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# MATERIALS SELECTION AND DEVELOPMENT FOR CENTRIFUGAL COMPRESSORS OPERATING IN EXTREME SOUR & ACID GAS SERVICE

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## ABSTRACT

The rising demand for oil and gas has led us to exploit oil fields and gas reservoirs with increasing amounts of contaminants. Reserves of natural gas are abundant, but about 40% of the fields contain high concentrations of hydrogen sulfide, carbon dioxide, and chlorides. The harshening environment represents a challenge for the suitability of common classes of materials used for design and manufacturing of centrifugal compressor components.

According to NACE MR0175/ISO15156, a fit-for-purpose approach has been extensively used to prove the steel's resistance in simulated field conditions and characterize the environmental limits of most martensitic and precipitation hardening stainless steels in terms of partial pressure of carbon dioxide, hydrogen sulfide, and chlorides. The literature available on the subject generally agrees that the contaminants' concentration levels exceed the possibility of risk presented by stainless steels to turbo-machine reliability, and in worst cases to operators' safety. Nickel-based alloys are the most robust solution to overcome the above limitations, guaranteeing high mechanical strength and resistance against stress corrosion cracking mechanisms in expected compressors' environments.

This paper describes the advance in nickel-based alloys' application and production of centrifugal compressors (CC) for extreme sour and acid conditions, with work that reveals the development of alternative manufacturing routes for rotor and stator components in turbomachinery. A detailed explanation of nickel-based alloys' metallurgy, application and manufacturing capability is also given, along with recent developments of new alloys to bridge the gap between iron-base and nickel-base alloys, providing cost effective materials with enhanced corrosion resistance.

## INTRODUCTION

Increasing energy costs and growing demand for natural gas have driven the development of sour gas fields around the world. Nearly 40% of the world's gas reserves contain levels of carbon dioxide (CO2) and hydrogen sulfide (H2S), with compositions exceeding 10% volumetric of the raw produced acid gas with, in most cases, contaminant or other unacceptable components including heavy hydrocarbons, mercaptans, mercury, and water. Because of specific refinery treatments involved, safety implications, and heavy detrimental effect on materials performance, the sour gas management is becoming a key challenge for oil companies and equipment manufacturers.

While the cost-effectiveness of technological solutions is a crucial factor for the future of sour gas development, safety for people and the environment is an equally requisite dimension.

For this reason, designing equipment for such harsh environments -- especially the high pressure centrifugal compressor -- requires deep knowledge of thermodynamics of gas mixture, high-tech sealing systems, material science, manufacturing technologies, and quality.

Material selection takes into account all parameters affecting alloys' behavior, with respect to the several phenomena able to compromise material ability to withstand the gas environment, such as general and localized corrosion, stress corrosion cracking, and low-temperature toughness dropping. In gas management systems, the above mentioned phenomena are associated to wet/dry conditions, partial pressure of hydrogen sulfide and carbon dioxide, and the amount of secondary contaminants (i.e. halides) that might generate unexpected failure of components.

Equipment manufacturers have gained experience by facing field issues and developing specific solutions to maximize the amount of contaminants tolerated by gas compressors and optimizing cost-effective answers for demanding applications. This is often done by imposing additional restrictions over the limits, defined by international standards and specifications (i.e. NACE MR0175/ISO15156), and aimed at minimizing risk of dramatic failures able to compromise the gas treatment facilities operation.

In recent years, nickel alloys have been the safer solution to deliver reliable products and maximize the service life of compressors, but their complex metallurgy and manufacturability routes are critical aspects to be carefully managed by manufacturers.

## DESIGN SPACE

Operating in extreme sour and acid environments requires specific attention from a design standpoint, particularly for components in contact with the process gas and with an increasing design margin based on safety considerations. Parts specifically requiring attention correspond to (Figure 1):

- Pressure retaining components, such as casing and covers
- Rotating components, such as shaft, impellers, balance drums, and spacers
- Internal static components, such as inner casing and diaphragms
- Sealing components, such as Dry Gas Seals (DGS) and gaskets.

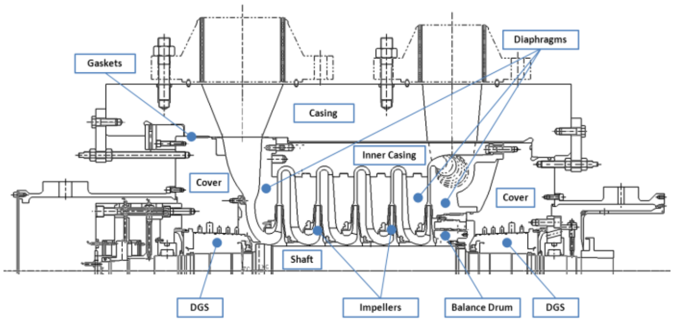

**Figure 1 Main Compressor Components**

Evaluating the operating environment should not be restricted to normal service operations, including settle-out conditions, but should also look to potential transients or well depletion, where some peaks of aggressiveness may occur. This part is directly related to the overall process of the plant and its dynamic, and should be handled by the equipment end-user. It's important that the results of process analysis in upset conditions clearly appear in the project specifications, because they could considerably affect design choices.

*Condensed Water or Moisture*

The presence of condensed water or moisture is an essential factor in failure mode risk analysis, while the absence of liquefied water (i.e. dryness) is sufficient to prevent any kind of concerns regarding general corrosion, galvanic corrosion, pitting, or other stress corrosion cracking phenomena, and shall therefore be specifically well computed in the design phase. The wet areas require dedicated material selection, whereas dry areas could be easily handled by CS (Carbon Steel) or LAS (Low Alloy Steel), with an evident influence on raw material cost and machinability.

It is very common that the compressors' inlet stream exits from the scrubber (i.e. separator) and falls in the water dew curve, resulting in an aggressive environment. For the definition of the wetness/dryness operations across the compressor, the dew curve of the gas shall be computed. For typical Acid Gas applications, Peng-Robinson equations of state are generally recommended (Figure 2).

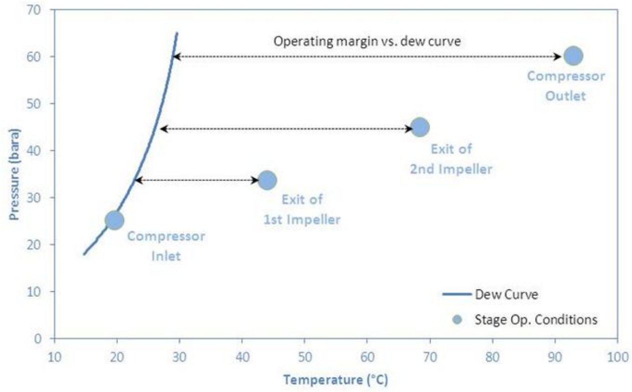

**Figure 2 Operating margin vs. dew curve**

In view of possible uncertainties regarding precise gas composition or tools accuracy, the standard recommendation is to consider a safety separation margin of 10°C between the real operating conditions vs. the dew curve (i.e. the operating conditions of a given stage shall be 10°C degrees hotter than the dew point to be consider dry).

Obviously, such analysis shall not be restricted to stabilized operations, but it should also look to the complete expected operating envelope of the machine, from surge to choke area. Thanks to the high compression on the surge side, this area is generally the most favorable, whereas the choke area is traditionally the design case.

*The partial pressures of acid gas and the related corrosion mechanism*

Sweet corrosion refers to corrosion phenomena primarily caused by dissolved carbon dioxide. The basic $CO_2$ corrosion reaction mechanisms have been well understood and accepted by many researchers through the work done over the past few decades, and its effects on CS and LAS under varying conditions of pressure, temperature, and pH have been widely researched. As well, authors de Waard [1] and Dugstad [2] have proposed models to predict its rate.

Carbon dioxide gas dissolves in water, forming a “weak” carbonic acid through hydration by water. This acid reacts with steel to form loose iron carbonates that tend to spall from its surface, generating a progressive general material loss defined as “general corrosion.” The CRAs (Corrosion Resistant Alloys) develop a passive film on the surface that blocks the carbonic acid’s reaction with the iron and serves as a reliable solution in $CO_2$ containing environments.

Corrosion caused by the combined presence of dissolved carbon dioxide and hydrogen sulfide is called sour corrosion. While various authors have written about the interactions of H2S with carbon steels, the understanding of the effect of $H_2S$ on $CO_2$ corrosion is still limited because the nature of the interaction with CS is complicated. Three different corrosion regimes have been identified based on the ratio between the two gases as reported below:

- For $CO_2/H_2S$ ratio < 20, the corrosion is fully governed by $H_2S$. In this case, $H_2S$ lowers the solution pH as it acts as a weak acid, like carbonic acid. It can also increase the corrosion rate by providing an extra cathodic reaction related to the direct reduction of $H_2S$. The primary corrosion product is a non-stoechiometric iron sulfide (FexSy), with varying protective properties depending on its crystallographic structure.
- For high $CO_2/H_2S$ ratio, the corrosion rate is fully governed by $CO_2$, even if the iron sulfide (FeS) film could interfere with the formation of the carbonate scale (FeCO3) [3]. The limit ratio is generally taken as 500, but depends on environmental variables.
- For intermediate ratios, the corrosion regime is complex and difficult to anticipate. In fact, the kinetics of scale formation in the $CO_2/H_2S$ system is complicated and still not understood well. The makeup of the surface scale under these conditions will not only depend on the chemistry of the brine and the respective solubility of iron carbonates and iron sulfides, but also on the competitive kinetics of the two scale formation mechanisms [4].

Another main effect of $H_2S$ on materials is a generation, under specific conditions, of a phenomenon known as sulfide stress corrosion cracking (SSC). The mechanism involves diffusion, generated by corrosion, of hydrogen atoms in the metal. SSC can occur only if the following three conditions are verified:

- Tensile stress (residual and/or applied)
- $H_2S$ + condensed water
- Material prone to SSC damage

The maximum SSC susceptibility occurs around ambient temperature [5]. CS and LAS, in proper heat treatment conditions and with an optimized metallurgy, are generally not susceptible to SSC. CRA, however, can be very susceptible to this cracking mechanism, depending on the alloy family, chemical composition and microstructure. Most CRAs exhibit a threshold strength in $H_2S$ that depends on pH and other contaminants in the water solution, under which the material can be safely used.

Another corrosion mechanism in the sour environment is HIC (Hydrogen induced cracking), which occurs when the atomic hydrogen generated by the corrosion reaction diffuses through the steel, accumulating as molecular hydrogen corresponding with non-metallic inclusion. This occurs particularly when these inclusions have been flattened by rolling operations or at bands of segregation or perlite when the local $H_2$ pressure generates cracks and blisters on the material. HIC is generated by the following conditions:

- Atomic hydrogen source (i.e. H2S) and condensed water
- Material prone to HIC damage

If only $H_2S$ is present, forged carbon or low alloy steels with a controlled cleanliness (low level of non-metallic inclusion) are suitable for service.

*Contaminants in the water (i.e Chlorides)*

Chlorides are a major contaminant to be considered in the design phase. Chloride content directly influences the localized and stress corrosion mechanism occurring mainly on susceptible CRA under certain conditions. Pitting and Chlorides Stress Corrosion Cracking (CSCC) can be faced on compressor components with different effects and associated risks, directly related to the part under examination (i.e. stator component can tolerate pitting due to low stress conditions, impeller in general cannot). Chlorides, like other contaminants such as halides, arsenic (As), antimony and cyanides (CN-) assist and increase the severity of the SSC by acting on passive film formation, or as a catalyst by increasing hydrogen atoms’ concentration on the surface and preventing their recombination in hydrogen molecules. Chlorides’ effect on CRA is generally maximized at high temperature [6].

*Stress distribution*

When selecting Corrosion-Resistant Alloys, due to susceptibility to stress corrosion cracking mechanisms, the stress load on the components shall not exceed the threshold stress of the material in the given environment. Whenever feasible, stress distribution in sour and acid application should be maintained in the lower ranges of materials’ structural performances.

## MATERIAL SELECTION BY STANDARDS

Once design space is defined, material selection should be optimized to achieve sufficient safety margins, with respect to the corrosion mechanisms described.

Indications on material selection from international standards can be good friends or dangerous enemies, depending on service experiences presented to standards committees on specific application, particularly for uncommon components like compressor parts. Manufacturer experiences are taken into consideration, specifically when they result in additional standards restrictions. NACE (International Association of Corrosion Engineers) developed several documents to define correct material selection in sour services relative to the SSC phenomenon. Of these, the most relevant are the NACE MR0175/ISO1515 (Materials for use in $H_2S$-containing environments in oil and gas production) and the NACE MR0103 (Materials Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Environments). These standards place limits and restrictions to the specific classes of alloys for different equipment. The NACE MR0175/ISO15156-3:2009, in particular, contains the indication of material selection on compressors for Martensitic Stainless Steels (i.e. UNS S4100, S41500) and Precipitation Hardening Stainless Steels (i.e. UNS S17400 or S15500) with restrictions on heat treatments, hardness and threshold strength (Table 1).

**Table 1 Extraction from NACE MR0175/ISO15156-3:2009**

| Material Class | Table | Restriction | Special Requirements |
|---|---|---|---|
| Martensitic Stainless Steels | A.22 | • Any combination of temperature, pH2S, chloride concentration and in situ pH occurring in production environments is acceptable.<br>• Double tempering heat treatment in specific ranges<br>• Hardness below specified limit (i.e.22HRC for S41000; 23HRC for S41500) | • If used for impellers shall exhibit a threshold stress ≥95% of actual yield strength in the anticipated service environment. |
| PH Stainless Steels | A.30 | • Any combination of temperature, pH2S, chloride concentration and in situ pH occurring in production environments is acceptable.<br>• Double tempering heat treatment in specific ranges<br>• Hardness below specified limit (i.e.33HRC for S17400) | • For use as impellers at higher hardness (strength) levels, these alloys shall be tested in accordance with Annex B at a test stress level of at least 95 % of AYS;<br>• If used for impellers at a hardness of > 33 HRC shall exhibit a threshold stress ≥ 95 % of AYS in the anticipated service environment |

The standard for martensitic stainless steels clearly indicates use without restriction, in any oil and gas environment for all the components other than impellers (to be tested at 95% of the actual yield strength).

Even wider application is left to the precipitation hardening stainless steels. If the hardness of the 17-4PH is maintained below the defined hardness limitation, there is no restriction in any oil and gas environment for all components, including impellers and pressure retaining vessels.

Above all implications that can lead to mistaken selections is the fact that the NACE is mainly considering SSC and SSC assisted by chlorides as failure modes. This doesn't take into account the implications related to localized corrosion, or same case chlorides stress corrosion cracking. Unfortunately, there are few indications on other international standards about these topics. The NORSOK M-001 standard helps define minimum requirements and maximum allowable temperatures for corrosion mechanism to occur on few materials classes; the ISO 21457 indicates selection options, based on possible contaminants in oil and gas on specific applications with no reference to compressors; and the API617 gives high-level restriction to materials' properties, without detailed references to corrosion mechanisms. None of the mentioned standards offers a comprehensive approach to the material selection, and these results in manufacturers and end-users relying on their own field experience or building a proprietary design practice through specific testing activities.

## FIELD EXPERIENCE

A continuous lesson learning approach is the best attitude for developing knowledge and practices. Real application challenges highlight serious leaks in the scientific or technical understanding of some phenomena, and failures raise concerns about international standards indications and encourage us to engage in innovation practices.

CRA, for their susceptibility to localized and stress corrosion mechanisms, most commonly fail in oil and gas use. In compressors, due to the higher stresses involved with the rotating parts, the impellers are most highly affected.

Figure 3 shows a typical example of impeller failure under the simultaneous attack of sulfide stress corrosion cracking, assisted by chlorides on a precipitation hardening stainless steel (UNS S17400) impeller. In this example, the material was in NACE MR0175/ISO15156-3 condition (hardness and heat treatment) and operating within the limitations reported in Table 1. Figure 4 shows the intergranular crack propagation typical of this phenomenon.

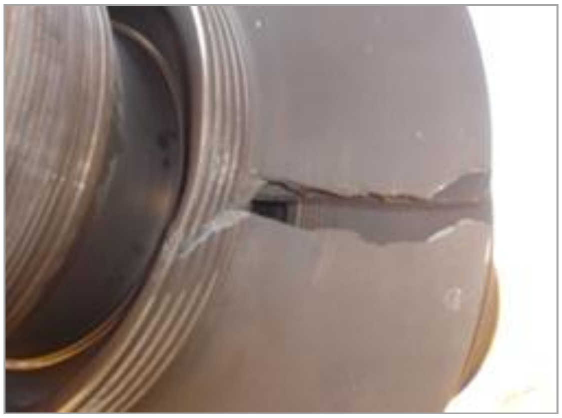

**Figure 3 Centrifugal compressor impeller failure**

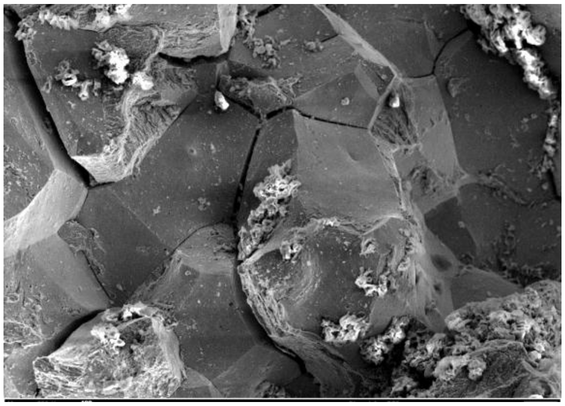

**Figure 4 Intergranular fracture surface**

Figure 5 illustrates severe pitting phenomena on a compressor impeller operating in a chlorides environment, where the base metal was UNS S41000 in NACE heat treatment. Localized corrosion might also be present on compressor flow paths and affect the compressor's efficiency or seriously compromise the integrity of the components, if the pits reach a critical dimension for crack propagation. Figure 6 shows a cross-section of a pit originating a crack path under stressed conditions.

**Figure 5 Heavy pitting on impeller flow path**

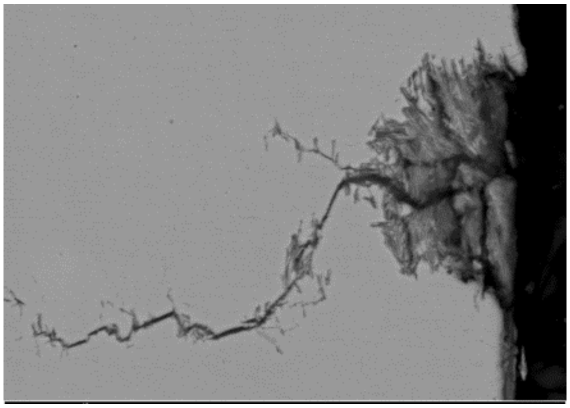

**Figure 6 Crack origin from pit and propagation**

It must be noted that the mentioned field experience cases fall under an area not properly covered by international standard references.

## RISK MANAGEMENT BY FIT-FOR-PURPOSE MATERIAL SELECTION

Risk management in selecting compressor materials should be based on a comprehensive understanding of implications related to the interaction between environment and materials. Complying with the standards, as shown, does not always guarantee against failure. Therefore, the manufacturer's expertise is vital to safe operations, and that expertise includes testing activities.

### *Testing Experience*

For a given application with specific severity, laboratory testing might be required to properly qualify a material selection. Corrosion test activities should include materials screenings, alloys qualification in simulated environments, and quality checks. Experiments should highlight or accelerate the specific mechanisms of failure under examination that may or may not emphasize alloys' susceptibility.

Based on NACE and ASTM specifications, manufacturers have developed protocols to maximize information about the LAS and CRA materials for sour gas applications. These include the evaluation of general corrosion rates, localized corrosion proneness, pit growth rate, and stress corrosion cracking susceptibility as related to the several parameters involved in sour gas compression (pH, $pH_2S$, $pCO_2$, T, etc). This is known as a "Fit-For-Purpose" approach.

Examples of safe/unsafe application maps developed by GE, based on SSC testing according to NACE MR0177 Method A for UNS S17400 and UNS S41000, are reported in Figure 7 and Figure 8. Material selection in the safe area, with the corresponding threshold strength, reduces the risk of sulfide stress corrosion cracking mechanisms intensified by the presence of chlorides.

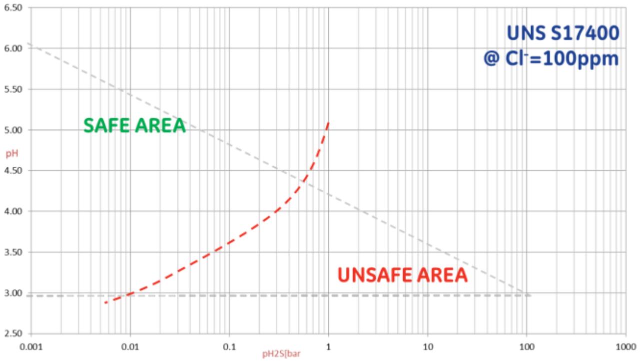

**Figure 7 Safe/unsafe maps for UNS S17400**

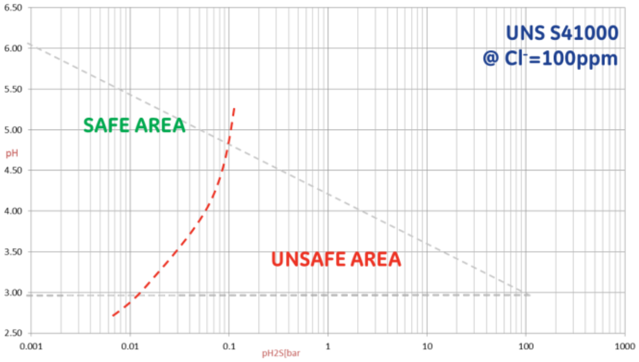

**Figure 8 Safe/unsafe maps for UNS S41000**

Chlorides stress corrosion cracking and pitting are other parameters to be tested in the fit-for-purpose approach. A typical evaluation test for screening the materials, with respect to CSCC, is the one described in ASTM G123. Comparisons reported in Figures 9 and 10 show the different behavior of UNS S17400 in purely chlorides environments (evident crack after few days of exposure) compared to UNS S41000 (which pass the 4 weeks test with pitting, but without crack formation).

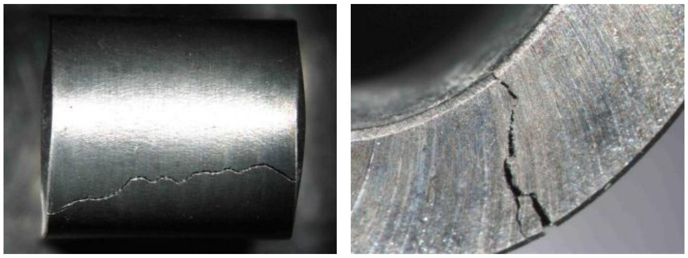

**Figure 9 Chloride SCC test on UNS S17400**

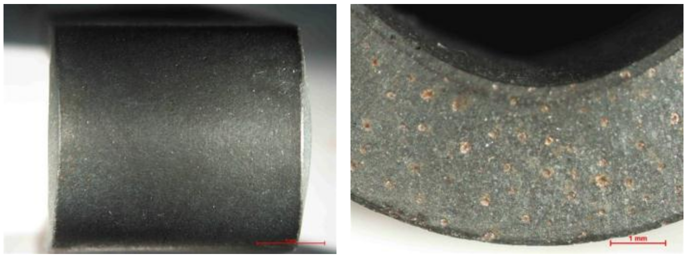

Figure 10 Chloride SCC test on UNS S41000

Testing results, matched with standards indication and field experience, allow manufacturers to select the most performant and cost-effective solutions from the materials portfolio.

## RECENT DEVELOPMENT IN MATERIAL FOR CC

The approach above fit in a standard material selection that includes CS, LAS, and Stainless Steel. In particular cases however, the environmental condition may require higher grades materials. Therefore, compressor manufacturers should develop quality and machining procedures to supply exotic alloys and reliable solutions. In recent years, this field has constituted about 70% of research and development projects in sour gas compression [7].

### *Wrought and Casted Nickel-Based Alloys*

When the expected environment overcomes stainless steel limits defined by testing experience, nickel-based materials are often the solving solution.

#### *Commercial Alloys*

For extreme sour gas service, the most commonly used nickel-based alloys are IN718 (UNS N07718) and IN625 (UNS N06625), depending on strength and corrosion requirements.

Obviously, experimental work must be performed to optimize the heat treatment sequence and metallurgy of nickel alloys in compliance with sour service and NACE requirements. For IN718 in particular, solution heat treatment should be well set up to minimize/avoid delta phase precipitation, without causing detrimental grain coarsening. Per NACE requirements, aging heat treatment is another parameter for reaching a maximum value of tensile and impact properties without exceeding 40 HRC. Extensive characterization of IN718 and IN625M at 95%AYS SSC testing has recently been performed and presented in extreme sour conditions, within the centrifugal compressor's design envelope.

IN718's high strength makes the material a perfect solution for rotating components, like impellers, manufactured in a single-piece construction to avoid joints (welding or brazing) that can reduce rotating speed capability. Manufacturers have developed and applied both conventional and unconventional methods to produce single piece impellers, each optimized for a certain range of dimension and shape. Electro Discharge Machining (EDM) has been extensively used in manufacturing bi-dimensional impellers characterized by low flow coefficients, resulting in narrow gas passages. Due to the more complex gas path of tri-dimensional impellers, other raw machining operations like Blu ArcTM Technology have been developed in conjunction with optimized finishing operations. Blu ArcTM Technology is a modified EDM process that drastically improves material rate removal with the use of a higher current. GE owns several Blu Arc TM patents, including general concept, tool shape, and wear compensation methods.

Figure 11 IN718 impeller under rough turning operation

Casting nickel alloys is another technology adopted to manufacture wide ranges of geometries, mainly for stator parts applications. Typical complex geometry produced in IN625 alloys is shown in Figure 12.

Figure 12 Casted Diaphragm in IN625

#### *Bridge Alloys*

Another important area of research from recent years focuses on the development of cost-effective materials to overcome limitations highlighted by fit-for-purpose analysis on stainless steel.

The main objectives, schematically shown in Figure 13, are:

1. To extend the area of application of martensitic stainless steels to higher p$H_2S$, lower pH and higher chlorides contents,
2. To develop a low cost nickel-base alloy with the same, or similar, corrosion properties of IN718.

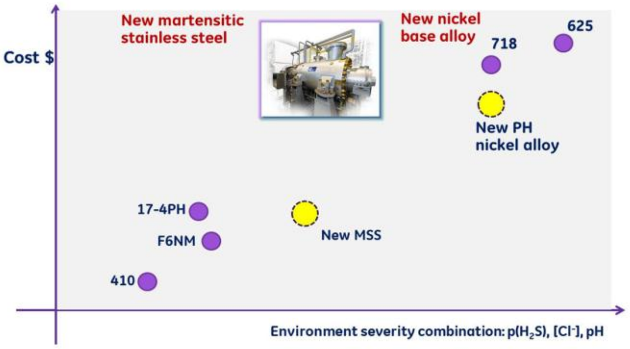

**Figure 13 Desired target properties of bridge alloys**

Alloy development has been performed using a comprehensive metallurgical design approach. The first step was a thermodynamics and kinetics modeling activity aimed to identify possible analytical variants from base compositions. Chemical variations were made by taking into account a set of critical requirements related to material performance (i.e. corrosion resistance and mechanical properties), or associated with the production of alloys (raw material and post processing). Through an array of calculations involving tens of variants, final compositional ranges were selected and experimental casts were made. The first attempt consisted of two variants for the new steels, and three for the new nickel-base alloys. After casting, a thermo-mechanical process consisting of hot deformation and heat treatment takes place, using the theoretical data obtained by simulation and the literature data of similar materials. Figure 14 shows the melting and forging process of one experimental material.

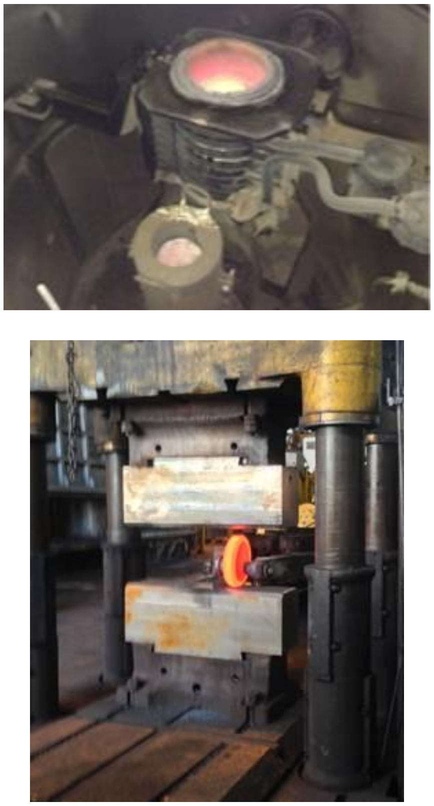

**Figure 14 Experimental alloy melting and forging**

### *Advanced Manufacturing Processes*

As the above information shows, manufacturing nickel-based alloys often results in high cost and increased lead times, even when feasible through the use of unconventional tools. For this reason, manufacturers are exploring alternative production routes.

### *Powder Metallurgy HIP (Hot Isostatic Pressing)*

Powder metallurgy opens new perspectives, making possible the production of impellers through Powder Metal Hot Isostatic Pressing (P/M-HIP). This technique is flexible and allows manufacturers to obtain materials with good mechanical properties, no porosity, and no macro-segregates or major defects. In a market where customers often require customized products, HIP technology often succeeds in overcoming issues connected to conventional manufacturing technologies. Casting is effective and efficient, and when a large number of products justify the high cost of realization of the mold and optimization of the process, HIP can be perfect for a single item or small production lots. At the same time, HIP can be cheaper than forging, and may shorten lead time and increase the range of materials suitable for specific applications.

The strength of Inconel 625M (UNS N07626 according to NACE MR0175/ISO15156-3:2009), a variant of the well-known Inconel 625 alloy, combined with its excellent resistance to corrosion make this material a valid solution for rotating components like shrouded impellers.

The first step of the P/M-HIP technology introduction processes resulted in the selection of two main approaches for producing impellers:

- The Near Net Shape (NNS) technology, intended to replace current raw material production processes, reduces lead time and enables technology for the Net Shape technology (anticipate the introduction in the market of P/M-HIP technology).
- The Net Shape (NS) technology, aimed to obtain complex parts with finished surfaces, improves the manufacturing capability and the design flexibility.

In both approaches, the critical step is the modeling phase where the hot isostatic pressing process is simulated (Figure 15) to optimize the design of the supporting insert (Figure 16) and capsule (Figure 17).

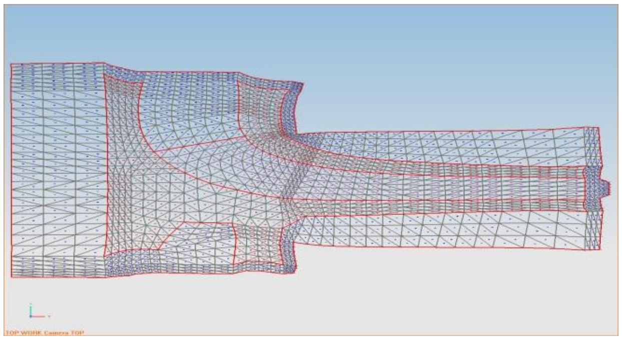

**Figure 15 Modelling of Deformed meshing after the HIP**

**Figure 16 HIP insert**

**Figure 17 HIP Capsule**

The capsule is filled with powder and Hot Isostatic Pressing is performed. After the HIP treatment, the part is dimensionally measured to assess expected deformation during consolidation, and the impeller is ready for final turning operations and released for rotor assembly.

Criticalities in the HIP process include powder quality and parameters that must be optimized to obtain optimal mechanical, toughness, and corrosion properties [8].

**Figure 18 Net-shape Impeller**

*Additive Manufacturing*

Another emerging technology to consider when building net-shaped components is Additive Manufacturing. Among the several AM processes, DMLM (Direct Metal Laser Melting) shows to be most promising for complex shaped full-scale components.

DMLM-- also known as Selective Laser Melting, Selective Laser Sintering, or Direct Metal Laser Sintering -- uses a focused laser to fuse alloy powders, layer-by-layer, into a three-dimensional object. The term “melting” is used, as the machines do not technically sinter, but instead overlap a series of fusion-welded layers. Metallic materials obtained through DMLM generally have a different microstructure than the same materials obtained through traditional technologies (forging, casting, etc.). The small localized melting point with rapid heating and cooling, repeated layer by layer, in addition to using different melting strategies and control parameters for various stages of building, lead inevitably to a material with heterogeneous anisotropic microstructures and high residual stresses. These characteristics determine particular mechanical properties, among them an anisotropic and a building-direction-dependent behavior of the material. The use of these materials in aggressive environments is made possible through specific thermal treatments that can homogenize microstructure and optimize mechanical and corrosion characteristics (Figure 19). GE has already defined such quality heat treatment for some Martensitic Stainless steels and IN718 [9].

Because the manufacturing equipment only allows a maximum diameter of 200mm, the technology is currently limited on large components.

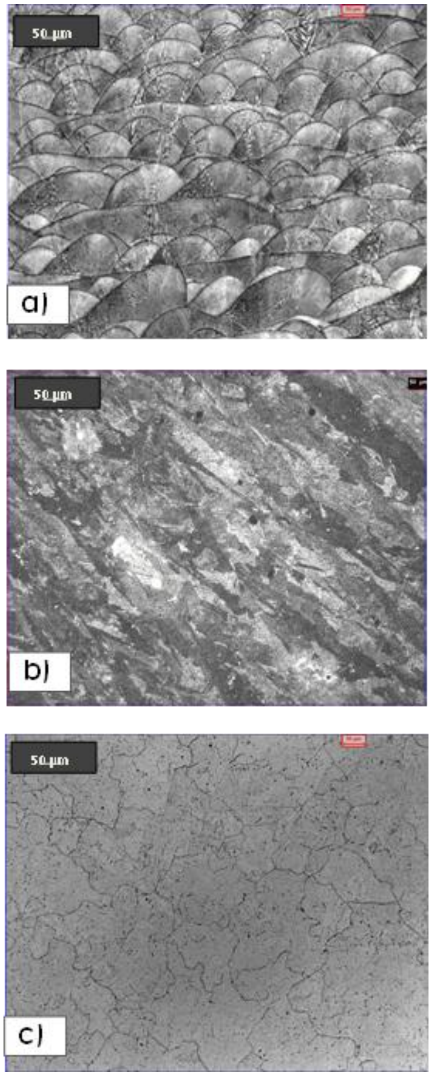

**Figure 19 DMLM IN718. a) As fused; b) homogenized; c) heat treated**

**Figure 20 DMLM IN718 Impeller diam.120mm**

## CONCLUSIONS

Exploitation of oil fields and gas reservoirs with an increased content of contaminants is a driver for research in the field of materials, design equipment and manufacturing technologies.

The field experience on centrifugal compressors presented in this paper highlights criticalities to properly address material performance in extreme sour environments. It has been shown how international standards indications often aren't considering the mechanisms that initiate damages and failures.

Our fit-for-purpose approach better redefines the limits of CRA application in rotating parts, allowing end-users to operate with robust safety margins, even in unexpected out of design conditions.

Over the application limits of stainless steels, state-of-art nickel alloys production highlights the possibility to forge or cast complex shape parts.

Research and development of new materials (bridge alloys) and new manufacturing technologies are focusing on improving product properties and performances to increase reliability and availability of equipment, without significantly affecting capital expenditure.

## NOMENCLATURE

CS = Carbon Steel
LAS = Low Alloy Steel
CRA = Corrosion Resistant alloys
SSC = Sulfide Stress Corrosion cracking
CSCC = Chlorides Stress Corrosion cracking
HIC = Hydrogen Induced Cracking
EDM = Electro Discharge Machine
P/M = Powder Metallurgy
HIP = Hot Isostatic Pressing
NS = Net Shape
NNS = Near Net Shape
AM = Additive Manufacturing
DMLM = Direct Metal Laser Melting

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