Reducing the risk of Hydrogen Induced Stress Cracking (HISC) on Duplex Stainless Steels with Hot Isostatic Pressed (HIP) Materials.

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Abstract

The increased usage of Duplex and Super Duplex stainless steels within the Oil and Gas business lately has enhanced the interest over these alloys, as well as the development of new technologies involved in its production and handling, aiming to minimize risks caused by its incorrect specification or manufacturing. The use of Duplex heavy forgings and cast materials in subsea applications, subjected to cathodic protection applied in subsea equipments, has resulted in spot failure cases – some of them mentioned here – due to Hydrogen permeation and embrittlement of the material.
As an alternative solution to existing limitations on large parts and hubs for equipments cathodically protected, Hot Isostatic Pressing (HIP) manufacturing route is already being used in projects worldwide. Duplex Stainless Steel parts manufactured by HIP are being increasingly used in subsea environments due to its refined microstructure and smaller austenite spacing, among other advantages that will be described here. This paper presents how the HIPed materials can reduce to a very safe level the risk of Hydrogen Induced Stress Cracking (HISC) occurrence in the materials, based on industry experiences and reports issued about this topic.

Key Words: Hot Isostatic Pressing - HIP, Hydrogen Induced Stress Cracking - HISC, Duplex Stainless Steels).

Introduction

One of the main issues that may cause failures on Duplex and Super Duplex Stainless Steels when used as heavy forgings or cast blocks for subsea application is the Hydrogen Induced Stress Cracking. This mechanism is characterized by the embrittlement, and consequent cracking, of the material due to Hydrogen permeation. The presence of Hydrogen is usually associated to cathodic protection that is applied to subsea equipments.
Hydrogen is the smallest atom, and so its permeation occurs in the Ferritic Phase of the Duplex material, due to the more spaced structure that it presents. This permeation may become critical if there is not an appropriate phase balance or austenite spacing in the structure, as the Austenitic phase act as a barrier for the Hydrogen diffusion due to its more compact structure. When the austenite spacing is too large, it may happen that single permeated atoms get together inside the Ferritic structure, forming Hydrogen Gas molecules, and thus generating stresses, and consequently cracking the material.
The Hot Isostatic Pressed (HIPed) Duplex materials are made of metallic powder compressed under high pressure (approximately 1000 bar) and high temperature (between 1000 and 1200ºC). The manufacturing of components using powder as raw material allows very good

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control of the grain size, phase balance and austenite spacing in the microstructure. This is possible because of the fast cooling of the small metal particles of powder, which avoids segregation, as well as due to the isostatic pressing that assures the isotropic and non-directional microstructure.
Those features indicate the HIPed materials as a good solution to reduce the risks of Hydrogen Induced Stress Cracking for subsea applications, as demonstrated by reports and tests mentioned in this paper.
The current paper presents results of HISC testing on Hot Isostatically Pressed Duplex stainless steel, and discusses the benefits of those materials towards prevention of HISC. The compiled information will show that Hot Isostatic Pressed materials arise as good alternative for the growing application of Duplex and Super Duplex materials in Subsea environments. With the right design and manufacturing process selection, taking advantage of the clean and refined microstructure achieved by HIP, it is possible to assure a good performance and safe application of these materials, even when exposed to cathodic protection.

Duplex and Super Duplex Stainless Steels

Introduction

Duplex stainless steels (DSS) may be defined as a family of steels that present two-phase – Ferritic and Austenitic - microstructure, both of them stainless (the general rule to consider steel as stainless is minimum Chromium content of 11-13%). Their main applications are found where the strength is of fundamental importance, like in pressure vessels and pressurized pipelines. They have excellent stress corrosion and pitting corrosion resistances and, in some cases, these properties are greater when compared to Austenitic stainless steels having equivalent price levels.
One important feature of the Duplex family is the combination of great mechanical and corrosion resistance properties by using a lower content of the expensive alloying elements like nickel and molybdenum then the Austenitic steels or even nickel alloys with comparable properties. This can be seen in Table 01, which presents the chemical composition of the main Duplex alloys. The table presents also the PRE number of these alloys. PRE is the short designation for Pitting Resistance Equivalent, which is calculated based in the below formula:

$$PRE = \%Cr + 3.3 \times \%Mo + 16 \times \%N \qquad \text{Equation I}$$

The PRE number is used as a reference for material ranking regarding localized corrosion resistance. The higher the PRE, the better is the resistance to pitting and crevice corrosion. It is the PRE number that is used to classify a material as Duplex or Super Duplex. If the PRE is greater then 40, the material is considered a Super Duplex (like SAF 2507); below that, is simply a Duplex alloy (like SAF2205, SAF2304).

Mechanical properties

The different mechanical behavior of ferrite and austenite act synergistically in order to provide Duplex and Super Duplex stainless steels great mechanical properties. Due to its more packed structure (see Figure 3), there are much more probabilities of atom plans slipping in austenite then in ferrite, which makes austenite a much more ductile phase.
Duplex is then a tough material, presents high yield strength and so high fatigue strength. The basic mechanical properties of the main Duplex and Super Duplex alloys are presented in

Table 02, that have also information about the typical mechanical properties of the classic Austenitic stainless steels.
The basic mean to achieve mechanical hardening of these materials is by avoiding the dislocations – always present in the crystal lattice – to move. It is natural then, that when the grains are refined, there are much more grain boundaries, considering the relation external surface/internal area. This leads to the conclusion that, when the grains are refined, the mechanical resistance is increased.

Corrosion Resistance

Stainless steels present a high level regarding corrosion resistance, and are in most of the environments good alternative to standard Austenitic stainless steels and even to highly alloyed materials. They present, though, some features that make them superiors to the traditional Austenitic steels.
Due to its high Cr content, to the Mo and N presence and their highly controlled content, Duplex Stainless Steels present great localized corrosion resistance – pitting and crevice corrosion – mainly associated to chloride. Besides that, Duplex structure makes these materials very resistant to the SCC (Stress Corrosion Cracking), the very weak point of the Austenitic stainless steels. Due to this same features, present also good general corrosion resistance in non oxidizing acid environments, or slightly reducing; The high Cr content make them resistant also to oxidant acid environments.

Applications in the Oil and Gas Segment

The advantages concerning mechanical properties, which reflect in thinner cross sections and parts in general, have been recognized and valued by the Oil and Gas industry. Because of these features, Duplex – and most of all Super Duplex – has been used in platforms for oil and gas production and for well drilling applications as hydraulic, instrumentation and heat exchanger tubes, or pipes for these areas.
Duplex grades have also experienced increased interest for use in subsea equipments and piping system, as well as hubs, fittings and valve bodies that can be manufactured by castings, forgings or HIP.

Hydrogen Induced Stress Cracking - HISC

Hydrogen Induced Stress Cracking is one among various designations that is given to the Hydrogen Embrittlement phenomenon in stainless steels, which in general consists on embrittlement of the material due to Hydrogen penetration in the microstructure. This problem may occur in subsea applications, mainly caused by Hydrogen from two sources: Hydrogen resulting from Cathodic Polarization electrochemical reactions, or Hydrogen present in sour environments, i.e. with Hydrogen sulfide (H2S) presence.

Hydrogen Embrittlement

Three conditions have to be fulfilled for Hydrogen embrittlement to occur (See Figure 01).:
- There has to be a Hydrogen source.
- Tensile stress must be present –and;
- The material has to be susceptible to Hydrogen permeation

Failures occurred in the field have been caused by a combination of the above conditions, specifically very high loads, coarse grains, intermetallic phases or high ferrite content.
There are basically two factors that control an alloy’s susceptibility to HISC:

1. The alloy's resistance to Hydrogen entry and;
2. The alloys capability of trapping Hydrogen.

Number 1 above is measured by the amount of Hydrogen that enters the material relatively to the total amount available in the external environment. Item 2 states that from the Hydrogen that enters the material caused by 1, a quantity stays irreversibly trapped in the material, while the remainder is partially trapped and so released after a while.

In the case of Duplex alloys the mobility, and therefore the diffusion of Hydrogen in the ferrite and austenite phases are different due to the different crystalline lattices (Figure 03). The ferrite structure (Body Centered Cubic - BCC) allows a high diffusion rate, and low solubility of Hydrogen atoms, while the opposite occurs in Austenitic FCC (Face Centered Cubic) structure – low diffusion and high solubility.

The main flux of Hydrogen occurs through the ferrite phase, and once inside the structure, this element will be in the ferrite phase as absorbed Hydrogen, reversibly trapped in the austenite grains or even trapped in microstructural defects.

What changes the susceptibility of a Duplex structure to Hydrogen uptake and consequent embrittlement are the following factors [1, 13, 15]:

- Austenite spacing: Austenite grains are barriers for Hydrogen diffusion. Therefore, when Duplex structure has low austenite spacing, the Hydrogen flux within the material is more difficult. It has also been stated [15] that austenite grains can act as barriers for the cracking propagation. Therefore, the closer the austenite grains are from each other, the more difficult it is to the Hydrogen to diffuse within the material and to the crack to propagate. This is considered as the most important parameter to characterize the microstructure in this case.
- Ferrite content; as diffusion takes place preferentially in the ferrite phase, the higher its content, the higher the susceptibility. This care shall be specially taken when welding the material. The general guidelines state the content of 35-55% of ferrite to achieve good properties. The nominal target, though, is to have 50-50% between austenite and ferrite.
- Grain size. Regardless the metallurgical phase, refined grains contribute to the better mechanical properties of the material. Considering the same mass and volume of the structure, as the average grain size decreases, the total number of grain boundaries grows. And grain boundaries, which can be metallurgically considered as microstructure imperfections, act as a trap for the diffused Hydrogen. Thus, less diffused Hydrogen is available during the embrittlement process, and so the time to failure increases. [15,23]

Another factor that influences the Hydrogen susceptibility of a system (Figure 01), since it will be cathodically protected anyway, is the amount of stresses applied in the parts. Among the cases of failure that were registered lately [15, 17, 24], all of them presented high stress levels applied, exceeding in some cases the yield limit of the material. And following the same trend of the metallurgical factors above mentioned, the material will be more susceptible to HISC as stress applied increase. Every kind of load applied to the system should be here considered, which means that all the combination of different stress point should be taken into account. This includes residual stresses, mainly the ones resulted from welding, which should be carefully analyzed as well.[13, 17]

It is important to consider that, due to temperature fluctuations in the operational environment, thermal expansion may occur. If the material is free to expand and contract, dynamic stress can be avoided. But if there is a mechanical restriction to this movement, the

stresses due to the deformation should be taken in account when considering the overall tension that the material will be subjected to.
Although less determining of the material's performance under Cathodic Protection conditions, other factors may also influence the material's resistance to HISC. Among them are temperature, pressure (both internal and external), axial loading and hydrogen pre-charging. Stress concentration points, geometry discontinuities, weld points, diameter changes, notches and sharp angles should be considered and avoided when designing a part to work at these conditions as well.
For specific design and geometry guidelines for designing of this kind of parts, the DNV RP-F112 [13] should be consulted and taken into account. By its orientation, if the design limits and the recommended limits are different, the more stringent shall apply.

Cathodic Protection as Hydrogen Source

In subsea applications, Duplex stainless steels are under cathodic protection. When a metallic material is subjected to seawater deleterious action, there are both a cathodic and an anodic electrochemical reaction occurring simultaneously. As a result, there is no net overall charge resultant in the metal.
The principle of the cathodic reaction is the reduction of the positive ions present in the aqueous solution. In this case, the ions that are being reduced are the H^+:

$$2H^+ + 2e = H_2 \qquad \text{Equation II}$$

In the anodic reactions, occurs that the metal is oxidized, transforming into its ions. In general one of the following, depending on the metal's valence:

$$Me = Me^{2+} + 2e \qquad \text{Equation III}$$
$$Me = Me^{+} + e$$

Figure 02 shows the scheme of these reactions occurring simultaneously in the surface of the same piece, in points nearby one to the other. The idea of the Cathodic Protection is to prevent corrosion by the electrons supplying to the base metal, through an external source, in order to keep this equilibrium dislocated in the direction of the metal integrity ($Me^{2+} + 2e = Me$). Although cathodic protection can be made by impressed current, directly inducing electrons flux to the base metal, the main method to cathodically protect the structure is the use of sacrifice anodes.
The reaction in Equation II occurs in the more noble metal surface. If there are Duplex components electrically connected to carbon steel, and consequently to the sacrifice anode, the Hydrogen nucleation will occur in the stainless surface.
Studies were performed [13, 15] and showed that Hydrogen flux is significantly larger on the steel surface under cathodic protection compared with a gaseous Hydrogen atmosphere. The susceptibility to HISC trends to grow with decreasing Cathodic Protection potential. Although this relation has not been quantified and it was not defined a guideline potential from which the material is not susceptible, this information is also important as a guideline.

Hydrogen Permeation and Cracking propagation

It is important to note that in order to cause HISC, there should be the atomic Hydrogen absorption by the metal, since the molecular Hydrogen is too big to diffuse, even in the BCC ferrite packing. There are many theories and studies behind the HISC mechanism and its

driving force [1, 15]. Hydrogen works through mechanisms in which the metal is weakened internally. The penetrating Hydrogen affects the strength and the ductility of the material.
Different types of testing for Hydrogen Embrittlement understanding have being performed and published [15, 26], as well as recent experiences acquired in the Oil and Gas Business [11, 15, 17, 24] show that failures occur in general in temperature, in most cases, below 25ºC. In the DNV guidelines it is stated that low temperature increases the risk of HISC. At higher temperatures, the localized effect of Hydrogen, allied to the strain effect is smaller.

HISC occurrence and historical cases in the Oil and Gas industry

Duplex stainless steels have been used for over 20 years in subsea equipment exposed to cathodic protection. In the great majority of the cases, the material performance has been well accepted. Spot failures due to Hydrogen embrittlement have occurred during the last 10 years, though, in specific environment and material conditions [17, 15]. Motivated by that failure cases, it has been discussed lately whether Duplex and Super Duplex stainless steels are suitable for subsea applications. In order to reassure the industry convictions and ensure its confidence in these materials, new guidelines [12, 13, 16, 17] have been issued.
The main reason of the failures reported as caused by Hydrogen embrittlement is a combination, as described above, of the three causing factors of HISC. In most of the cases, unusual high loads applied in the parts, unfavorable material condition (coarse grained microstructure, intermetallic phases presence or high ferrite content mainly in welds), and project conditions (sharp angles, notches, etc) are the factors that combined, caused the material failing [15] under cathodic protection..
A failure of a forged Super Duplex hub which occurred close to the weld bead, was attributed to Hydrogen embrittlement [17, 24]. Besides residual stresses resulted from welding, the design presented stress accumulation points, like a diameter reduction point, a flange connection and the weld bead itself [17].
As could be expected by the previous topics, the registered failure cases in the industry [12, 13, 15, 17] occurred in big forged or cast hubs and connectors. One of the main issues was the low toughness caused by intermetallic phases in the base material, which may have been caused by two different reasons:
- Wrong heat treatment procedure/execution or
- Inappropriate welding procedure or execution.

Due to these factors, verified by mechanical and metallurgical testing, failures in bored forgings were registered and stated [15].

Hot Isostatic Pressing - HIP

Powder metallurgy basics and history

The powder metallurgy as known today is recent if compared to other metal working methods. Combining shape-making technology for powder compaction and the development of final material and design properties during subsequent densification or consolidation process, powder metallurgy or P/M process results in near-net or net-shape products.
To achieve the required properties of a specific application, several P/M methods are available, and to choose the right one, some design characteristics should be considered, concerning size, shape complexity, tolerances, material systems, properties, quantity and cost. The HIP method is the least constrained P/M technique; however this method involves low production rate and costly equipment, being only applicable for special materials, such as tool steels, super alloys, special steel grades and titanium. Also the process requires a high purity

powder, normally spherical shape ones, so the quality of the starting material should be evaluated as well. [8]

Heavy parts production by HIP process

HIPing a part stands for forming and compacting the powder in a high-temperature (approximately 1100ºC) and high-pressure (approximately 1000 bar) vessel. This situation provides Isostatic pressing and compaction for the powder, which will imply in features to be mentioned later.

<u>HIP Process step-by-step [11]</u>

The metal processing for this powder production resembles any classic mill process. The metal is melt in an electric furnace, and than refined in different steps like AOD converter, slag removal and ladle furnace. The difference starts at the solidification point. Through an orifice on the down side of the ladle, the molten metal flows and, as soon as it gets out, the flux is exposed to a gas jet, producing small spherical particles within a diameter range from 0-500µm. After blending, homogenizing, inspection and approval of cleanliness the powder is stored in containers. The process continues through the below steps:

- Capsule making: The capsule is the equivalent of a mould in this process. It is projected in a 3D CAD software and then built with mild steel plate welded with TIG process. The capsule, named can as well, is about 10% larger than the final shape to compensate the shrinkage of HIP process, and has controlled chemical composition so there is no contamination of the main part. [11, 12]
- Capsule filling and evacuation: The capsule is completely filled with the powder, and then it is sealed and put into a HIP chamber where the high pressure and temperature will be applied. The chamber is closed; the air is removed and then filled with the pressure gas, which normally is argon.
- HIPping: With high temperature, around 1150ºC and pressure above 1000 bar, the HIP compaction takes place in a solid state for 2-3 hours. The time inside the chamber is empirically determined and depends on the alloy [6]. Figure 06 shows the main figures of the HIP process.

The component is then heat treated still with the capsule, which is afterwards removed by pickling. Normally the Near-Net-Shape component is ready to inspection; however an eventual machining step might be required. Non-destructive tests are applied before the final check to customer specifications.

Main HIPed parts features and properties

- Microstructure: The resulting microstructure of a HIPed component is achieved by the basic characteristics of the process, which are high purity metal powder, high temperature and inert gas pressure during controlled time. Starting from spherical powder, the Austenitic grain size reached with the HIP process is approx. 20µm, which characterizes a refined structure, allied to the 15µm average Austenitic spacing size. [11]

- Isotropic Properties: Since there is no melting of the metal during the process, the compaction takes place through the whole component in all directions at the same time. Together with the isostatic pressure, the compaction is homogeneous and so is the resulting microstructure. Therefore, the mechanical properties are the same in all regions and directions of the component.

- Phase Balance and Segregation: Unlike the casting process, where the solidification starts from the mold walls, the HIP compaction deforms the powder plastically [8] and there is no relevant movement of the particles, thus the phases formed have no preferred orientation. The factors needed for each phase formation are then the same in every part of the component and the phase balance reached is close to 50/50.
- Mechanical Properties: In a single phase microstructure, fine grain size provides high strength. When it comes to a dual phase structure, each grain has its properties and the combination of both properties is better used when the structure is homogeneous. The HIPed pieces have both characteristics, which give them higher mechanical properties than materials produced by other methods.
- Near Net Shape: To reach the final shape, conventional production methods usually are assisted by welding processes. But welded joints are commonly known as week points, especially in corrosive environments. With the HIP method it is possible to produce big sized components with a reduced number of welds. For example, in subsea modules such as manifolds, the necessary welding is reduced up to 70-80% [12]
- Geometry freedom: The almost unlimited design capability of HIP method allows, by constructing special high pressure capsules, to manufacture pieces with internal holes in more than one direction, as illustrated in Figure 07 (Steam Chest made by HIP) such as internal elbows, which are not possible to produce with machining steps on forged pieces or special casting methods.

HIP as a solution for HISC

The DNV Recommended Practice DNV-RP-F112 [13] – Design of Duplex Stainless Steel Subsea Equipment Exposed to Cathodic Protection – discusses the issue of the Hydrogen embrittlement in subsea equipments, both design and material wise. By aligning the material orientations here commented, with the design and project guidelines that can be founded in this RP, it is possible to apply Duplex materials in subsea equipments, even if exposed to cathodic protection, in a very safe condition. As it is stated in this very specification, the Hydrogen embrittlement study and knowledge is not yet totally established, so it’s still not possible to consider it as an exact science, making the failure probability a function of measurable parameters as CP potential, stress or strain applied and others. It is possible, though, to control all these conditions, and set the project variables (design and material) in order to ensure a very low failure possibility.

When dealing with HISC in DSS and SDSS, as has already been shown, the cracks usually propagate through the ferrite phase, and austenite phase acts like a barrier for this process, although in some cases the crack could propagate through it, depending on the crack size and on the level of the stresses applied [15]. Based on that, the RP emphasizes the importance of fine austenite spacing, as was discussed previously in this paper.

The main orientation is that an austenite spacing good enough to avoid the Hydrogen embrittlement as described here should be less then 30 micrometers. This is taken as a reference value, as this is not an inflection point, but a point from which the material trends to be more prone to HISC occurrence.

The most used way to measure austenite spacing currently is to follow the ASTM E112-96 (14), section 17 - Specimens Containing Two or More Phases or Constituents - which is known and applied worldwide. There are different suggested methods, within which the most popular is the intercept method (section 17.5).

In addition, it has been shown [13] that when the microstructure is directional, i.e. there's no isotropy in the material, caused by unequal mechanical work (like forging, rolling, extrusion), there could be a negative performance of the material due to the grain orientation. If the ferrite grains are perpendicularly oriented to the main stress axis, the material will be more susceptible to HISC occurrence. Therefore, dealing with an isotropic material, there will be no problem regarding the direction of the stress applied in the part, and the design and project of the system will be much easier, when concerning to efforts and stresses.

Based on that, materials that have being processed by methods which present no directional forming or pressing, are much more resistant to HISC occurrence that the ones produced by the traditional ways [13, 23].

As can be seen in Figure 04-a, cast materials tend to have a non directional microstructure, although this is most of the times a coarse-grained structure, due to the fact that no mechanical work have been applied. This can make the material prone to the Hydrogen diffusion, as well as for the cracking propagation, causing bigger probability of failure due to HISC.

Figure 04-b, with the same magnification, that the austenite spacing for a rolled material is much better – smaller - then for the casted one. There is, instead, a problem that is not present in the casted material. The microstructure is highly directional, and so the stresses applied in shall be controlled, and the maximum stresses allowed in distinct directions are different. This has many implications in the project of the parts, and may also lead to material failure in case of bad specification or project.

It is stated by the practice, though, that materials processed by some directional methods as rolling or extrusion may present austenite spacing fine enough to present low susceptibility to HISC. This is the case of extruded, seamless rolled or drawn tubes, as well as fittings and components made from these tubes and pipes. This means that if these materials are properly specified, and applied preferably according to the design recommendations [13, 16, 17, 24], there should be no problem for the Duplex materials, even if subjected to cathodic protection.

By analyzing figure 04-c, it is noted that, with the same material and same magnification, the HIPed microstructure is much more refined, moreover presenting a non-directional microstructure. This reflects directly in the performance of the material in the conditions and environments here discussed. The proper phase balance – no segregation due to very quick solidification and small solidified particles – allied to the very fine austenite spacing, leads to the conclusion that HIPed hubs and blocks are much more resistant to HISC than the traditional ones.

Although there's no way to assure or control the precise austenite spacing (mainly because there are different methods for the measuring), the usual spacing for HIPed parts is 15 micrometers, far below the recommended one for DNV. This fact, aligned to the ones described before, builds the liability of the HIPed pieces.

The advantage of the fine grained materials can also be seen by the threshold limits of the allowable strain for different materials. Materials with finer austenite spacing are supposed to support a bigger strain level than the ones with coarse microstructure [13]. This implies directly in the design and project parameters that may be optimized if a material with fine austenite spacing is considered.

The right material selection and the recommended practices for design and project will only be valuable, though, if a trustable material supplier is chosen. The choice of the fabricator is as important as the right material and fabrication method, since the quality control and the control of the whole fabrication process are mandatory to assure the properties achieved by the correct project and specifying.

Besides that, as it was already said in this paper, it should also be considered that the material is only one of the factors that may lead to the failure by HISC. By specifying the correct process and material, one of these items can be solved. It is very important, though, to assure that the other two items are carried. As Hydrogen presence is a consequence of the cathodic protection of the huge structures underwater, the correct load applying should be made, in order to keep in a safe and liable level the usage of Duplex steels as huge parts in subsea applications.

Conclusions

The collected data and the third-party reports here shown lead to the conclusion that the use of Duplex and Super Duplex materials in subsea equipments can be very trustful. Considering the good cost-benefit of these alloys, in comparison to the other metals with similar mechanical and corrosion properties, their usage trend to grow continuously in this market segment among others as the experiences and confidence on them spreads out within the industry worldwide.
HIPed materials, due to its metallurgical features – refined structure and isotropic properties – present a significant increase in resistance towards HISC in comparison to the traditionally fabricated ones. Additionally, the geometry and design freedom, the smaller need of mechanical work operations, as well as welding points reduction, are interesting advantages of powder metallurgy parts, and can directly impact in costs and delivery time of a project. HIP offers a reliable and safe way to manufacture critical components for demanding environments.

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Tables

Table 01 – Chemical composition of some Duplex (SAF 2304, SAF 2205), Austenitic (316L, 904L), and Super Duplex (SAF 2507) alloys.

Alloy	Alloying Element					
	Cr	Ni	Mo	N	Cu	PRE
SAF 2304	23	4	-	0,1	-	25
3R60 (316L)	17	13	2,5	-	-	25
SAF2205	22	5,7	3,3	0,2	-	35
2RK65 (904L)	20	25	4,5	-	1,5	35
SAF 2507	25	7	4	1,3	-	43

Table 02 – Basic mechanical properties of the alloys above mentioned.

Alloy	Yield Strength		Tensile Strength	Elongation	Hardness
	Rp 0.2 (Mpa)	Rp 1.0 (Mpa)	Rm (Mpa)	(%)	(HV)
3R60 (316L)	220	250	515-690	45	155
2RK65 (904L)	220	250	520-720	35	160
SAF 2304	400	450	630-880	25	310
SAF 2205	485	500	680-880	25	286
SAF 2507	550	640	800-1000	25	318

Pictures

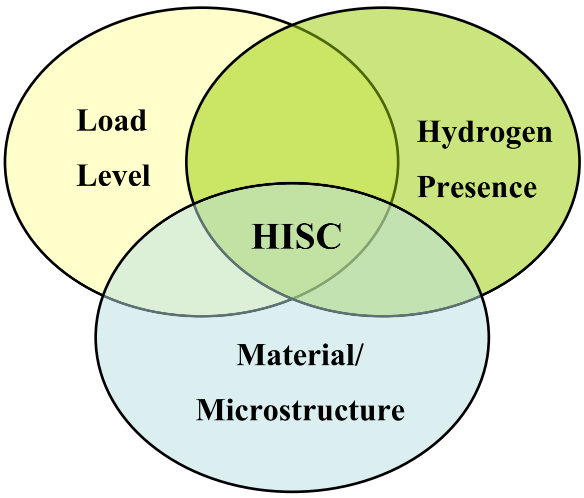

Figure 01 – Schematic representation of factors affecting HISC.

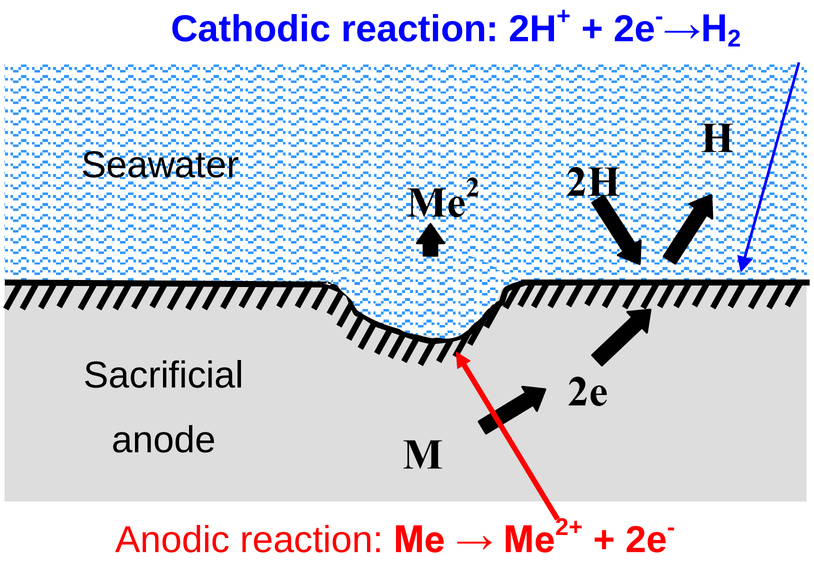

Figure 02 – Schematic representation of the electrochemical reactions involved in the cathodic protection process.

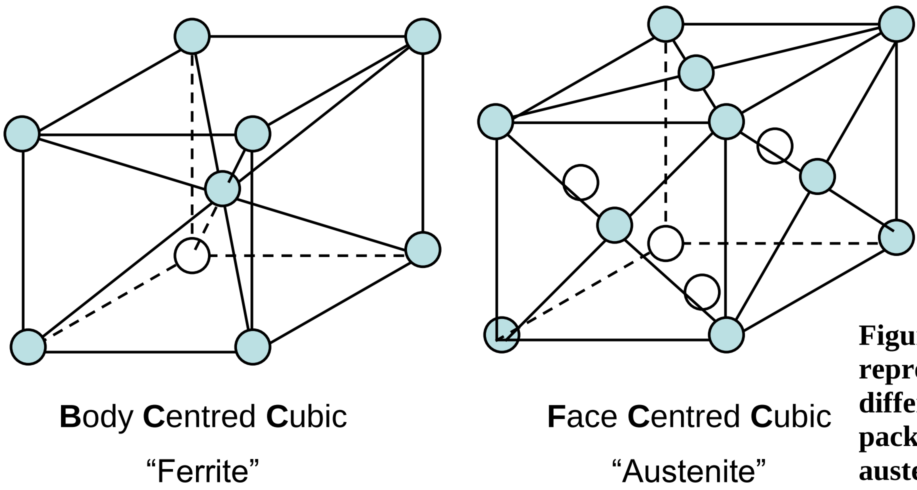

Figure 03 – Schematic representation of the different crystal lattice packing for ferrite and austenite.

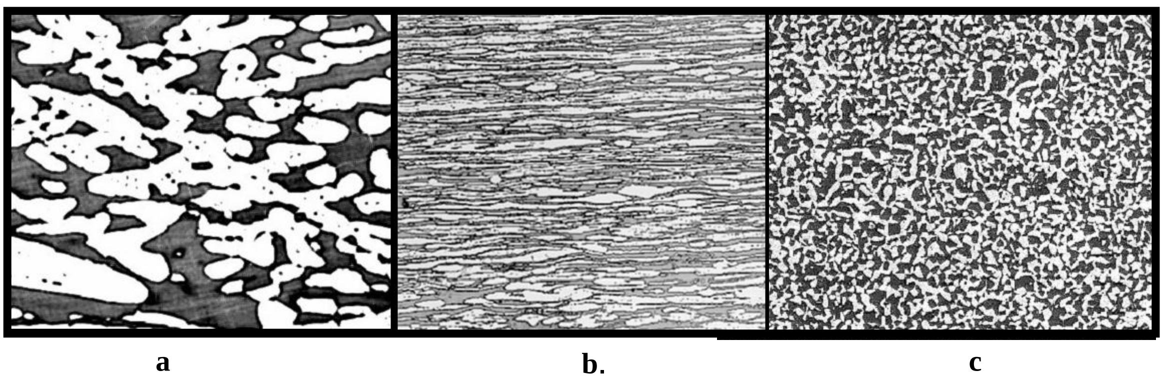

Figure 04 – Typical Microstructures for Casted (a), Hot rolled (b) and HIPed (c) Duplex material with same magnification.

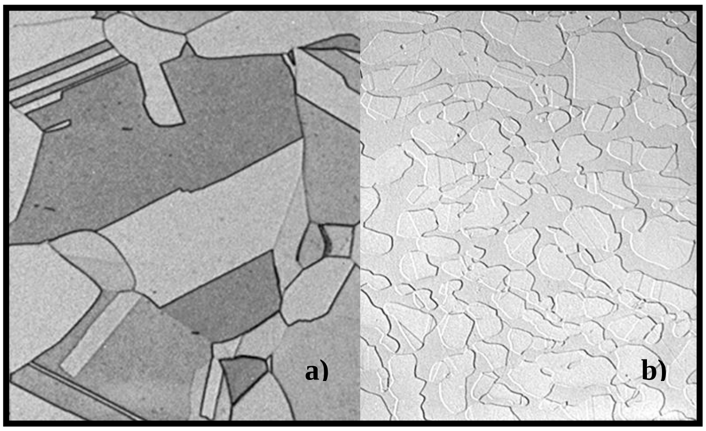

Figure 05– Typical Microstructures for Austenitic (a), and Duplex material (b).

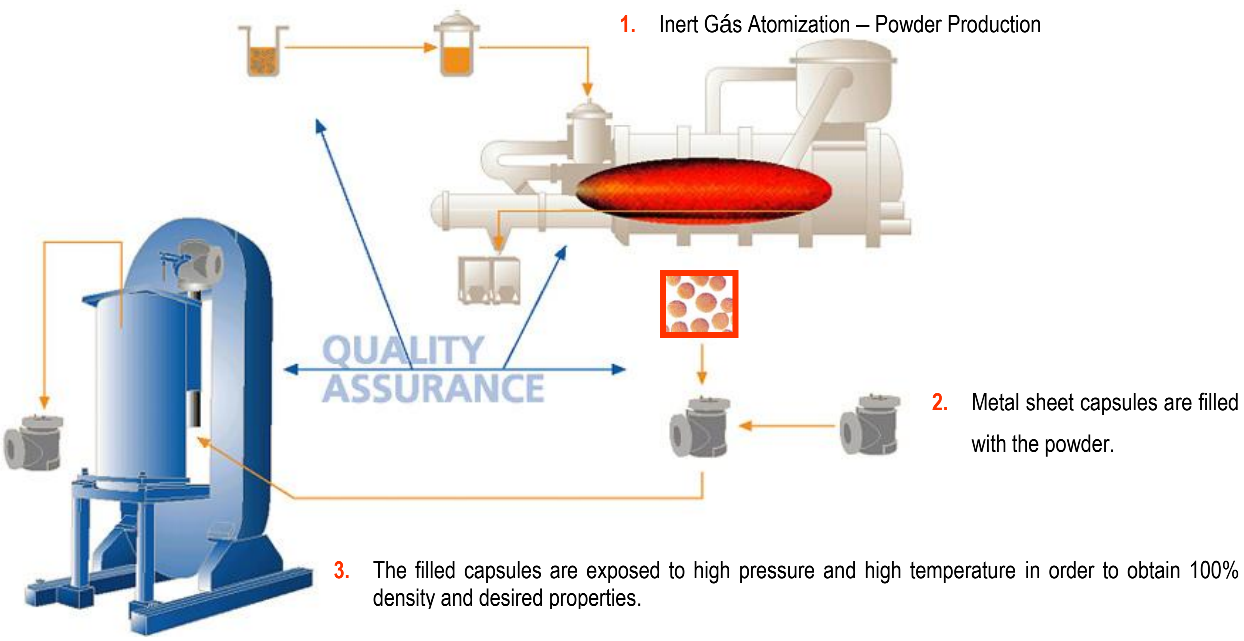

Figure 06 – Scheme of the steps of the HIP process performed by Sandvik Powdermet.

Figure 07 – Steam chest made by the HIP process, in the as-HIPed condition, with a finish machined surface.