CORROSION CONTROL IN INDUSTRIAL AXIAL FLOW COMPRESSORS

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ABSTRACT

Rotor blade, stator vane, and rotor disk or drum corrosion continues to be one of the leading causes of rotor failures in industrial axial flow air compressors, aero derivative turbine engines, and industrial gas turbines. Conventional 12 percent chromium rotor blades and low alloy steel rotors experience accelerated corrosion due to the presence of airborne corrosion contaminants.

This paper describes and shows a number of these corrosion related problems noted in various axial flow air compressors. The causes and solutions to those problems are discussed. The corrosion related problems have been found to be very much related to the compressor's location or local environment. Similar corrosive environments have been found at many compressor installations despite very different geographical locations, applications, or industry (air separation, cogeneration, offshore gas compression, refinery, steel mill, etc.). Various methods for the reduction or elimination of in-service corrosion problems are discussed including inlet filtration, online cleaning, material selection, material treatments, and coatings.

BACKGROUND

Industrial axial flow compressors and gas turbine compressor sections move large volumes of air for the process needs. In these large volumes of air there are often significant amounts of airborne debris, water, and potentially corrosive gaseous species that can combine under suitable conditions to form destructive acidic compounds. A wide variety of corrosive compounds can be formed in the various sections of the compressor as the compressed air conditions change.

The inlet sections of industrial air compressors generally operate at pressures that are below the ambient pressure. Typical compressor inlet pressures range between -0.014 and -0.035 kg/cm^{2}g (-0.2 and -0.5 psig). The reduced pressure in the inlet of the compressor can cause the separation of large amounts of water from the air, which can cause flow path erosion, deposition, fouling, and the formation of aggressive corrosive compounds.

Airborne corrosive species such as sulfur and nitrogen oxides readily combine with the moisture in the air to form corrosive acids. pH levels as low as 3.5 have been measured in a number of industrial axial compressor applications. Very few materials are capable of resisting this environment without some form of corrosion resistance enhancement.

The discharge conditions of typical industrial compressors normally run between 2.8 and 5.2 kg/cm^{2}g (40 to 75 psig) and 175 to 260°C (350 to 500°F).

CAUSES OF CORROSION

A majority of the industrial axial compressor corrosion problems are aqueous corrosion problems related to the formation of aggressive acids. The corrosive environment is often very complex with the presence of both sulfur and nitrogen bearing acids, as well as a variety of airborne salts. This is particularly true for coastal compressor installations. The presence and amount of corrosive species, moisture levels, and materials of construction determine the amounts and rates of corrosion. The inlet stages of the compressor are most susceptible to corrosion damage during normal operation of the compressor. The first four to six stages of the compressor are the most susceptible to corrosive attack due to the large amount of liquid water that is present in the early stages of the compressor. The presence of liquid water is due to the reduced operating pressures and the operating temperatures that occur in the inlet stages of the compressor. These stages generally operate at subatmospheric pressure and the gaseous water in the air condenses into water droplets that readily combine with the other airborne contaminants. As the air continues to travel through the compressor, the compressed air and water droplets increase in both temperature and pressure. The increased compression drives the liquid water back into a gaseous state. With the latter stages being the hottest and driest, the corrosion potential is greatly reduced despite the presence of the same corrosive compounds that exist in the early stages of the compressor. The amount of corrosion that occurs in the compressor is also very much related to the degree of flow path fouling that has occurred. Figure 1 shows typical compressor flow path fouling after several years of continuous operation. The fouling is due to both airborne particulate and gaseous species that are carried in with the air. The fine particulates that foul the compressor make an ideal place for the water droplets to form or agglomerate in the flow path. The flow path deposits are very harmful from a corrosion perspective, since the deposits also tend to hold the acidic conditions on the surface of the compressor blades and vanes. Figure 2 shows a set of installed inlet guide vanes from a compressor that has experienced significant flow path fouling that includes salt deposits. The lighter colored areas are salt deposits that have caused corrosion pitting of the base material. The corrosion pits can be readily seen centered in the salt deposits. Compressor component corrosion damage can be quite severe and readily seen in Figures 3 through 6. Corrosion pitting is the most common form of flow path corrosion damage. The damage shown in the photographs can lead to component mechanical failures if allowed to continue to progress.

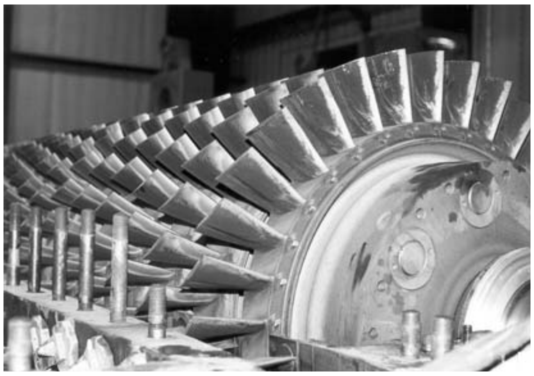

Figure 1. Typical Industrial Axial Flow Compressor Flow Path Deposits.

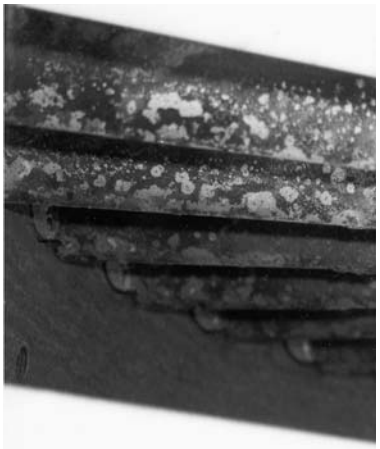

Figure 2. Inlet Guide Vane Deposits with Corrosion Pitting from Airborne Salts.

A number of preventive steps need to be taken in the compressor design, construction, and operation to prevent corrosion damage and subsequent component failures. These include:

- The judicious selection of materials.
- The mechanical and heat treatments of the materials in use.
- The use of corrosion resistant coatings.
- The reduction of corrosive compounds entering the compressor (air filtration).
- The minimization of liquids entering the compressor (air filter design and location of the compressor inlet are critical).
- The removal of corrosive compounds within the compressor (cleaning).

MATERIALS

Essentially all the major axial compressor manufacturers utilize the same materials of construction. The chosen materials are generally selected based upon mechanical strength, fracture toughness, ductility, vibration damping characteristics, manufacturability, corrosion characteristics, and cost. The material selection for the compressor flow path components is very important for minimizing the potential effects of corrosion.

Rotor Blading

A majority of the rotor blades for industrial axial flow compressors are manufactured from 400 series stainless steels (12 percent chromium (Cr)). The most common blade materials are AISI 403, 410, or 420 stainless steel. Although relatively scarce,

Figure 3. Corrosion Pitting on 410 Stainless Steel Inlet Guide Vane.

Figure 4. Corrosion Pitting on 403 StainlessSteel Rotor Blades.

Figure 5. Corrosion Pitting in an Alloy Steel Dovetail Blade Attachment Region.

Figure 6. Corrosion of 4140 Alloy Steel Balance Piston Region.

high-pressure ratio compressors with high discharge temperatures may utilize super alloys such as A-286 or Inconel® 718. Figure 4 shows significant corrosion damage to uncoated 403 stainless steel blading.

Under severe corrosive conditions, a number of the compressor manufacturers have upgraded the blade materials to hardenable martensitic stainless steels such as Carpenter® Custom 450, 15-5, and 17-4, or duplex stainless steels such as Irrubigo (25 Cr). These higher alloyed materials are generally very effective in preventing corrosion problems caused by the ingestion of airborne salts. Nonferrous alloys such as titanium (4 Al-6 Vn) have also been used in the most severe corrosive environments.

Rotor Disks/Drums/Stub Shafts

Essentially all rotor disks, drums, or integral rotors for industrial compressors are manufactured from low alloy steels such as AISI 4140 or 4340 (nickel (Ni), Cr, molybdenum (Mo) alloys). The lower alloying of the disk attachment region of a 4340 alloy steel rotor disk or drum material makes these components very susceptible to corrosion by the same corrosive species as the blades. The blade attachment regions of the rotor can be very susceptible to crevice corrosion, due to the collection of the corrosive species in the close clearance regions of the attachments. The lack of oxygen and the buildup of acids and contaminants within the tight gaps or crevices of the attachments are cause of aggressive corrosion. The dissimilarity in materials between the blades and disk also has a tendency to create anodic sites on the disk that can further promote galvanic corrosion. While the rotor components are more susceptible to the corrosion damage than the blading, the material is very forgiving of the damage due to robust designs, the high strength, and fracture toughness.

The corrosion potential of the blade attachment region is further accentuated due to the fact that most blade attachment designs do not allow for a thorough cleaning and inspection of the region during normal rotor overhauls and refurbishment and are often overlooked. This leaves the corrosive products and compounds in the attachment regions during subsequent rotor runs and allows for further corrosion damage to occur. It is well documented that corroded materials experience a significant reduction in material fatigue strength. Figure 5 shows corrosion damage in the dovetail attachment region of an alloy steel rotor disk. Figure 6 shows corrosion damage in the balance piston seal region.

Stator Blading

The stationary vanes of industrial axial flow compressors can show the same corrosion characteristics as that of the rotor blading. Figure 3 shows severe corrosion pitting of a 410 stainless steel variable inlet guide vane.

Stationary vanes of axial flow compressors are typically manufactured from the AISI 400 series (403, 410, 422) stainless steels and 300 series (304, 347) stainless steels (18 percent Cr, 10 percent Ni). The 400 series stainless steel vanes are far more susceptible to the corrosive attack than the 300 series stainless steels. In general, the 300 series stainless steels have been immune to corrosion damage from the acids formed in the compressor. Unfortunately, the 300 series stainless steels do not have adequate strength to be used as inlet guide vanes or for rotating parts.

Similar to the rotor blading, martensitic or duplex hardenable stainless steels (SS) such as Carpenter® Custom 450, 15-5, 17-4, or Irrubigo have also been successful in minimizing stator vane corrosion in many applications. In the most severe applications, titanium alloys have provided an even greater level of corrosion resistance.

The most commonly used base materials utilized for axial compressor flow path components are summarized in Table 1.

Table 1. Summary of Commonly Used Compressor Flow Path Materials.

Trade Name	Typical Industry Specification	Nominal Chemistry
Alloy steel	AMS 6414	Fe, 1.8Ni, 0.8 Cr, 0.25 Mo
403/410 SS	AMS 5611 AMS 5609	Fe, 12 Cr
420 SS	AMS 5621	Fe, 13 Cr, 0.35 C
300 SS 321/347	AMS 5645 AMS 5646	Fe, 18 Cr, 10 Ni
15-5	AMS 5658	Fe, 15 Cr, 5 Ni, 4 Cu
17-4	AMS 5643	Fe, 17 Cr, 4 Ni, 4 Cu
Carpenter Custom 450	AMS 5763	Fe, 15 Cr, 6 Ni, 1.5 Cu
Irrubigo	NA	Fe, 25 Cr, 5 Ni
A-286	AMS 5735	Fe, 25 Ni, 15 Cr, 2 Ti
Inconel 718	AMS 5663	Ni, 19 Cr 17 Fe, 5 Cb,3Mo
Titanium	AMS 4928	Ti, 6 Al, 4 V

MATERIAL TREATMENTS

Material Cleanliness/Quality

The cleanliness of the compressor flow path materials can have a major effect on the overall corrosion resistance of the material. Commercial grade materials tend to have a greater amount of impurities in the base material that can lead to inclusions and alloy segregations. The use of a multiple remelt manufacturing process such as vacuum or electro-slag remelting removes many of the impurities found in commercially produced materials and is highly recommended.

Heat Treatment

The corrosion resistance of most of the materials listed above is very dependent upon the heat treatment and resulting material hardness. Many of the materials in use should have a hardness less than Rc-23 to minimize corrosion damage.

Shot Peening

Shot peening of the typical compressor materials has been found to be effective in reducing the degree of corrosion. Materials under compression are known to have reduced rates of corrosion. Shot peening also has the major advantage of increasing the material's resistance to fatigue crack initiation. Many compressor blade failures initiate at the site of corrosion pitting or damage. Shot peening of both the airfoil and blade attachment regions is commonly performed. Care must be taken during the shot peening operations to prevent airfoil distortion and degradation of the flow path surface finish.

COATINGS

Flow path and rotor coatings have been an effective way to reducing compressor corrosion damage. Two basic types of coatings have been utilized for corrosion protection of the compressor flow paths: barrier and sacrificial.

- *Barrier coatings*—are overlay coatings applied to the flow path surfaces to prevent the contact of corrosive compounds with the base materials.

- *Sacrificial coatings*—are also overlay coatings that provide barrier protection, as well as being electrically conductive and interact with the corrosive compounds, providing corrosion protection to the base material. Sacrificial coatings can be damaged and still provide corrosion protection to the base material.

A number of coatings have been successfully utilized in industrial air compressors that include:

- *Electroless nickel*—a plated barrier coating
- *Nickel/chromium/cadmium*—a plated barrier or sacrificial coating
- *Silicone aluminum*—a paint-on barrier coating
- *Aluminum/ceramic*—a sacrificial coating

Many coatings such as the nickel and cadmium coatings are utilized less today due to the environmental considerations associated with metal plating processes used to apply the coating. The most widely used coatings today are the sacrificial aluminide coatings. These coatings have been very effective in reducing compressor component corrosion. Chromate and phosphate corrosion inhibitors/sealants are often utilized in the coating system to provide additional corrosion protection. The sacrificial coatings have the added advantage of providing corrosion protection to the base material despite imperfections in the coating.

While the application of compressor flow path components is commonplace, care must be taken to assure compatibility of the coating to the base materials and its suitability for the operating conditions. A number of coatings have been found to be incompatible with the base materials.

Completely assembled rotors have also been coated to minimize the corrosion potential of the rotor disk and/or drum. It must be remembered that coating over existing corrosion or corrosive species, in the attachment cavities, does not prevent further corrosion and can lead to both coating and component failures. The ideal condition for coating a rotor is to coat the individual components and then assemble the rotor.

Improved compressor performance and the reduction of flow path deposits have been added benefits to the use of flow path coatings.

INLET AIR FILTRATION

While most industrial axial flow compressors utilize inlet filtration systems, there are many installations that do not. Inlet filters are effective in reducing the amount of particulate, liquids, and some of the corrosive species such as many of the metallic salts from entering the compressor. It should be pointed out that many of the corrosive species (SOx and NOx) are not captured by the use of inlet filters. Many of these corrosive species enter the compressor in a gaseous form and deposit in the compressor due to the change in air conditions as the air is drawn into the compressor and compressed to higher pressures and temperatures. In addition, many of the corrosive salts can be washed through the filter elements during periods of high humidity or rain.

The removal of airborne particulate is most important because the particulate can deposit on the flow path surfaces, carry over corrosive species on them, and are nuclei for the formation and collection of water droplets. Today's modern inlet filter systems can be very effective with the removal of virtually 100 percent of particulate 5 microns or larger in size. The most effective filter systems are multistage filters that reduce the amount of moisture as well as particulate entering the compressor.

COMPRESSOR CLEANING

Periodic cleaning of the compressor flow path has been found to be quite effective in reducing the amount of compressor corrosion. Flow path cleaning has the tendency to remove many of the flow path deposits via either a liquid wash dissolving the deposit or an abrasive scrubbing of the deposits off the blade surfaces. The two most commonly used methods of cleaning the compressor are a liquid wash often referred to as water washing and an abrasive cleaning.

Water washing generally includes the use of a liquid detergent or solvent that helps to clean the surfaces of the flow path. Cleaning is accomplished both chemically as well as by a scrubbing action of the liquid media droplets. Many of the commercially available cleaning solutions also contain surfactants that help prevent the deposition of particulate onto the blade path surfaces. Compressor washing is most effective if performed on a regular basis. It is common in many installations to water wash the compressor every few days (72 hour intervals). The prevention of flow path deposits is a far more effective approach in maintaining compressor performance and in the prevention of corrosion, rather than trying to remove heavy deposits that have built up over long operating periods.

Abrasive compressor cleaning is accomplished by injecting an abrasive media into the compressor inlet during normal operation. Walnut shells, rice, fluid catalytic cracking (FCC) catalyst, glass beads, and other media have been utilized. The size and quantity of the cleaner are important for obtaining a good flow path cleaning and not causing damage to the compressor flow path components. Aggressive abrasive cleaning can readily cause erosion damage to both the corrosion resistant coatings and the compressor airfoils.

Compressor washing and abrasive cleanings can be accomplished both on and off line. Online cleaning can be performed with minimal effects on the process operation. Unit operators should be prepared for rapid changes in the compressor flow from heavily fouled compressors. Due to the fact that both the liquid and the abrasive cleaning media are centrifuged outward in the flow paths, the online cleaning is generally most effective in the first few stages of a compressor. Despite the fact that only a few of the compressor stages are being cleaned, the capacity of the compressor is greatly affected because the first few stages of the compressor typically set the flow capacity of the unit.

Partial speed or slow roll cleaning is much more effective in cleaning more of the compressor stages than the full speed cleaning. Prior to performing a partial or slow speed cleaning of the compressor, care should be taken to identify and avoid rotor, coupling, or blading natural frequencies or critical speeds through the entire train.

COMPRESSOR SHUTDOWN CORROSION

As previously discussed, a majority of the corrosive species typically found in the compressor are aqueous in nature (i.e., they require the presence of water to cause corrosion). These corrosive species do exist in all stages throughout the compressor, but are not necessarily active due to the individual stage operating conditions (pressure and temperatures).

Many of the corrosive compounds in the compressor are hydroscopic in nature (i.e., they pick up and absorb water from the atmosphere). These deposits will often become saturated during a unit shutdown. During these conditions, the later stages of the compressor become subjected to the same corrosive compounds as the early stages of the compressor. The normally inactive corrosive compounds can become quite active and aggressive for even short-term exposures.

Experience has shown that cleaning and drying the compressor on shutdown can minimize the effects of shutdown corrosion. In addition, a number of compressor installations have installed air heaters, dehumidifiers, or nitrogen purges to keep the compressor warm and dry during the unit shutdown conditions. This is particularly important in process applications that "steam out" the system during a unit shutdown.

These shutdown concerns carry over into the storage of the compressor rotors and stator vanes. After removing from service, these items should be thoroughly cleaned immediately on unit shutdown to remove any flow path deposits. Too often, the removed compressor components are put aside for future disposition after the unit turnaround is completed. During these idle periods, significant corrosion damage can occur.

CASE STUDY I— COASTAL REFINERY

Many axial flow compressors utilized in refinery applications (generally as fluid catalytic cracking air blowers) experience severe in-service corrosion. The corrosion is the result of airborne sulfur, ammonium, chloride salts, and occasionally fluorides. High levels of airborne salts are often noted in these coastal applications. The presence of hydrated corrosive compounds created very aggressive acidic conditions and resulted in severe compressor flow path corrosion.

The original material of construction for both the rotor and variable stator blading in the subject compressors was the commonly used 403 SS. The original material of construction for the stator vanes was 347 SS.

Significant corrosion pitting was noted in the early stages (stages 1 through 4) of the compressors, and a number of blade failures were experienced as a result of the corrosion damage. The flow path corrosion damage was occurring in as little as one and one-half years of operation.

Initial attempts to mitigate the corrosion included the application of a sacrificial aluminide flow path coating. The coating was found to provide a significant reduction in the flow path corrosion. Problems were noted with the life of the coating in the first several stages of the compressor. Portions of the blade airfoil were experiencing erosive wear of the coating due to the ingestion of airborne particulate and water droplets. In addition, spalling of the protective coating could be noted in crevice regions such as the blade attachment region of the rotor blades.

The rotor blade and stator vane materials were upgraded to an uncoated Carpenter® Custom 450 material in several applications with good success. In one installation, the extremely aggressive corrosive environment also caused severe pitting of the Custom 450 material (Figure 7). Titanium alloy flow path components were implemented in this application with excellent success (Figure 8). Rotors that were experiencing significant corrosion damage in as little as 18 months of operation have now been able to achieve operating campaigns in excess of five years with minimal if any corrosion damage.

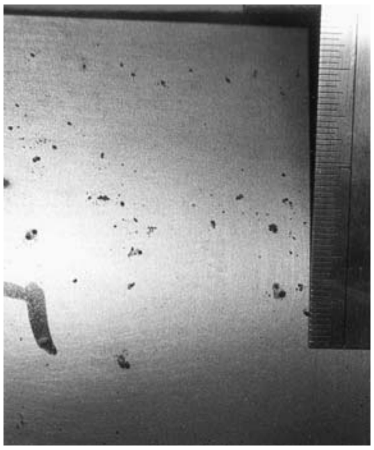

Figure 7. Corrosion Pitting of C450 after 18 Months of Service.

Figure 8. Upgraded Rotor Assembly Utilizing Titanium Alloy and C450 Blades, and a Coated Rotor Body.

CASE STUDY II— STEEL MILL

A major United States steel company had experienced significant axial compressor rotor blade and stator vane corrosion in several of the company's locations. Despite the mills having drastically different locations (midwestern and eastern United States), deposits removed from the main air compressors showed surprisingly similar results. The primary corrosive species were various sulfates and ammonium hydroxides.

The original material of construction for both the rotor blading and stator vanes was 403 SS in several compressors and 420 SS in a number of other compressors. Both materials were found to be inadequate due to corrosion pitting problems. Significant corrosion pitting was noted in the early stages (stages 1 through 6) of the compressors and several blade failures were experienced as a result of the corrosion damage. The flow path corrosion damage was occurring in less than two years of operation.

The front-end stages of the compressors were upgraded from the conventional 12 percent Cr stainless steel to hardenable stainless steels. Carpenter® Custom 450 was utilized with success in one installation, while Irrubigo was used successfully in the second installation. The differences in material selection were related to different original equipment manufacturers.

SUMMARY/CONCLUSIONS

- Flow path corrosion continues to be a major cause of component failures in industrial axial flow compressors.
- Industrial compressor corrosion is caused by a number of airborne corrosive species that tend to form aggressive acidic conditions.

- Flow path corrosion can be minimized in the compressors.
- Corrosion control is best accomplished by a multiphase approach that includes:
    - Minimizing the source of contaminants.
    - Upgrading the compressor materials of construction to address known contaminants.
    - Utilizing corrosive resistant coatings.
    - Utilizing improved inlet filtration to reduce the amount of flow path deposits and erosion.
    - Utilizing improved inlet filter designs to reduce the amount of moisture and corrosion compounds entering the compressor.
    - Keeping the compressor flow path clean with online cleaning.
    - Keeping the compressor clean and dry during unit shutdowns.

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Carpenter® Custom 450 is a trademark of the Carpenter Specialty Metals Company