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-ultradeepwater-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.

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, 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/cm². 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...
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

at 350-5700W/cm². 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 this 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/
lack 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
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/cm² 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
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$_2$O$_3$ 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 cladings met requirements of API 5L D 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 cladings were able to withstand 1,000 hours of salt fog exposure.

• The titanium cladding developed by the HDIR process will have advantages over the cladings 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 cladings 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 for infrastructure applications, and tungsten carbide based coatings for wear resistance applications. Work is also currently ongoing on developing cladings of high molybdenum stainless steel composition, AL6XN and nickel based alloy, Alloy 825. Thus, cladings developed by the HDIR technology have potential applications in 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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