Corrosion resistant alloy cladding for the oil & gas industry using a high-density Infrared fusion cladding process

Corrosion resistant alloys (CRAs) are commonly used in the oil & gas industry to protect metal assets in the exploration and production, refineries, and processing plants from corrosion. A carbon steel pipe clad with CRA provides a highly economical alternative to the use of solid CRA pipe. The high-density infrared (HDIR) cladding process is a high productivity fusion process that offers a scalable alternative to laser and weld overlay, an easier to inspect and install alternative compared to mechanical cladding, and a seamless weld-free alternative compared to roll bonding for corrosion- and wear-resistant alloy claddings for manufacturing CRA clad pipes. The HDIR technology uses a high-density infrared thermal source (an artificial 'sun' captured in a reflector) to rapidly melt, fuse, and metallurgically bond metal and composite coatings on steel pipes, plates and bars at very high fusion rates. Current well established processes for producing clad steels have product limitations and/or require large capital investments to modify or expand capacity and offerings. HDIR fusion cladding offers the product flexibility and low capital costs of laser or arc-weld overlay cladding process but offers a higher purity overlay and much higher and scalable production rates. Cladding deposited by HDIR process typically show a higher corrosion resistance, stronger metallurgical bond, lower dilution, and lower porosity compared to conventional cladding technologies.

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1. Introduction

Cladding refers to a process where a metal, CRA or composite (the cladding material) is bonded electrically, mechanically or through some other high-pressure and temperature process onto another dissimilar metal (the substrate) to enhance its durability, strength or appearance. The majority of clad products made today uses carbon steel as the substrate and aluminum, nickel, nickel alloys, copper, copper alloys and stainless steel as the clad materials to be bonded. Typically, the purpose of the clad is to protect the underlying steel substrate from the environment it resides in. Clad pipe is typically produced by cladding a low-cost carbon steel substrate with a corrosion-resistant stainless steel or nickel alloy, which costs a fraction of using a more expensive solid steel alloy for the entire product. For example, a solid nickel alloy pipe would cost about five times more than a carbon steel pipe that is clad with nickel alloy on its inside diameter.

The global oil & gas capital expenditure (CapEx) is expected to increase from $1,036 billion in 2012 to $1,201 billion in 2013, registering a growth of 15.9%. The trend of increasing capital expenditure is expected to continue for the foreseeable future, especially driven by reserves that are deeper and farther away from the shore. The Infield Systems Deepwater and Ultra-deepwater Market Report states that the largest proportion of deepwater investment to be directed towards pipeline installations; comprising 39% of total global deepwater expenditure [http://www.infield.com/market-forecast-reports/deepwater-ultra-deepwater-market-report] – and with International Energy Agency estimates that more than 70% of the remaining energy reserves being corrosive; it is expected that CRA clad pipes would be used heavily for offshore risers and flowlines.

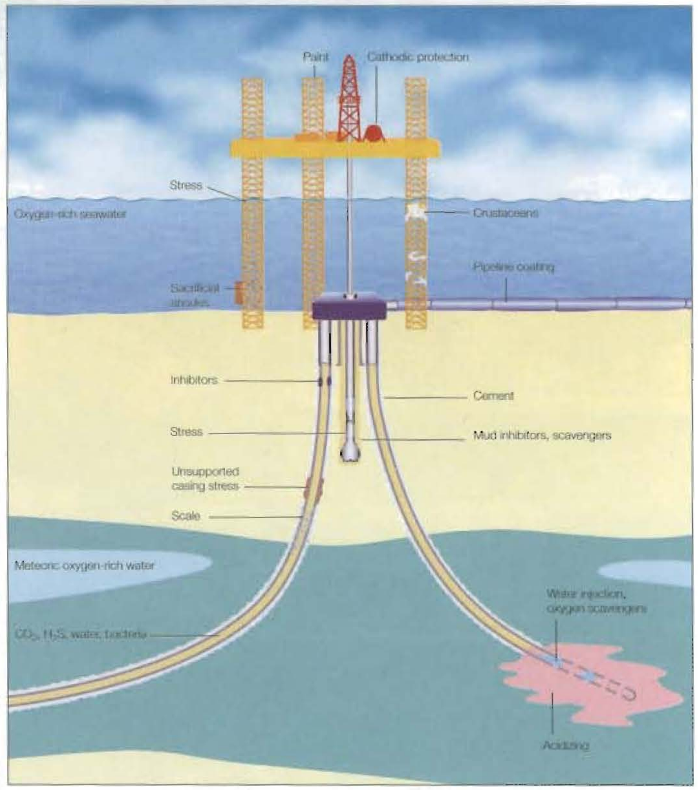
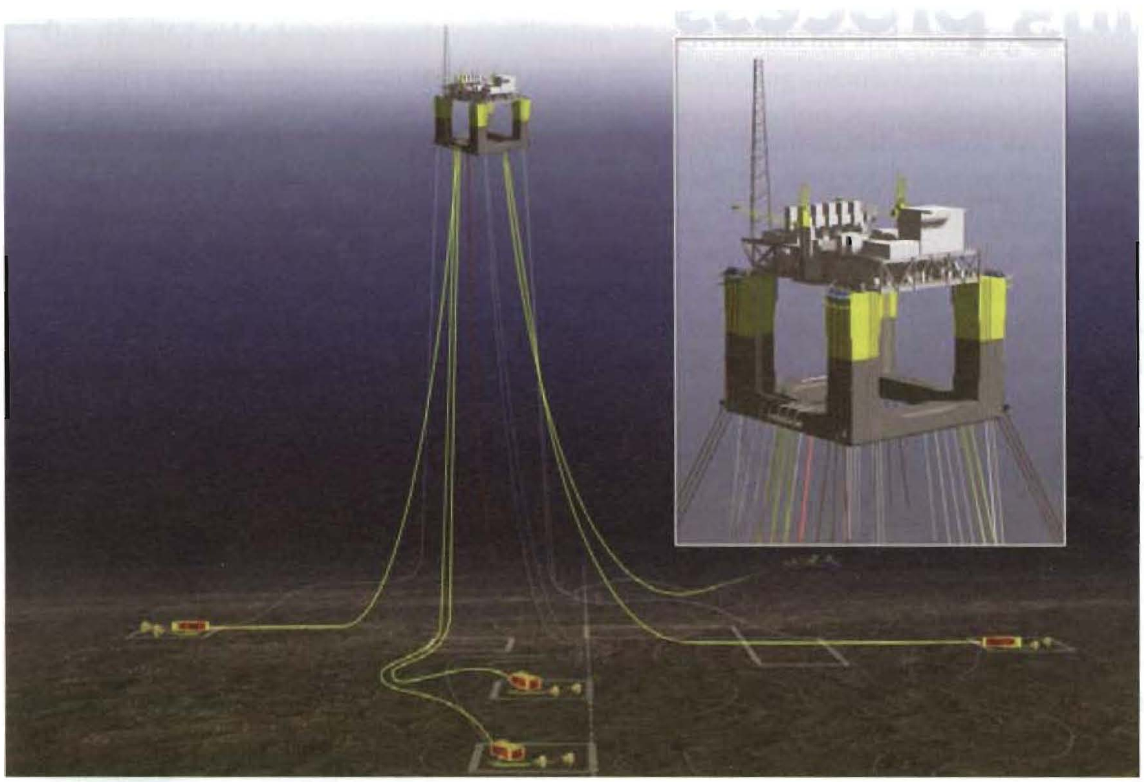


Fig. 2. Different areas of corrosion in the oil and gas industry [Brondel et al., 1994].

The offshore environments and subsea reservoirs are more corrosive than their onshore counterparts, and internal corrosion is attributed to more than 50% of failures that take place in offshore pipelines. Seawater is naturally corrosive but the internal reservoir fluids can also add to this corrosion. The contents of the pipelines typically contain aggressive elements such as chlorides, sand, organic acids, carbon dioxide (sweet crude), and hydrogen sulfide (sour crude). Coated tubing, inhibitors, and corrosion resistant alloys (CRA's) are commonly used to combat corrosion in these areas. Corrosion due to sour crude increases with temperature [rapid increase after 427° C (800° F)] and with increasing sulfur content. Chromium based alloys are commonly used for resistance to sulfur compounds. Steels with approximately



1 % Mo are generally suitable for less than 0.2 % H_2S in the gas stream while high sulfide contents require 5% Cr or more [http://corrosion-malaysia petroleum.blogspot.com/2008/06/corrosion-in-petroleum-industry.html]. Furthermore, the high temperatures and pressures encountered in the subsea well can lead to corrosion in pipelines and risers that are required to get the oil and gas products to the market [NACE interview, 2011].

Corrosion Resistant Alloys (CRAs) are typically used to withstand all the corrosion situations encountered in offshore drilling, such as high temperatures, pressures, and stresses, to provide long term corrosion resistance [Brondel et al., 1994, Craig and Smith, 2011]. The environmental factors affecting performance of CRAs are temperature, chloride ion concentration, partial pressure of CO_2 and H_2S, environmental pH, and presence or absence of sulfur. This work will discuss the application of CRAs using a novel technology called as the HDIR cladding process.

2. Overview of the current clad pipe solutions

While cladding carbon steel pipes is cheaper than using solid stainless steel alloy, the conventional technologies used to produce clad pipe have several limitations. Metallurgical clad pipes are normally made using roll-bonded clad plate which is then bent and welded to form a pipe; though a higher productivity process, it involves a lot of welded area especially in pipes larger than 14" diameter which require spiral welding since the plates are not large enough to produce longitudinally welded pipes – failure of weld is the single most common reason for pipeline leaks. The mechanically lined (bi-metal) pipe that now makes up a significant portion of the clad pipe market is lower in cost than metallurgically clad pipe, but provides only marginal contact between leading to a higher possibility of buckling, wrinkling and disbonding under stress, bending, during reeling, and application of external coatings on these pipes. These pipes also raise concerns with respect to uniformity and reliability; and the air gap, coupled with the mixture of materials, leads to challenges in Non-Destructive Testing (NDT) inspections that contribute to risks associated with reliability. There is huge need for clad pipes as more deepwater corrosive reserves come into production, and the current solutions not only have several limitations but also limited in availability creating an increasing large demand supply gap.

There are also other techniques for manufacturing clad pipes such as weld overlay where the clad metal layer is deposited on the base metal using arc-welding-type processes; and co-extrusion where a composite billet where the outer surface is carbon steel and the inner surface is corrosion resistant alloy, and this composite billet is then extruded to form clad pipes - however these technologies have been used on a very limited scale due to several limitations.

3. HDIR fusion : novel technology for production of metallurgically bonded parts

This process (Fig. 3a) is a large area based surface coating technology that develops smooth, metallurgically bonded coatings with low levels of dilution. A high intensity broadband light is emitted from a HDIR lamp (Fig. 3b) which is concentrated into a line focus of 350-5700 W/cm^2. The lamp consists of two electrodes separated by argon gas contained in water- cooled quartz envelop. The high pressure argon gas produces a high radiance output when an electric current applied to the gas column forms an arc. The heat input from the lamp can be controlled to control the phase and microstructure of the coatings. Reducing the time and temperature of fusion will slow down the hetero diffusion and thus minimize the diffusion zones.

The arc lamp generates an intense, indirect heat source capable of heating the surfaces without the electrode and Marangoni convective stirring effects encountered in Gas Metal Arc Welding (GMAW) and laser welding processes leading to high purity overlays (lower weld dilution from the base material). Different alloys (625, 825, 316L), metallic glass, titanium, molybdenum, copper, metal matrix composites, and aluminum have been fused by this technology.

The HDIR fusion cladding process is primarily developed for application to large areas and simple shapes, such as clad pipe used in sour service applications.

In the process, high intensity broadband light is emitted from a HDIR lamp (Fig. 3b) which is concentrated into a line focus

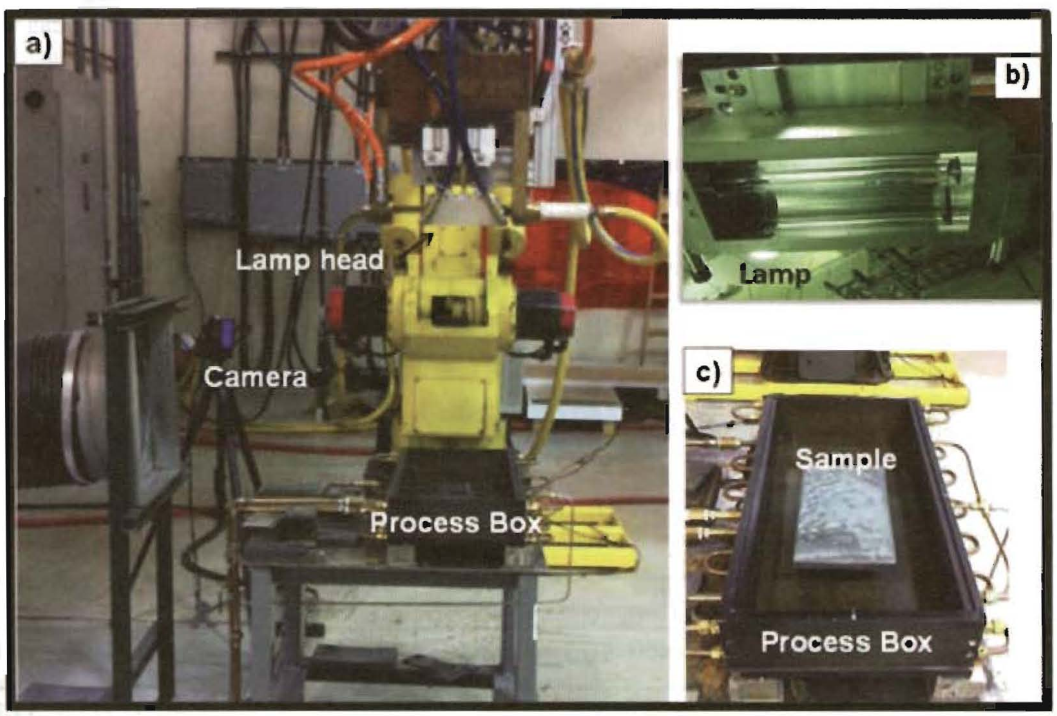


Fig. 3. (a) A HDIR laboratory cladding system; (b) a high-density plasma arc lamp; and (c) a process box with clad coupon. The actual width of this plasma arc lamp system is 20 cm while the effective thickness of each weld

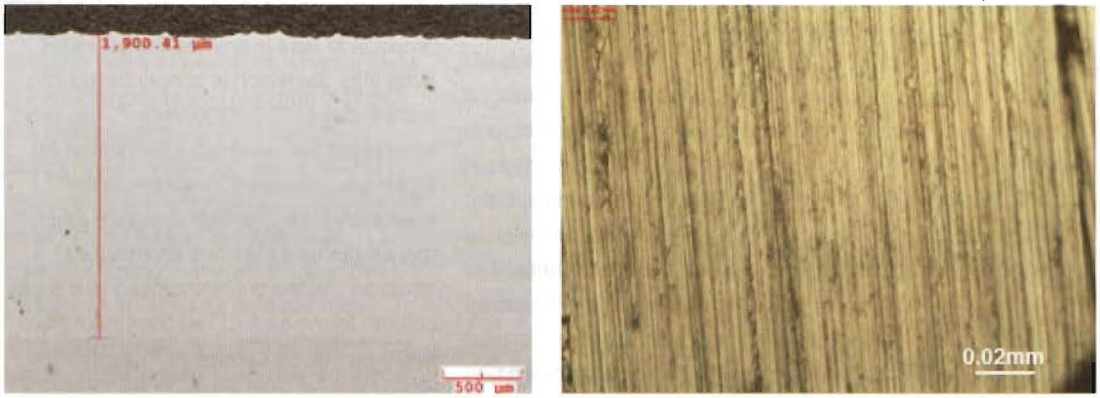


Fig. 4. (a) Cross-sectional microstructure of a 2 mm thick SS316L coating fused by HDIR technology. (b) Surface microstructure of a SS316L coatings fused by HDIR technology after ASTM A262 test.

at 350-5700W/cm^2. This light is used to fuse (melt) and bond a uniform layer of pre-applied powdered alloy metal to a base metal structure. The arc lamp itself is made up of two electrodes separated by argon gas contained in a water-cooled quartz envelope. The high pressure argon gas generates a high radiance output when electric current is shorted through the gas column to form an arc. Standard production units range from 300–1200Kw's of power capacity which can rapidly fuse and heat treat anything placed under the lamp at rates of up to one million degrees/second. (Fig. 3c). Surface temperatures of 3000°C and higher can be readily achieved.

For deep offshore applications, the fusion cladding process can be used to apply alloy 625, alloy 825, and 316L claddings to risers and flowlines without the wall-thickness and large-diameter limitations of other currently available cladding process at production rates of up to a dozen 40-ft. lengths per day per fusion system. This is enabled due to the additive nature of the process, which is largely independent of base metal thickness and chemistry, and the ability to separately control heat treatment of the cladding and base metal during the process, versus the requirement to simultaneously deform both cladding and substrate in other processes.

The primary value propositions of this technology include true metallurgical bond (bond strength greater than 75,000 psi), low dilution with iron, and fast application rates (40 times faster than laser welding processes). Unlike the mechanically lined clad pipes, the clad pipes manufactured using his process would be much easier to inspect, bend, reel, and install; and provide a seamless clad pipe compared to the roll-bonded clad pipes. As this process is area based, thermal gradients in the cladding are reduced and dilution with base metal and weld solidification/ liquation cracking are significantly minimized or eliminated compared to laser and arc welding method.

4. SS316L coatings fused by the HDIR process

Coatings varying from 0.25mm to 3.0mm have been applied by the HDIR technology on plain carbon steel substrates at MesoCoat. Microstructure of 2mm thick SS316L coating (Fig. 4a) shows that a dense coating is produced which is metallurgically bonded to the base metal.

The composition of the coating (as applied and after different levels of grinding) is presented in Table 1. It can be seen that the original SS316L composition is retained in the as applied coating and there was no dilution of iron from the base material. This in turn provided excellent resistance of these coatings to intergranular corrosion (Fig. 4b) [ASTM A262]. This test was conducted with 10% oxalic acid at 20V at 1Amp/cm^2 for 1.5 minutes. The main criterion for rejection of coatings under this test is the appearance of ditching in the microstructure. The fused SS316L coatings by HDIR showed no ditching. Even at very low thickness of the coating (115µm after grinding), there was very low Fe dilution and the Cr content was always greater than 13% which would be very beneficial for improving the corrosion resistance of low thickness (LT) SS316L coatings.

5. Next generation Structurally Amorphous Metals (SAM) alloy coatings fused by the HDIR process

SAM alloys were primarily developed under DARPA sponsorship and have excellent corrosion resistance due to the glassy metal phases along the grain boundaries. In addition, they also have ductility, formability, and strength similar to the high strength steels. A significant challenge in applying SAM alloy coatings is the difficulty in maintaining the amorphous

Table 1: Chemical compositions of the 2mm thick SS316L coatings fused by HDIR method (as fused and at different levels of grinding)

	Coating thickness (mm)	Fe	Cr	Mn	Ni	Mo
Composition of SS316L powder (Wt %)	-	68.88	16.6	1.3	10.2	2.12
Average Composition of coating (as applied) (Wt %)	1.9	68.8	17.625	1.275	8.9	1.775
Average Composition of coating (after 1. grinding) (Wt%)	0.42	74.44	13.27	1.19	9.38	1.43
Average Composition of coating (after 2. grinding) (Wt%)	0.115	75.83	12.64	1.07	8.88	1.34

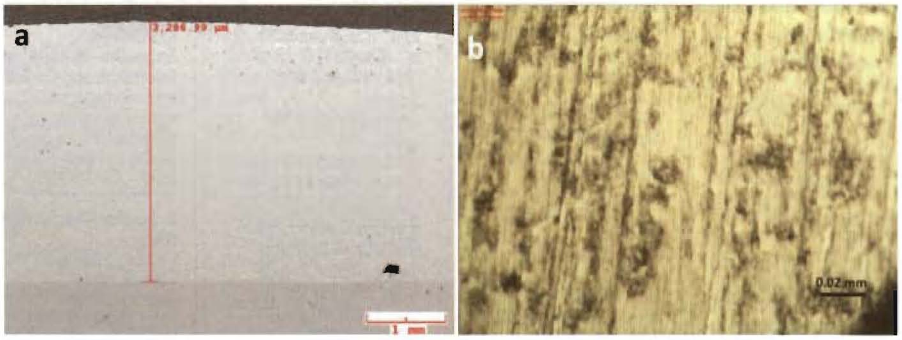


Fig. 5. (a) Cross section of SAM alloy coatings fused by HDIR technology. (b) Surface microstructure of coating after an ASTM A262 test.

grain boundary structure of these alloys during processing. A cross-sectional view of the SAM alloy coatings fused by the HDIR lamp is presented in Fig. 5a, while Fig. 5b shows the surface microstructure of these coatings after ASTM A262 test (no ditching indicating good resistance for intergranular corrosion).

6. Titanium coatings fused by HDIR process

Titanium (Ti) is now being used in a large number of industries as it has high strength, is tough, and provides protection from corrosion for multiple applications. Corrosion resistance of Ti is due to the formation of a strong, and protective thick oxide film (composition varying from TiO_2 at the surface to Ti_2O_3 to TiO at the metal interface) [Tomashov et al.,1961]. Ti coatings fused by the HDIR process (Fig. 6) were dense and well bonded to the base material. This material has vast applications in the petrochemical and desalination industry.

- Applied 625 claddings met requirements of API 5LD and DNV-OS-F101 standards, which can be applied to the ID of seamless and pre-welded pipe X42-X65 pipe with diameters of 10" and greater.
- The SS316L claddings were able to withstand 1,000 hours of salt fog exposure.
- The titanium cladding developed by the HDIR process will have advantages over the claddings developed by explosion cladding as it does not involve the risks associated with explosion cladding.
- The SAM alloy coatings which passed the test for intergranular corrosion will have applications in areas where there is exposure to salty environments.

Other claddings that have been developed using this technology include Ni-Cr alloys for high temperature applications, copper, tungsten, and molybdenum based coatings for nuclear applications, aluminum coatings

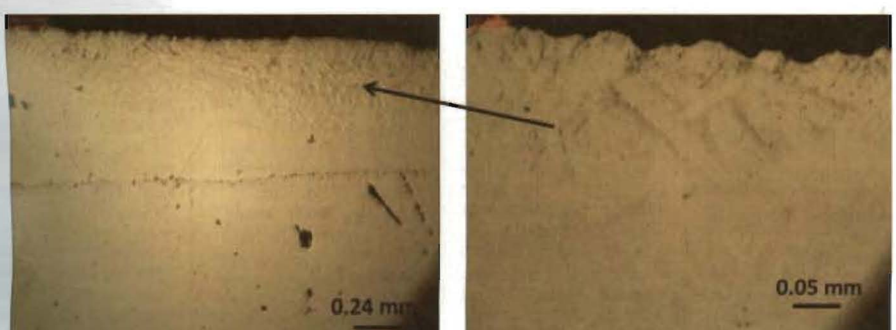


Fig. 6. Titanium cladding fused using a HDIR process.

7. Conclusion

An innovative approach to developing corrosion resistant coatings by the HDIR technology has been presented in this paper. Cladding of different materials such as Alloy 625, SS316L, titanium, and SAM alloys, have been fused by

for infrastructure applications, and tungsten carbide based coatings for wear resistance applications. Work is also currently ongoing on developing claddings of high molybdenum stainless steel composition, AL6XN and nickel based alloy, Alloy 825. Thus, claddings developed by the HDIR

several areas, such as oil and gas, marine, infrastructure, transportation, aerospace, defense, energy, automotive, chemical and petrochemical, nuclear, desalination, pulp and paper, and several other fields without the limitations of the current cladding methods.

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