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OPTIMIZATION OF CRA IMPELLERS HANDLING CHLORIDES AS CONTAMINANTS -A CASE STUDY

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ABSTRACT

Centrifugal compressors are widely used in gas lift and gas gathering and transportation services. The gas from well generally have some contaminants like H2S, C02 and chlorine which are detrimental to structural integrity of impellers caused by Stress induced corrosive cracking (SCC). To mitigate such issues CRA (Corrosion resistant alloys) are used based on operating environment and corrosion agents. A well deliberated study can not only control the phenomena but also avoids using more expensive alloys than required. This paper discusses various aspects of diligent selection of CRA impellers of Centrifugal Compressors handling Chlorides as contaminants through a case study.

KEYWORDS: Optimization of CRA Impellers Handling Chlorides as Contaminants

INTRODUCTION

In the late 1990's, the NACE Task Group (TG) 081, began working on a complete rewrite of MR0175 that included a number of fundamental changes. One of the most significant proposed changes was the expansion of the scope of the document to include chloride stress corrosion cracking (SCC), based upon the fact that most oil and gas production streams contain chlorides in sufficient levels to cause SCC in susceptible alloys. The rewrite proposed that the temperature limit for type 316 stainless steel be set at 60°C as maximum. For petroleum refineries, where chloride ion concentrations tend to be low enough that chloride SCC isn't a common concern

Stainless steel are alloys of iron, chromium and other additives which resists the corrosion. The chromium of steel combines with oxygen to create a tenacious, ultra-thin layer of chromium oxide which is stable to create a passive film barrier between steel and environment. When chloride ion is attacked on steel at weak spots (spots with high dynamic or residual stress), it cannot further construct the passive film and "pitting" occurs. Further to this phenomena, if operating / residual stresses are combined, then Chloride induced stress corrosion cracking (CSCC) occurs. The cracks on the surface due to CSCC can be easily distinguishable as lighten bolt strike type pattern on surface. Chloride content, pH, temperature, stress, presence of oxygen and alloy composition are critical factors for CSCC occurrence.

There are certain influencing factors related to Chloride stress corrosion cracking which are listed below for a quick recap -

- All 300 Series SS are highly susceptible. • Duplex stainless steels are more resistant, Nickel base alloys are highly resistant
- Increasing levels of chloride increase the likelihood of cracking.
- No practical lower limit for chlorides exists because there is always a potential for chlorides to concentrate.

- Heat transfer conditions significantly increase cracking susceptibility because they allow chlorides to concentrate. Alternate exposures to wet-dry conditions or steam and water are also conducive to cracking.
- SCC usually occurs at pH values above 2. At lower pH values, uniform corrosion generally predominates. SCC tendency decreases toward the alkaline pH region.
- Cracking usually occurs at metal temperatures above about 60deg C although exceptions can be found at lower temperatures.
- Stress may be applied or residual. Highly stressed or cold worked components are highly susceptible to cracking.
- Oxygen dissolved in the water / gas normally accelerates SCC but it is not clear whether there is an oxygen concentration threshold below which chloride SCC is impossible. Critical Factors • Chloride content, pH, temperature, stress, presence of oxygen and alloy composition are critical factors.
- Increasing temperatures increase the susceptibility to cracking.
- Increasing levels of chloride increase the likelihood of cracking.
- No practical lower limit for chlorides exists because there is always a potential for chlorides to concentrate.
- Nickel content of the alloy has a major effect on resistance. The greatest susceptibility is at a nickel content of 8% to 12%. Alloys with nickel contents above 35% are highly resistant and alloys above 45% are nearly immune.
- Low-nickel stainless steels, such as the duplex (ferrite-austenite) stainless steels, have improved resistance over the 300 Series SS but are not immune.
- Carbon steels, low alloy steels and 400 Series SS are not susceptible to Cl-SCC subject to working under specified stress limit.

It is known that CSCC initiates with pitting and three contributors present together -

Moisture, temperature, oxygen environment, Chlorine in ppm (salinity)

Introduction to Materials Commonly Used in Centrifugal Compressor Impellers

CA6NMare used as impellers in centrifugal compressors in wet sour natural gas production which is a cast, low-carbon martensitic stainless steel. The popularity of this material stems from its reasonable cost and the need for higher strength, stainless materials to obtain optimum performance of the compressor The susceptibility of martensitic stainless steels to sour environments, especially when significant chlorides are present is well known. At low temperatures, sulfide stress cracking (SSC) is the main damage mechanism with synergistic effects from chloride stress cracking. Vitale et al conducted a study to define a safe chloride limit where these materials could be used up to the material yield strength. The result seemed to indicate that 100 to 300 ppm chlorides were the limit.

Duplex stainless steel consists of approximately 50 -50 ferritic and austenitic material with high strength of ferritic steel and corrosion resistance of austenitic steel. In sweet service as defined by NACE, these materials are suitable at temperature up to200 degC for high salt concentration. In sour service the susceptibility of Stress corrosion cracking is found at 70-80 degC. The presence of oxygen these steels are susceptible to pitting corrosion and phenomena is exponentially increased with chloride ion presence

Nickel Alloys – Those alloys containing more than 40% of nickel have excellent corrosion and pitting resistant capability till there is no oxygen and compressor suction temperature is below 90 degC.

Case Study

There were 4 centrifugal compressors installed in a gas gathering station which used back to back impeller configuration. The impellers were of @ 500 mm diameter and were made of martensitic stainless steel (X1213Cr). They have been operating for more than four years. After a scheduled inspection of compressors after two years of operation, the impellers were found to be in good condition.

As the well started depleting, a further boost in compressing gas was necessitated and design review concluded to change the bundle with increased operating speed. The preliminary design suggested to increase one stage using larger diameter impellers. Purchaser's design audit revealed that X1213Cr (ASTM A276 Gr410), cannot meet the stresses generated using 630 mm diameter impellers and with increased RPM using the following formula -.

σ = [u2 squared x ρ] / C N/mm2 where u is peripheral velocity of impeller (over-speed trip speed) in meter / sec, ρ is density of impeller material in kg / m3 and C is constant based on impeller flow coefficient. <1>

Based on above, it was proposed to use 17-4 PH impellers. This is a precipitation hardened stainless steel (ASTM A 705) used widely in centrifugal compressor having compatible mechanical properties with high strength and tackle droplet erosion when liquids are carried over in gas. Taking NACE MR0175 as guide note, it was suggested to keep the hardness of impeller material less. After selecting the impeller material, the attention was on contaminants of gas on which Chloride was dominant as contaminant as shown in Process design basis. The chloride contents were shown as @ 300 ppm to 1500 ppm based on case to case basis.

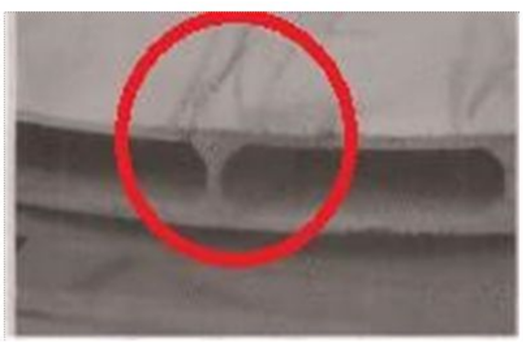

Figure 1: Stress Corrosion Cracking Initiation in Impeller Tip

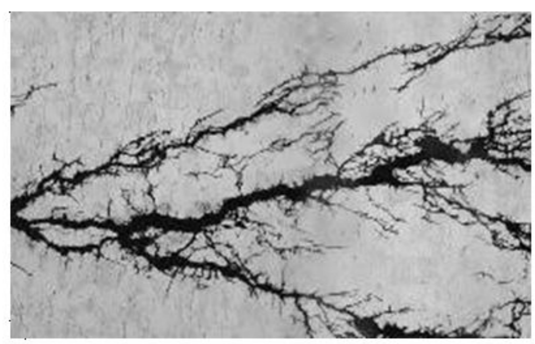

Figure 2: Shape of CSCC Crack

Based on some failures of 17-4 PH impellers centrifugal compressor in saline environment in gas industry, OEM (Original Equipment Manufacturer)offered to use Inconel 718 material for all six impellers. This means 24 numbers of impellers were to change from 17-4 PH grade to exotic Inconel 718 grade steel. This change had consequential schedule and cost impact on project.

Past experiences and available knowledge of metallurgy, together with the workability (e.g. weldability) and other economic factors, two materials were considered to tackle chloride contaminants for operating environment of centrifugal compressor impellers -

A. martensitic stainless steel X12Cr13 (AISI 410) forged; B. nickel-base Inconel 718 (UNS N07718)

A detailed analytical study carried out by purchaser's engineering team as it was found that removal of moisture and chlorides needs a major modification which does not match the schedule requirement and plant layout.

Analytical Study

It was found that 12X13CR impeller did not get affected by CSCC as impellers were found in very good condition. To investigate further, one impeller was used for further testing for typical CSCC cracking and pitting. It was confirmed that 13Cr steel impeller was fully tolerant to such level of chloride. As explained earlier, 13Cr impeller could no longer be used due to higher combined stresses during impeller rotation.

Investigation on Protective Coating

As known 17-4 PH was a very sought after material for impeller, idea and available methods of undertake application of protective coating were also carried out. For the purpose of meeting rotor-dynamic stability only spray able type ceramic coating were explored. It was realized that such action is plausible only when a series of tests are carried which is quite time consuming as coatings require some heat treatments which thereby compromises the strength of material. It was the concern of end user that proven-ness of such coatings were not established with their existing machines in operation. It is necessary to introduce EN technique to readers on same context.

Electro less Nickel deposition technique is one of the technique which can tackle salt deposit on those impellers which are handling relatively dry gas with chloride. This can be applied in any complicated shape. Although it is ametallic coating but does not have crystalline microstructure, rather it has an amorphous microstructure just a metallic glass.

Threshold Limit of Stress to Trigger CSCC

It is known that corrosive environment can create a potentially dangerous situation if static stress or vibratory stress or combination of two are higher at certain point of operating regime of centrifugal compressor. Mechanical strength study of 17-4 PH impeller was carried out in two parts – Static analysis using FE method. Impeller blade in respect of lean and thickness were checked from family of impeller supplied by OEM under confidentiality agreement and found to have satisfactory performance record. Static analysis using KINH table (nonlinear material properties) confirmed the design adequacy of impeller in over speed, aerodynamic loads.

A full scale dynamic analysis was performed using Campbell diagram and SAFE (Singh advanced frequency evaluation) interference diagram to check if the impeller natural frequencies are excited by diffuser – impeller interaction. This exercised confirmed that impellers are structurally sound and safe. The maximum stresses are generated at tip of impeller and if required the scalloping of impeller was agreed to carry out if required by outcome of modal analysis. This activity can lower the performance of compressors in terms of decimals. Nevertheless, calculation output suggested such modification was not required.

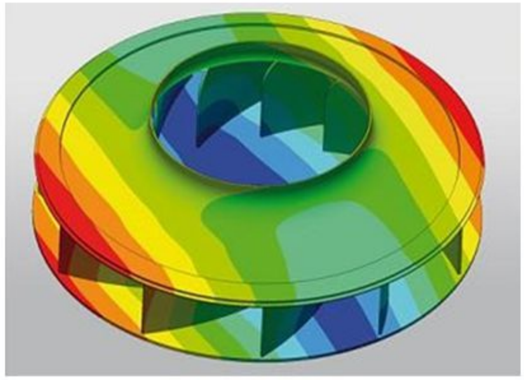

Figure 3: Finite Element Analysis of Impeller – Stress Profile

Stress Intensity Factor

It is known that SCC does not occur / crack shall not propagate below a threshold limit of stress. During manufacturing and its geometry, a mechanical item may have notches, sharp changes in profile, residual stresses etc. To quantify the CSCC, fracture mechanism technique is applied to find stress intensity factor (SIF). Below a certain stress intensity factor stress corrosion crack does not propagate.

The crack propagation life prediction is studied based on the fracture mechanics. First the finite element structure strength analysis is carried on the three dimensional entity model of the impeller, and the concerned area of the structure is identified.

Then based on geometric similarity principles, a simplified two dimensional model of the area is established.

The fatigue life prediction method and calculation procedure of the impeller structure is summed up based on the fracture mechanics.

ΔKH (threshold intensity factor for the material) is determined by using fatigue crack growth rate data available from OEM or using bellow relationship **ΔKH =6.4 (1-0.85R) Ksi**$\sqrt{in}$

Normally, for martensitic steels a value of 3.6 Ksi$\sqrt{in}$ can be used.

Calculation result shows that the axial crack growth rate exceeds the radial expanding rate on the crack face, the axial stress intensity factor is greater than the radial stress intensity factor, and the stress intensity factor of the crack front increases with the increase of the crack radius of the 3-D crack front of the compressor impeller hub axle hole.

In determining both the probability of failure and the consequence of failure by cracking processes the techniques of fracture mechanics may be very valuable. Ashby and Jones have given a very clear introduction to these techniques, and we shall only attempt to summarize the theory here. Fracture mechanics is concerned with the mechanical conditions at the tip of a crack, and the properties of the material that determine whether or not that crack will propagate. Providing the region of plasticity at the tip of the crack is small compared to the crack length and the thickness of the specimen, we find that the stress state at the crack tip is defined by the stress intensity factor, K, given by:

K = Σ √ (Πay)

Where = applied stress, a = crack length Y = geometrical correction factor (»1). It is imperative to take care of required thickness of the zone which are more prone to develop cracks. This phenomenon should be considered while designing keyed impeller than to shrink fit impellers for centrifugal compressor. The subject compressor had shrunk fit impellers and hub were protected by shaft sleeves.

A specific thermodynamic calculation using HYSYS was carried out to find out water dew point at entry of compressor impeller and they are slightly lower than gas temperature at suction of compressor. Then a stage wise calculation was carried out to see the gas temperature at entry of each consecutive impeller stages. As the gas was carrying traces of TEG (Tri ethylene glycol), this also was construed as carrier of chlorides. Later on HYSYS bulletin clarified that TEG should not construed as moisture content in gas.

As per calculation, gas temperatures at 2nd impeller of both stages were above water dew points even for worst Case. Hence no liquid drops out is expected. Besides this, it was finally concluded that process hydrocarbon gas does not possess any Oxygen which also acts as contributing factor to CSCC.

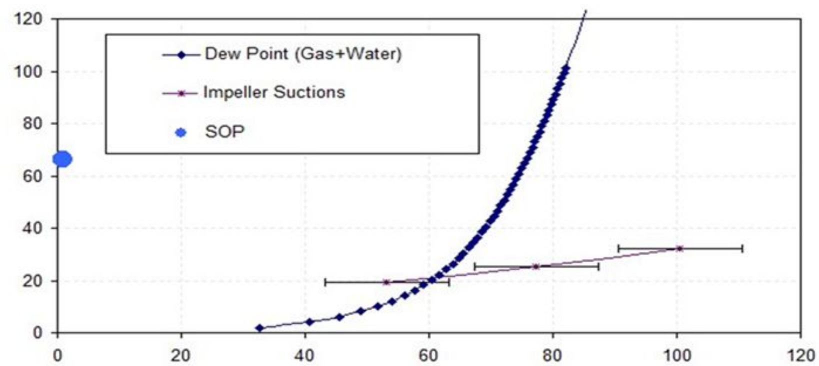

Figure 4: Dew Point Analysis of Gas Entering Into Compressors

The new process datasheet was prepared to be shared with OEM as contaminants 2380 ppm of Chlorides (worst case) and zero percent oxygen content and 15 ppmv H2S which are solely determinant for the changes of the material.

After good deliberation with OEM, the above material was jointly agreed upon. Based on assurance that compressors shall not see the condensation (gas blowdown after every four hour Settle out Pressure conditions casing weld overlay with SS 316 was agreed.

This perpetual study undertaken by engineering team from purchaser not only optimized the exotic CRA material but also created a benchmark and clear understanding among OEM, Purchaser and End user.

CONCLUSIONS

Effect of Chloride stress induced corrosion cracking must be taken well before detailed engineering commencement by OEM. It is imperative to utilize multidisciplinary knowledge and data bank of OEM and End User.

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