shafts for both compressors and steam turbines have been successfully weld repaired by various OEMs. Welded rotor restoration, like any other critical repair technology, requires a highly analytical approach to assure component and machine reliability. Most OEMs develop property data for weldments and heat affected zones for the various materials. This would include materials for both steam turbines and centrifugal compressors. The data that are generated, but are not limited, are as follows:

- Room and elevated temperature tensile properties
- Impact and fracture appearance transition temperature data
- Creep/stress rupture data
- Fatigue properties
- Stress corrosion cracking (SCC) threshold limits

Several papers (LaFave, 1991; Dowson, 1995; Dowson and Wiegand, 1996) outline some of the material property data that can be generated. Figures 41, 42, and 43 show some generic examples of data that are typically used. These data allow for the weld metal properties to be compared against mechanical analysis results and company design criteria to assure that the proposed repair will be reliable. Shorter term testing such as weldability, tensile hardness, and toughness is routinely done on the base metal, weld metal, and HAZ for each engineered rotor repair.

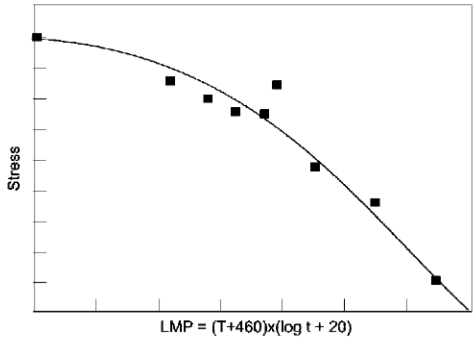


*Figure 41. Typical Larson-Miller Curve Generated from Various Weldments.*

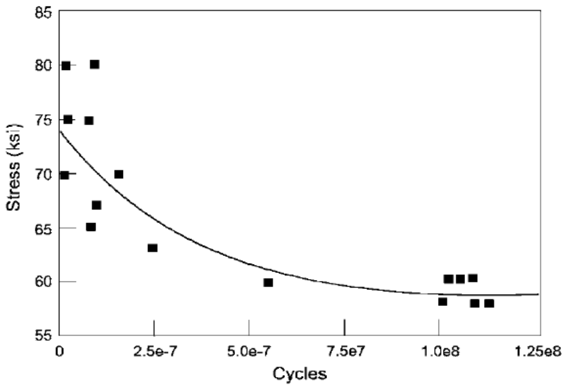


*Figure 42. Typical S-N Curve from Fatigue Testing of Weldments, Fully Reversed (R = −1), Endurance Limit Set to $10^8$.*

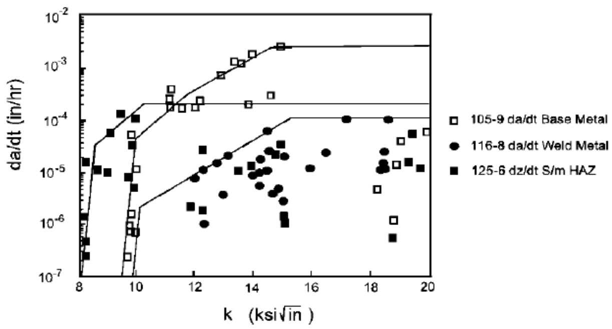


*Figure 43. Stress Corrosion Crack Growth Rate as a Function of Stress Intensity of Weld Metal, HAZ, and Base Metal.*

When repairs to impellers are required, it is generally due to some form of mechanical damage or corrosion/erosion attack. If the impeller has failed by fatigue, the component is generally replaced. When corrosion attack has occurred, repairs will be made by applying corrosive resistant welding consumables. For erosion attack, various coatings can be applied to extend the life of the impeller.

## COATINGS

Despite best efforts in choosing a suitable alloy, it is frequently impossible to find a single material that is ideal for the particular application. In this case, composite systems, i.e., coatings, may be used to exploit the properties of two or more materials. There are several reasons why coatings may be used, ranging from enhancing a particular property for a specific application to reducing cost by allowing for the use of less expensive substrate materials. Coatings are also often designed to be multifunctional, addressing multiple problem areas simultaneously. The petrochemical industry presents several opportunities for the usage of coatings due to the frequently harsh conditions encountered in this service.

### *Compressors*

#### *Corrosion*

Corrosion is a common problem in several industries, including turbomachinery. It is an electrochemical attack that can occur as an even attack of the surface (general corrosion) or uneven attack (pitting), as well as lead to stress corrosion cracking. Coatings for corrosion protection work by acting as a barrier that separates the substrate material and the environment. Typically, the coating material is viewed as a sacrificial layer and has slower reaction kinetics than the base metal in the particular environment.

For selection of materials for sour gas service, API 617 (2002) refers to NACE MR0103 (2005) and MR0175 (2003), which allow the use of coatings for general corrosion resistance, but not for protection against stress corrosion-cracking. This is due to the fact that localized defects in the coating can lead to a stress corrosion crack. With any coating, there is always a risk that the coating will be removed at a small location, either by erosion, localized pitting, or foreign object damage, which will expose the substrate to the corrosive environment. Diffusion coatings are too thin to provide a complete barrier between the substrate and the environment. Metallic, electrolytic coatings contain microscopic cracks that will allow the $H_2S$ to contact the substrate material. Hydrogen sulfide can diffuse through polymer coatings to reach the substrate while thermal spray coatings are porous and will not provide adequate protection.

There appears to be a limited number of coatings advertised by the various OEMs that are applied solely for corrosion protection. Part of this is due to the fact that changing the base metal to a more corrosion resistant material, such as a stainless steel, often gives satisfactory results. A second reason for the lack of corrosion coatings is that corrosion is often accompanied by fouling in centrifugal compressors and therefore the antifoulant coatings, discussed below in more detail, typically are designed to prevent corrosion as well. One coating that the authors' company has used with some success is a baked phenolic coating. This coating is used in certain applications where it performs better than stainless steel or where the increased price of using stainless steel cannot be justified by the end user.

#### *Fouling*

Fouling is a common problem in compressors and to some extent, steam turbines. Fouling refers to the build of solids, usually polymeric materials, on the internal aerodynamic surfaces of the machine. While it does not usually lead to catastrophic failure, it does gradually reduce the efficiency of the machine by increasing the mass of the rotor, altering the aerodynamics, and blocking flow paths. If left unchecked, fouling can block the flow path to the extent that production is stopped or cause imbalances that can damage the machine. Depending on the service, fouling substances may come from outside of the machine or be generated internally. External foulants may come from airborne salt, submicron dirt, and organic or inorganic pollutants in the process gas. A well-maintained filtration system usually helps to minimize this type of fouling (Meher-Homji, et al., 1989; Guinee and Lamza, 1995). In petrochemical compressors, the situation is much more complicated, as the foulants can be generated internally. For example, in ethylene cracked gas compression, fouling results from the polymerization reactions intrinsic to the compression process. Fouling has imposed significant cost on petrochemical production.

A material that is required to resist fouling must have excellent release properties. Materials with a combination of low coefficient of friction and chemical inertness are usually used for this application. A common and widely known coating material for centrifugal compressors is polytetrafluoroethylene (PTFE [Teflon®]). These are multicomponent, sprayed coatings designed for fouling and corrosion resistance. Wang, et al. (2003), showed a dramatic decrease in time required to release an applied foulant on samples coated with two PTFE type coatings offered by the author's company versus bare steel samples (compare E and E+ versus steel in Figure 44). Figure 45 shows an example of a compressor rotor with PTFE coated impellers. Unfortunately, PTFE coatings are removed by erosive liquids (example water washing) or solids. Electroless nickel (EN) has also been shown by Dowson (2007) to exhibit excellent release properties (523 in Figure 44), while remaining adherent in erosive conditions. In fact, the release properties are as good as or better than results from PTFE. EN is applied by submerging the part into a Ni and P containing solution where an autocatalytic process plates the part with a well-bonded, amorphous Ni-P alloy. The P in the alloy is believed to be responsible for the release properties, while amorphous nature aids in corrosion resistance.

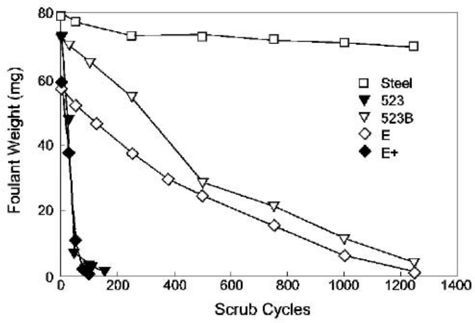


*Figure 44. Comparison of Fouling-Release Performance of Bare Steel and Coated Panels.*

*Figure 45. Centrifugal Compressor Rotor Coated with a PTFE Type Coating.*

*Case Study of Electroless Nickel Coating*

The application of electroless nickel as an antifoulant coating is a relatively recent advance. A brief survey of antifoulant coating offerings by OEMs shows that the majority do not offer an electroless nickel coating. Due to the current lack of offerings, an update of a case study initially introduced by Wang, et al. (2003), is presented below in order to justify the use of electroless nickel as a corrosion and foulant resistant coating option.

*Background*

A major chemical plant in Corunna has a centrifugal compressor that used to be coated with the coating 3P for antifouling. The coating had suffered severe deterioration two times during the four year operation since 1997. Analysis indicated that the deterioration was related to the heavy washing injection, which contained aggressive chemical additives, and steam-cleaning operation. However, the washing and cleaning were essential to the plant because of the extensive fouling and efficiency drop. In order to withstand the injections, the compressor rotor and diaphragms were recoated with EN during a plant turnaround in September 2001. The compressor had been in service until 2006 with satisfactory performance.

*Operating Status of the Electroless Nickel Coating*

The compressor with EN coating had been successfully operated since the 2001 turnaround until 2006. The rotor vibration has been monitored at a much lower level than the previous run periods, as shown in Figure 46, which indicates that the fouling has been effectively controlled by the EN coating. This improvement is attributed to the ability of EN to withstand the heavy washing operation as compared to the 3P coating. The oil washing and chemical injections have been kept in the same manner as in the previous operating periods. The Corunna plant feels that the EN has successfully functioned as an antifouling coating. When the unit was replaced in 2006 with a new machine, the customer requested the same successful EN coating to be applied to the rotor and internals.

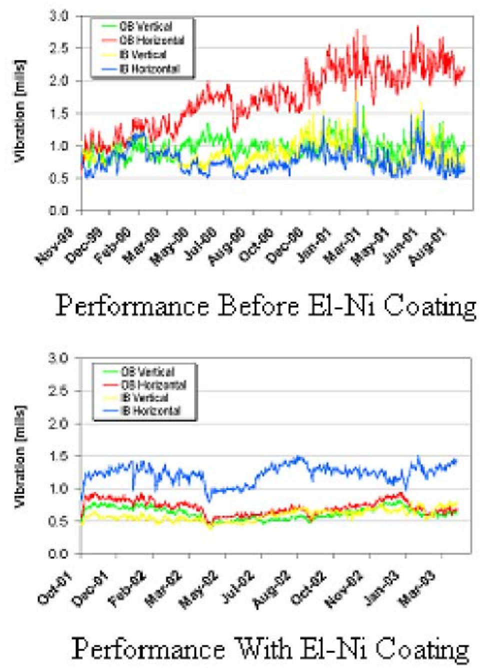


*Figure 46. Vibration Data Before and After Application of Electroless Nickel to the Rotor.*

After the original unit was pulled out of service, examination of the rotor shows that the EN coating remained in tact after the five year operational period. Pictures of a coated impeller are given in Figures 47 and 48. The coated impeller is free of corrosion and foulant buildup, and the impeller serial number remains readable. This is proof of the remarkable antifoulant properties of the EN coating.

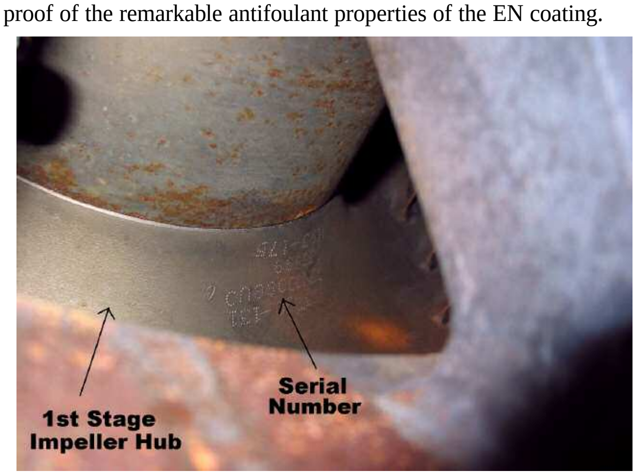


*Figure 47. Picture of First Stage Impeller with Electroless Nickel Coating after 5 Years of Service. The Coating Remains Intact and the Serial Number Is Clearly Visible.*

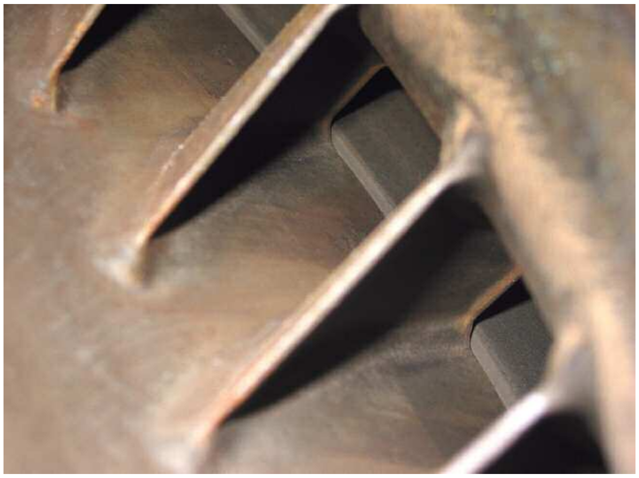

*Figure 48. Picture of First Stage Impeller with Electroless Nickel Coating after 5 Years of Service. The Gas Path of the Impeller Has No Foulant Buildup.*

*Erosion*

Erosion can be a significant issue in some applications of centrifugal compressors. It can occur as solid particle or liquid droplet erosion. Solid particle erosion is usually caused by external contaminants, such as those mentioned above. Liquid droplet erosion can be due to the condensation during compression or intentional injection of liquid for cleaning. The particle or droplet is accelerated by the carrier gas. The resultant impact upon the metallic compressor components removes small amounts of metal; creating pits and microcracks at the surface. Typically, the compressor design is robust and the material removal rate is such that erosion on its own is not a major problem. Problems arise when erosion is combined with other factors such as corrosion and cyclic stresses. In corrosive environments, erosion can compromise protection schemes and cause an accelerated corrosion attack. An example of this was mentioned above, where erosion can remove some antifoulant coatings. When cyclic stresses are present, the microcracks created can easily serve as initiation sites for fatigue cracking. Figure 49 shows the leading edge and fracture surface of a compressor impeller blade that failed by fatigue initiated by damage from liquid droplet erosion.

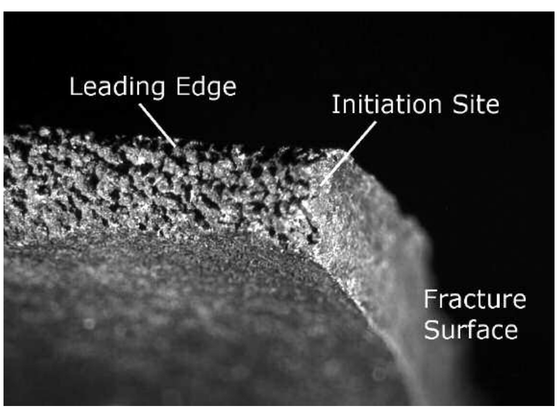


*Figure 49. Stereomicrograph Showing a Centrifugal Compressor Impeller Blade that Failed Due to Liquid Droplet Erosion.*

Erosion can often be thought of as a type of wear; therefore, similar coatings are used to prevent both. Coatings used for erosion protection are usually hard coatings, such as tungsten or chromium carbide. Any surface exposed to the gas path should be coated in applications where erosion is a problem. One problem that is an issue with all coatings for compressors, but is particularly true for these hard, erosion coatings, is the method of application. Carbide coatings are typically applied using techniques such as high velocity oxyfuel (HVOF), plasma spraying, or detonation gun. These processes have certain requirements, such as spray distance or line-of-sight, that may not be possible for the gas paths of smaller, closed impellers or other parts with poor accessibility.

*Steam Turbines*

*Corrosion*

Under ideal conditions, corrosion is not a major issue in steam turbines. Stainless steel materials perform extremely well without coatings in the elevated temperature, steam environment. The corrosion product formed on the stainless steel is usually a thin, uniform layer that grows slowly with time. Corrosion becomes a problem when there is an underlying problem with the process. Steam purity is the most common problem. Impure steam carries with it elements that increase the corrosion process. Typically, the amount of impurities in the steam is not large enough to change the general corrosion rate; rather they cause localized attack that leads to pitting. These pits provide easy initiation sites for fatigue cracks, as shown in Figure 50. Figure 51 is a plot of stress amplitude versus cycles to failure by fatigue. The drastic reduction in stress amplitude required for a given fatigue lifetime illustrates the ease in which fatigue cracks form in corrosion pits.

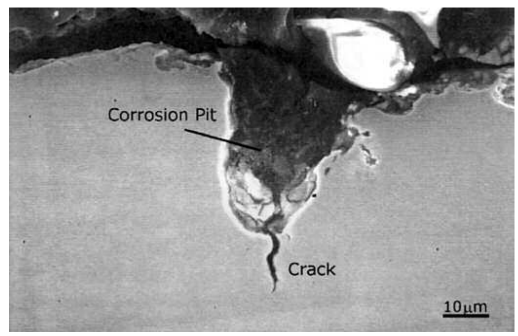


*Figure 50. Micrograph Showing a Crack Initiating from a Corrosion Pit.*

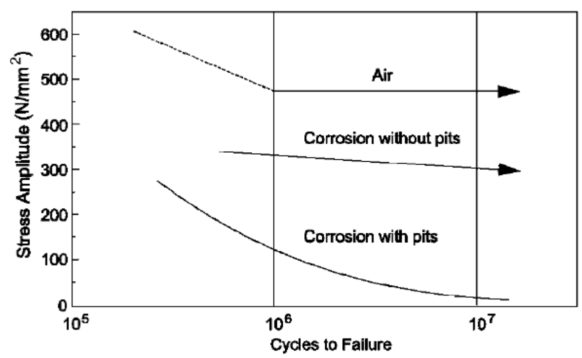


*Figure 51. Plot Showing the Effect of Corrosion and Pitting on Fatigue Life.*

Similar to compressors, there are not many coatings applied to steam turbine components for corrosion only. If there are problems with corrosion, usually other problems are occurring, such as erosion, which also must be addressed by a coating. The authors' company has used chromium diffusion coatings in the past where pitting corrosion was a problem.

*Erosion*

Erosion is a serious problem in steam turbines. The gas path of a steam turbine is much more closed than that found in a centrifugal compressor, providing more area for erosive media to impact.

Erosion-corrosion mechanisms are more prevalent due to the higher temperatures. The chances of cyclic stresses are also very high due to the complicated stress state found in turbine blades.

*Solid Particle Erosion*

The erosion occurs on the blade-vane leading edges caused by the exfoliation of scales from the boiler tubes mainly during transient conditions. For rotating blades, sprayed $Cr_3C_2$ coatings are applied using processes such as detonation gun, plasma, and high velocity oxygen fuel processes to protect against the scales. Other processes such as diffused boride coatings have successfully been applied to stationary nozzles. Figure 52 shows a photomicrograph of boride coating on AISI 422. The boride diffusion coatings applied by pack cementation and the $Cr_3C_2$ coatings applied by the spray processes mentioned above will continue to be the industry best choices.

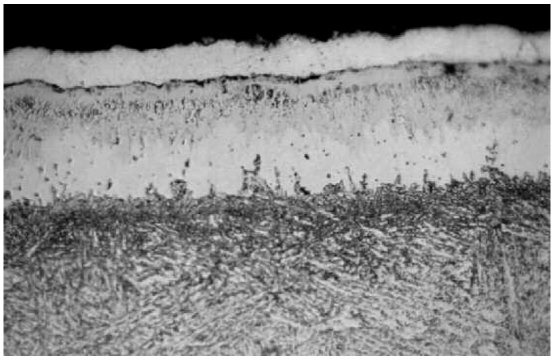

*Figure 52. Cross-Section of a Boride Diffusion Coating on AISI 422.*

*Liquid Droplet Erosion*

The damage of rotor blades in the latter low pressure stages of steam turbines by condensed water droplets can be a problem that has troubled designers and operators for many years. The damage consists of removal of material from the leading edge and adjacent convex surfaces of the moving blade. It is related to the wetness conditions in the low pressure regions and the velocity with which the surface of the blade strikes the water droplets. Stresses produced by impact of drops have been calculated by existing theories to be sufficiently high to initiate damage in the latter stages of blades in a steam turbine. Turbine experience and laboratory testing have shown that erosion rate is time dependent with three successive zones: a primary zone in which damage is initiated at slip planes with little or no weight loss, a secondary zone where the rate rises to a maximum, and finally a tertiary zone where the rate diminishes to a steady-state value. Moreover, it is this tertiary region that is important to designer and operator alike rather than the initial and secondary zones since it is this region that the turbine erosion shields operate for most of their lives (Figures 53 and 54).

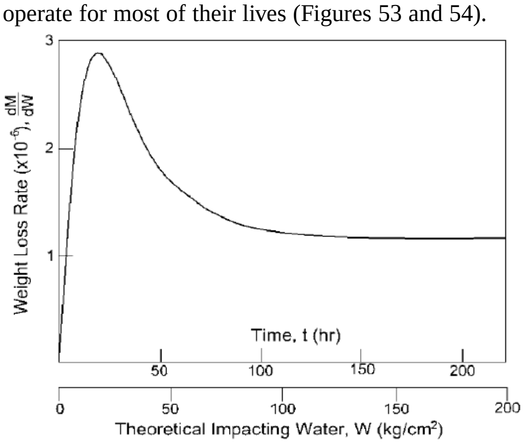


*Figure 53. Erosion Rate of 630 DPH, 18W-6Cr-0.7C Tool Steel Comparator Specimens.*

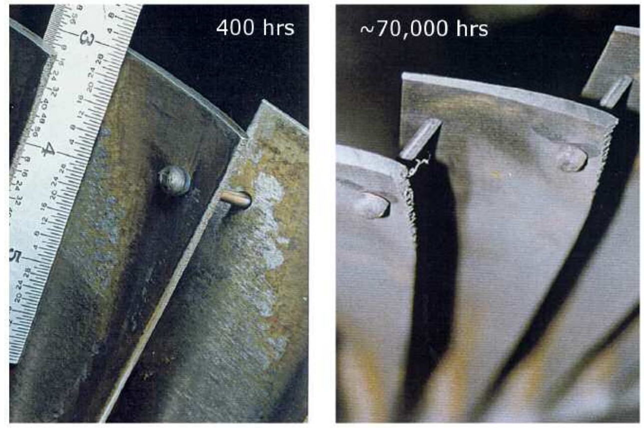


*Figure 54. Images Showing Erosion of Blades from the Same Turbine after 400 Hours and 70,000 Hours.*

While not strictly coatings, various countermeasures have been utilized by OEMs, including water drainage devices in a cylinder wall, flame or induction hardening of the leading edge of the blade, and applying stellite or tool steel strips to the leading edge of a blade by welding or brazing. All of the above methods show some degree of success, with the stellite material providing the better performance in the more stringent water droplet environment.

*Fouling*

Fouling and corrosion can also be a problem in steam turbines not only causing material damage but also can gradually reduce the efficiency of the turbine. Industrial turbines, whether condensing or noncondensing, can encounter problems with deposits building up on the turbine airfoils. In a turbine, hydroscopic salts, such as sodium hydroxide, can absorb moisture when superheated steam becomes saturated and condenses in the latter stages of the turbine/Wilson line. Wet sodium hydroxide has a tendency to adhere to turbine metal surfaces and can entrap other impurities such as silica, metal oxides, and phosphates. Once these deposits have formed they can be difficult to remove. Build up of these deposits may be a cause of decrease in efficiency and possibly an increase in vibration. A smooth clean steam path will not collect deposits so easily as a dirty, previously contaminated surface. Consequently, a previously contaminated turbine will accumulate deposits more rapidly than a clean one. Therefore, it is desirable to prevent further deposit buildup and to remove the problems associated with the presence of the deposits by cleaning the turbine. The authors' company has provided support to end user turbines for water washing of steam turbines (Watson, et al., 1995). The effectiveness of the water removal procedures mainly depends on the adherence of the deposits to the substrate.

A second route is to coat the surface with a material that has superior antifouling or antistick/corrosion characteristics. This in turn is beneficial to the turbine blades by reducing the tendency for contaminants to stick to the blades and increase the effectiveness of the water washing. Titanium nitride coatings with a chromium undercoat (Cr-TiN) have also been used by steam turbine OEMs to coat turbine blades. This coating provides corrosion protection and can be used on all stages of a steam turbine rotor, however, the Cr-TiN only provides limited antifoulant benefits. The authors' company has recently developed a proprietary coating, which is a corrosion resistant antifoulant coating designed for the later stages of the turbine rotor (where the deposit buildup is most severe). Testing has shown that this coating provides significant improvement in foulant release ability (Figure 55), excellent corrosion protection (passes over 1000 hours of ASTM B117 corrosion testing under a 5 percent salt solution), and erosion protection (Figure 56), and, while having little effect on the fatigue properties (Figure 57).

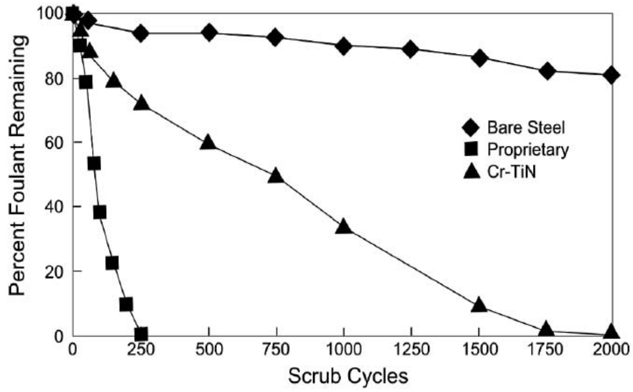


*Figure 55. Comparison of Foulant Release Performance of Bare Steel Against Proprietary Coating and Cr-TiN Coated Samples.*

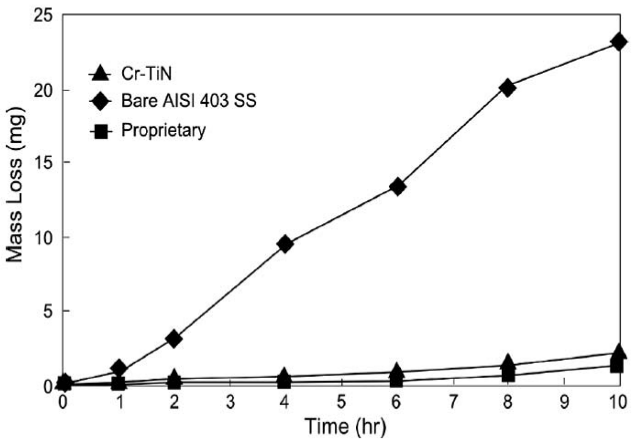


*Figure 56. Comparison of Bare AISI 403 Stainless Steel Against Proprietary and Cr-TiN Coated Samples after 10 Hours of Modified ASTM G32 Testing.*

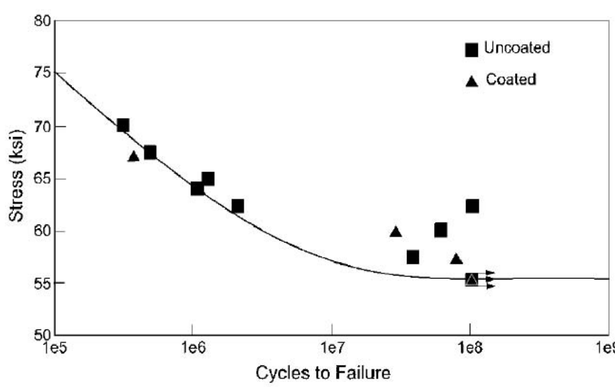


*Figure 57. Results of R.R. Moore Fatigue Testing.*

## SUMMARY

An overview of materials and material related processes has been presented for centrifugal compressors and steam turbines. Special attention has been given to address some of the problems associated with material selection for the various components and the steps taken to prevent and/or minimize reoccurrence.

What will the future bring to materials/or materials related processes? The application of composite materials for rotating components in compressors may be seen in the not so distant future. The application of refined existing processes to manufacture components to near net shape such as P/M net shape, HIP process, or metal rapid prototyping based on laser microwelding of metallic powders may also be seen.

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