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CRA Clad Downhole Tubing - An Economical Enabling Technology

Bruce E. Urband – P.E.; Grant Prideco L.P.

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Abstract

Corrosion Resistant Alloy (CRA) tubulars provide the corrosion resistance needed when gas drilling and completion operations involve severe downhole conditions where CO_2 and H_2S are present. These alloys are utilized when the traditional stainless steels (SS) do not provide adequate corrosion resistance. Over the last ten years, CRA tubulars, made out of Ni based alloys like 825, G3, G50 and C276 have met the material requirements for these wells but the cost of these tubulars are exorbitant. Recent advances in technology have facilitated the development of a clad tubular for downhole use composed of an API C90 and T95 outer tube and an 825 corrosion resistant liner. The carbon alloy, C90 or T95 outer tube, provides the structural integrity of the tubular while the CRA liner provides the necessary corrosion resistance. Past attempts to produce a threaded and coupled tubular have failed due to the pipe industries inability to provide a structurally sound, corrosion resistant connection.

This paper discusses the Ni based CRA’s, general application environments, clad and lined tubular manufacturing techniques, material properties and the economical advantages of CRA clad lined tubulars. Details are also presented on Grant Prideco’s recently developed CRA downhole tubing product with a threaded and coupled (T&C) connection design. Material discussions are centered around the Ni based CRA’s as these materials have show the most promise technically and economically for use in clad lined production tubing applications.

Introduction

Over the last five years there has been an increasing need for downhole tubing suitable for severe CO_2 and H_2S environments. Numerous Ni base alloys have well established corrosion resistant attributes for these production applications but are extremely costly when utilized as a solid wall tubular. The exorbitant cost of solid wall CRA tubulars has resulted in many projects being deemed uneconomical or postponed and therefore have not been pursued. A CRA clad lined tubular has been developed in conjunction with a premium threaded connector which provides the necessary corrosion protection, structural integrity and also offers considerable cost savings over solid wall CRA tubulars. International demand for gas is expected to increase 85% from 1995 to 2015 (78 tcf to 145 tcf). Over the next 20 years, gas usage will be three times that of oil[1]. With the increasing need worldwide (especially in the non-developed industrial regions) for more gas to satisfy world demand, this new clad tubular will provide the economic incentive to explore and produce oil and gas in regions that were previously uneconomical.

1. Corrosion Risks

Because the tubing in an oil and gas well acts as the conduit through which fluids are transported to the surface from the reservoir, the tubing must withstand corrosion from aqueous solutions of hydrocarbons as well as dissolved gases like CO_2 and H_2S. Over the last 15 years a significant improvement has been made in the prediction of CO_2 corrosion rates as well as the susceptibility of sulfide stress cracking (SSC) from H_2S. Although the analysis for specific material selection is beyond the scope of this paper (there are many resources available to the drilling and production engineer to address specific applications of materials[2,3]), a general overview is provided. For the traditional carbon steel grades of tubing detailed in API Specification 5CT[4], water must be in contact with the steel surface for corrosion to occur. In oil wells, analyses of the hydrocarbon flow stream reveals there is typically no direct wetting of the steel surface and therefore very little chance of corrosion. Gas wells, on the other hand, present corrosion problems due to the condensation of water when the temperature of the gas falls below the dew point. This occurs at a specific point in the tubing string based on the temperature profile of the well. When multiphase (gas-liquid) conditions exist, the wetting of the steel surface is greatly dependent on the flow regime. When production tubing is completely full with oil and water mixtures, the water typically exists as an emulsion. Providing the fluid stream is not stagnant, and sufficient flow rate exists, there is usually little chance of corrosion to occur as the water does not have a chance to settle out and contact the steel surface.

When CO_2 is present in the flow stream, additional corrosion considerations are necessary. The presence of CO_2 can considerably increase the weight loss corrosion of carbon and alloy steel tubing. The corrosion rate is a function of the temperature, CO_2 concentration and the partial pressure. Since regulatory and environmental guidelines usually prohibit the allowance for predictable weight loss corrosion (i.e. increasing the wall thickness to compensate for corrosion through the wall of the pipe), the selection of alternate SS and CRA materials are made.

When H_2S is present the corrosion problem switches from a weight loss (pitting and crevice corrosion) issue to a sulfide stress cracking (SSC) phenomena. There is a wealth of knowledge that exists with respect to the use of carbon alloy steels for use in H_2S environments downhole, especially for high strength casing applications[5]. The referenced paper provides details on the use of L80, C90, T95 and proprietary high strength casing and tubing products made from the more traditional carbon alloy materials.

Considerable literature exists detailing the theories of the hydrogen SSC mechanism.[6,7,8,9] Hydrogen sulfide stress cracking (SSC) is defined as the spontaneous fracturing of steel that subjected simultaneously to an aqueous corrosive hydrogen sulfide medium and a static stress less than the tensile strength of the material. It usually occurs in a brittle manner, resulting in catastrophic failures at stresses less than the yield strength of the material. Hydrogen SSC is basically a hydrogen embrittlement mechanism resulting from the formation of hydrogen ions (H^+) in the presence of aqueous hydrogen sulfide (H_2S).

$$2(H_2S) + Fe + H_2O \rightleftarrows FeS + 2H^+ + S^- + H_2(gas) + H_2O$$

Some of the hydrogen released by the reaction does not recombine to form molecular hydrogen (H_2) due to the presence of sulfide; but forms nascent or ionic (H^+ hydrogen. These extremely small hydrogen ions (proton nucleus, stripped of its electron) are considerable smaller than the H_2 molecules or the metal atoms of the steel. These ions easily diffuse into the metal crystal lattice. The diffusion of ionic hydrogen can occur rapidly due to its small size and failures can result in amazingly short periods. After migrating into the metal, the hydrogen ions recombine to form H_2 molecules at normal impurities and discontinuities (dislocations) in the steel. Because the hydrogen gas molecules (H_2) occupy more volume than the individual hydrogen ions (H^+), they cause extreme stress on the metal crystal lattice. Hydrogen SSC resistance is a function of both the material and the environment. There are four major contributing factors for the sulfide stress cracking process to occur:

1. Absorption of a significant quantity of H^+ from the environment
2. Tensile Stress of sufficient magnitude
3. Susceptible metallurgical properties of the material and,
4. Time

2. CRA Materials

The use of CRA's for controlling corrosion in oil and gas operations has numerous benefits. Production systems that are designed and constructed with the properly selected CRA, based on established material properties, laboratory testing and previous field experience, will provide a safe and leak free system for the full life of the project. Although the material costs of these systems are significantly greater than the cost of standard carbon alloy systems, there are many wet corrosive environments that cannot safely be explored and developed without the use of these CRA materials. Additional cost savings and safety can be realized since corrosion inhibitor injection is not required. Maintenance costs are also greatly reduced compared to carbon steel production systems. When a lifetime costing analyses is conducted, CRA materials often demonstrate to be a viable economic option.

Over the last 20 years, improvements in alloy metallurgy, melting technology and thermo-mechanical processing; together with a better understanding of the fundamental role of various alloying elements, has let to the development of new nickel alloys and stainless steels. The utilization of stainless steels is limited compared with that of the Ni based CRA alloys. It is well established that as the Ni content is raise to 25% and above, time to failure is markedly increased. At about 45% Ni, the alloys do not crack[10] (Figure 1) in the commonly used and very severe 42% magnesium chloride test solution. Corrosion Resistant Alloys (CRA's) are defined as those alloys whose mass-loss corrosion rate in produced fluids is at least an order of magnitude less than carbon steel, thus providing an alternative method to using inhibition for corrosion control. Table 1 shows the composition of various Ni based CRA grades that are utilized for maximum corrosion resistance in aqueous H_2S and CO_2 environments. The Ni based alloys are categorized as Nickel-Chromium-Molybdenum grades and are versatile for use in most critical service production environments. The mode of cracking in Ni based alloys is occasionally intergranular.

Proper alloy selection is dependent on the presence of other corrosive media in the production stream. Table 2 provides general guidelines for alloy selection.

3. Environments

Over the last 25 years there has been considerable experience attained when drilling and completing deep oil and gas wells that contain hydrogen sulfide (H_2S) and carbon dioxide (CO_2). There is a significant amount of literature[11,12,13] detailing material selection for these environments as well as environments which produce acid by-products that further add to the severely corrosive environment for tubulars downhole. CRA materials have significantly better corrosion resistance than that of traditional carbon alloy steels that are utilized when drilling in sweeter and more benign environments. The material selection for corrosion resistant alloys in the oil and gas industry is also well documented[2, 3]. The tables detailed below represent field experience with specific CRA's

- Table 3: UNS N08825 (Alloy 825)
- Table 4: UNS N08825 (Alloy 925)
- Table 5: UNS N08625 (Alloy 625)

Literature exists which describe the corrosion resistance in H_2S and CO_2 at various temperatures based on laboratory testing (in the absence of elemental sulphur with corrosion rates of $\leq$ 0.05 mm/yr and no SSC or SCC).

- Figure 2: UNS N08825 (Alloy 825)
- Figure 3: UNS N00276 (Alloy C276)

4. Clad/Lined Pipe Product Development

Over the last ten years there have been several manufacturing methods developed for producing CRA clad/lined tubulars. The American Petroleum Institute (API) has also developed a specification for the CRA clad and lined line pipe (API 5LD[14]) Clad ans lined tubulars have gained relatively wide acceptance for use in transporting petroleum products and for refinery applications. The use of these tubulars has not gained acceptance for downhole oil and gas operations primarily due to the lack of a threaded connection that has demonstrated adequate performance. Clad or lined CRA tubulars are classified in two basic categories: metallurgically bonded and mechanically lined.

Metallurgically Bonded Tubulars

Metallurgically bonded tubulars are those in which there is a metallurgical bond between the structural outer pipe and the corrosion resistant inner pipe. There are several manufacturing techniques currently employed to produce these products and are described below. The metallurgically bonded tubular tends to be more costly than those that are mechanically lined. Longitudinally welded pipe is produced today from clad plate produced by hot roll formed or explosively bonded plate. Although length restrictions exist with these two methods of manufacture, it is common to girth weld two lengths together to fabricate a longer length. Before forming the plate into pipe the plate should be thoroughly cleaned and examined for surface defects. The edges of the plate are machined to prepare the surfaces for welding The plate is then formed into a tubular shell by three common methods: UOE, press bending, traditional pipe rolling methods. Nondestructive testing of the metallurgically bonded plate used to produce a tubular usually involves ultrasonic inspection of the carbon alloy steel backing material and the CRA layer. It is not uncommon to achieve bonding of greater than 98% of the surface area being joined. In addition to monitoring thickness of the individual material components, intergranular corrosion tests (ASTM A263)[15] and bond shear tests (ASTM A264)[16] are typically conducted to assure an adequate metallurgical bond has been attained.

Extrusion Method: This production method involves taking a combination billet of carbon steel and CRA material and hot extruding the hollow to longer lengths. A thick wall carbon steel tubular is machined to very tight tolerances and then a CRA tubular is inserted into the bore. The CRA tubular shell is also machined to exacting tolerances. Several techniques have been used to produce the combination billet. One technique involves heating the outer carbon steel billet so it expands and then the CRA billet is inserted into the bore. The other technique is to cool the inner CRA billet to extremely cold temperatures and then insert it into the carbon steel outer billet. For both techniques, when the temperatures of the two components reach equilibrium at room temperature, a tight mechanical fit is created. This prevents the CRA inner billet from moving within the outer billet. The ends of the combination billet are commonly seal welded prior to extruding to prevent the intrusion of air, oxygen and other contaminants into the interface. This practice varies based on the specific producer but it's main objective is to facilitate a higher percentage of bonding between the two tubular surfaces. This heavy wall tubular billet is then extruded. Extrusion is performed at temperatures in excess of 1260^0C (2300^0F) which results in a metallurgical bond between the carbon steel outer pipe and the CRA material on the ID surface. There are various techniques being used and developed to improve the bonding efficiency between the outer carbon steel pipe and the inner CRA liner. The final length of the clad extrusion is limited by the capacity (capable forces to hot work the tubular) of the extrusion press. Metallurgically bonded extruded pipe, has had some limited use for the bends of transmission, gathering and flow lines as this method of manufacture is more costly than the mechanically lined CRA tubulars which have found significant application for the straight portions of these oil and gas transportation systems.

Clad Plate Forming: Clad plates can be produced by three common methods; hot roll bonding, explosive bonding and weld overlay. Clad plates have been used extensively for many processing vessels, separators, heat exchangers and plate. Hot, roll bonding accounts for more than 90% of the clad plate production, worldwide (~ 55,000 tons/year). Once the clad plate is produced it is formed into a tubular shell and longitudinally welded full length.

Hot Roll Bonding: The typical roll bonding technique involves the independent preparation of the structural, backing carbon steel and the CRA alloy slabs. The surfaces of the slabs that are joined together are precisely ground and chemically processed prior to assembly to assure a high quality bond with minimal defects. The formation of the bond in hot rolled plate is dependent upon atomic diffusion between the two materials. Special techniques are employed to eliminate detrimental hardening and the formation of oxides at the interface due to the precipitation of intermetallic phases or carbides. Careful control of the carbon steel backing material chemistry can also be utilized to reduce the risk of the formation of these precipitates at the interface layer. Once the two slabs are ground and chemically prepared it is common practice to sandwich two carbon steel/CRA plates together with the two CRA layers in contact with one another. This facilitates two clad plates being rolled at the same time. By rolling two clad plates at the same time there is no contact between the CRA material and the high carbon rolls that eliminates any possibility of contamination of the CRA material during the rolling process. Once the ground and cleaned surfaces are put together the interface between the two clad layers is coated with a separating compound, typically Cr_2O_3 or ZrO_2 powder. This prevents the two CRA alloy surfaces from sticking together and also minimizes oxidation at the interface during the rolling operation. After the interface is coated, the edges of the plate are seal welded to prevent separation of the individual plates during the hot rolling operation. Another technique that is sometimes used to minimize oxidation involves evacuating the sandwich of slabs of air, replacing the air with argon and then welding the edges of the sandwich. The sandwich of carbon steel and CRA material is then heated to rolling temperatures in excess of 1540^0 F (2800^0F) and rolled to form two clad plates of the proper dimensions with a metallurgical bond between each of the carbon steel and CRA interfaces. Roll bonded plates have been produced with clad thickness between 6 and 200mm (.236 and 7.874 inches). The typical clad layer thickness is between 2 and 4mm (.08 and .16 inches) for lengths of plate from 14 to 20m (46 to 66 feet).

Explosive Bonding: Explosive bonding uses a very short duration, high-energy impulse from an explosion to drive two surfaces of metal together. The explosion cleans away surface oxides and creates a metallic bond between the carbon alloy backing steel and CRA layer. The two surfaces do not collide instantaneously but do so progressively over the interface area. The explosion creates a collision front that results in plastic deformation of the surface layers. The plastic deformation removes any surface contaminants and oxides in the form of a jet projected ahead of the collision front. This results in extremely clean surfaces under pressure and results in a wavy bond line that is characteristic of explosion bonding. The manufacturer selects the explosive charge based on the strength and surface area of the materials being joined. The maximum amount of explosives that can be detonated depends on the environmental conditions at the manufacturing site. Some manufacturers detonate the explosive in vacuum chambers to reduce the noise level. Bonding is more difficult for materials that have low impact toughness. By controlling the variables of the process, explosive bonding can be achieved for most material combinations. Incorrect bonding parameters can lead to cracking of the materials so careful control of the process is important. Clad thickness of between 3 and 25 mm (.118 and .98 in.) are possible. Thinner clad layers pose problems due to the wave amplitude of the bonding mechanism increases as a function of the distance from the source of explosion. A point is quickly encountered where the wave amplitude is greater than the CRA layer thickness and failure occurs as a result of shear initiating from the wave crests.

Weld Overlaying: Early in the development of clad tubulars, clad plate produced from welded overlays on carbon steel backing materials were common, especially for forming into vessel shells. Today this method is predominantly utilized for completed vessels. Various welding methods have been proven over the last 30 years. GTAW and GMAW techniques are well established. For applying weld overlays on existing structures and vessels. The welding method is chosen based on access, welding position (downhand or positional), alloy type and dilution requirements and economics. Overlay deposits may require machining which may be difficult for enclosed vessels. In addition machining issues have made this cladding method unecomical for long lengths of tubulars. Because of the economic issues this method of cladding is utilized for short tubular sections where thick (>10mm) CRA thickness is required and machining after welding is not critical.

Mechanically Lined Tubulars

The simplest and most economic method of producing clad pipe is to internally line carbon steel tubulars. This method of manufacture does not create a metallurgical bond between the outer pipe used for structural integrity, and the inner liner pipe that is selected for the appropriate corrosion resistance. For applications where bending is critical for the serviceability, this method of manufacture is unsuitable due to buckling of the liner. Over the last 5 years, mechanically CRA lined line pipe has gained wide market acceptance. This method of manufacture provides better quality control features compared to metallurgically bonded pipe because each of the pipe components (outer pipe and liner) can be independently inspected utilizing traditional inspection techniques. The lack of a metallurgical bond at the interface of the outer pipe and liner eliminates the difficulties associated with ultrasonic flaw inspection of the piping components.

Outer Carbon Steel Pipe

For line pipe applications (transmission, gathering and flow lines), ERW, SAW or DSAW carbon steel pipes have been successfully used. These methods of carbon steel pipe making involve forming a tubular shell and then full length longitudinally welding a seam. A full length longitudinal weld seam does not present significant quality concerns because access to the tubular during service is easily attained, pressures are relatively low compared to downhole oil and gas production operations and there is no exposure of the carbon steel tubular to the corrosive media. For the limited downhole oil and gas drilling and completion applications that have employed to date with clad tubulars, seamless carbon steel has been used. This preference eliminates the issue of full-length weld seam quality issues and provides the end user with additional confidence for downhole production operations where failures can be extremely costly.

Inner CRA Liner

The inner CRA liner has been successfully and economically produced by forming a CRA tubular shell and longitudinally seam welding. The GTAW welding method has successfully been used for the Ni based CRA liners but other automatic welding techniques have been used depending on the CRA liner being produced. Once the liner is inserted and processed to provide the necessary mechanical fit, seal welding is typical in order to prevent the entrapment of deleterious gas and fluids through the annulus after manufacturing is complete and the product is put into service.

5. Clad Downhole Tubing

Clad and lined CRA tubing products have been experimented with in the past for downhole oil and gas production applications. Previous attempts of utilizing the product were hindered by connection integrity issues.

New Development for Down-Hole Tubing

An improved, mechanically lined CRA tubular, has been developed by Grant Prideco L.P., which is designed for use in downhole production applications. The product incorporates a proprietary threaded and coupled connector that is discussed below. The utilization of mechanically lined tubulars was chosen due to the industry acceptance of these clad tubulars for oil and gas transportation applications and the economic advantages over solid CRA tubulars. Significant work has been done over the past two years to further develop the product. The outer pipe of this tubing is the traditional carbon alloy steel that is fairly resistant to SSC. Since the outer surface (OD) of the tubing will be protected with drilling fluids and corrosion inhibitors (like the inside surfaces of casing), this surface does not have to have the same corrosion resistance as the ID of the tubing that is transmitting the highly corrosive oil and gas products from the reservoir. The inner CRA liner can be a variety of CRA materials. Special solid CRA tubular sections are welded onto the ends of the carbon steel pipe prior to lining in order to assure a complete barrier to the produced fluids. After the solid CRA tubular sections are attached to the carbon steel, the CRA liner is inserted into the tubular and hydro formed to provide a tight mechanical fit. The ends are seal welded and a special designed threaded connection is machined on each end. The tubulars are connected to one another using a solid CRA coupling. (Figure 4.) Below are further details of the product attributes.

Outer (C90 or T95) Pipe:

The outer pipe is seamless, carbon alloy steel tubular that complies with the requirements of API Spec 5CT – 6th Edition[4] for sour service products. This carbon steel alloy is an AISI 4130 type steel that is quenched (water) and tempered and is suitable for sour service environments per the guidelines in NACE MR0175-2000[17]. Table 6 details the mechanical properties of the two basic sour service carbon steel tubing grades that have been developed for this product. They are assessed for resistance to H_2S by the use of a qualifying test detailed in NACE TM0177-96[18] (latest edition). The outer pipe is produced in 13 m (~43 ft.) random lengths. The heat treatment of this product is performed in a continuous line, gas fired walking beam furnace to assure consistent metallurgical uniformity through-wall. Computer control and monitoring of the processing operations are employed to further improve process control variability. After the initial heating to an austenitizing temperature of approximately 927^0C (1700^0F), the tubular is simultaneously water quenched on the ID and OD surfaces to further improve the desired metallurgical uniformity. The tube is then tempered to the required mechanical properties. After tempering the tubular is hot sized and/or straightened as necessary to provide a finished product ready for lining. The use of hot sizing and/or straightening, rather than cold sizing and/or straightening, is required in order to minimize any cold working which is detrimental to SSC and collapse resistance.

Inner Pipe (Alloy 825) CRA Lining

The inner pipe lining can be produced in various thicknesses from 2 to 8mm (.078 to .315 in.). Prototype tubing has been produced utilizing a 3mm (.118 in) Alloy 825 liner. This CRA liner alloy was selected for the first prototypes because there is considerable field experience for this alloy in transmission and gathering line applications. The CRA liner is longitudinally TIG welded utilizing automated welding equipment. After welding the longitudinal seam of the liner it is NDT inspected and subsequently inserted into the carbon steel outer pipe. The OD dimension of the liner is carefully controlled. This is done to assure that when it is hydro formed into place, it plastically deforms while the carbon steel elastically expands and then contracts to properly grip the liner. Two hydro forming machines are available for liner processing. One can process liners up to 6 m (20 ft.) lengths while the other is capable of hydro forming the liner up to 12 m (40 ft.) long (Figures 5 and 6). Since this product is designed for production tubing applications the final length of the tubing will be approximately 12m (40 ft.) long to minimize the number of connectors necessary. After the CRA liner is hydro formed into the carbon steel alloy pipe, the ends are seal welded to prevent the infiltration of deleterious fluids and gas at the interface. The seal weld is accomplished using the TIG welding process. A compatible filler metal is used to make the seal weld (Figure 7).

Special End Pieces

Prior to lining the pipe, a solid CRA tubular section, approximately 102mm (4 in.) long is arc welded to each end of the lined tubular. Protoypes have been produced utilizing CRA 925 material that is precipitation hardened and solution annealed to provide the proper strength level for the connector design.

End Piece Welding

Both GMAW and GTAW arc welding methods have been developed utilizing INCO 725 NDUR^{TM} filler metal[19] for attaching the end pieces. Full penetration welds are made from the ID to OD surfaces. Automatic welding machines are utilized to provide a consistent, high quality weld. The purpose of the solid Alloy 925 CRA end pieces is to facilitate a complete barrier to the production fluids transmitted through the bore while also providing the necessary strength for the structural integrity of the connector. Since a CRA liner is applied to the ID surface after the end piece welding is complete the weld region and heat affected zones are protected from the producing fluids of the well.

Corrosion Testing of End Piece Welds

Corrosion (pitting) testing of the end piece weld has been conducted in accordance with ASTM G48 – Method C[20]. This standardized test method is designed to determine the susceptibility of pitting[21] (Figure 8) and crevice corrosion. Test results performed to date indicate that the corrosion resistance of the weld region is better than that of Alloy 825, the CRA material utilized for the liner.

SSC corrosion testing is currently underway to demonstrate that the end piece weld region has adequate resistance to cracking in sour environments. NACE TM0177-96: Method A[18] testing is a 30 day endurance test. Although the weld metal and heat affected zones will be covered by the CRA 825 liner on the ID surface, sufficient SSC resistance on the OD surface of the tubular will be demonstrated upon completion of these tests. Together with proper inhibition with packer and completion fluids the OD surface of the tubing, like the ID surface of the casing will have sufficient resistance to SSC and weight loss corrosion.

INCO 725 NDUR Filler Metal

INCO-Weld Filler Metal 725NDUR^{TM} is an age hardenable version of INCONNEL Filler Metal 625. After heat treatment, this alloy combines the excellent corrosion resistance of Alloy 625 with higher strength and hardness.[19] The typical chemical composition is shown in Table 1. 725NDUR^{TM} filler metal was not only selected for it's corrosion resistance and strength capabilities but also because it is hardened in the same temperature range at which the carbon alloy steel C90 and T95 are stress relieved at. The mechanical properties of 725NDUR^{TM} are exceptional. At room temperature the yield strength of the aged and hardened alloy is approximately 130 KSI with extremely high ductility. Elongations over 30% and reductions of area over 40% are typical at a room temperature of 38^0C (100^0F). At elevated temperatures between 150 to 260^0C (300 to 500^0F), there is no degradation in ductility with only a slight reduction in yield strength at 260^0C (500^0F) to approximately 115 KSI. These properties are optimal for downhole tubing applications where deep sour gas and CO_2 are present.[22]

Heat Treatment of End Piece Welds

The end piece welds are quenched and tempered after welding unless end pieces must be reattached after product is initially manufactured and shipped. A temper-only heat-treating procedure has been developed to enable the reapplication of new end pieces and threaded connections in the event there is damage to the threads in service or in transport. This facilitates a practical solution for the common occurrence of damaged threaded connections.

6. Clad Tubing Connector

The threaded connector for this product has an excellent track record with significant field usage. The Grant Prideco threaded and coupled (T&C) connector provides sufficient strength and leak resistance and has been used on traditional casing and tubing for many years. The location of the end piece weld was positioned utilizing finite element analysis (FEA) in a region of the connector where loading is predominantly in compression. The pressure seal is the result of a "metal to metal seal" at the pin nose and a precisely machined sealing surface in the coupling (Figure 4). The connector design allows for the use of a secondary PTFE seal ring to provide redundancy.

7. Economic Saving

Considerable cost savings can be attained by the use of clad and lined materials compared to solid CRA materials. This is particularly evident when the heavier wall thickness and larger outside diameters of a solid CRA tubulars are necessary to satisfy the downhole corrosion issues, strength, pressure containing ability and flow rates for a specific downhole application. An example of the cost savings[2] associated with using metallurgically bonded clad plate is shown in Figure 9. The cost savings are further enhanced when lined CRA tubing is used rather than the more expensive metallurgically bonded product.

Conclusions

The development of Grant Prideco's T&C, CRA lined tubular now provides the oil and gas industry an alternative product for use downhole, in severe applications. The utilization of an established threaded connector should eliminate the prior concerns over connector integrity. The ability to produce these tubing products at considerable savings when compared to solid CRA tubulars will open up new areas of the world to drilling, as it will now be economically feasible to complete and produce these reservoirs which up until now were not economically viable. The significant increase in the demand for gas[1] will further prompt the oil and gas industry to utilize downhole CRA lined tubing products.

Nomenclature

AISI = American Institute of Steel Industry
API = American Petroleum Institute
CRA = corrosion resistant alloys
DSAW = Double Submerged Arc Welded
ERW = Electric Resistance Welded
FEA = Finite Element Analysis
Ft. = feet
g/L = Grams per Liter
GMAW = Gas Metal Arc Welding
GTAW = Gas tungsten Arc Welding
ID = Inside Diameter
in. = inches
M = meters
mm/yr = millimeters per year
NACE = National Association of Corrosion Engineers
OD = Outside Diameter
Psi – pounds per square inch
PTFE – Polytetrafluoroethelene, i.e. Teflon™
SAW = Submerged Arc Welded
SCC = Stress Corrosion Cracking
SS=Stainless Steel
SSC = Sulfide Stress Cracking
T&C = Threaded and Coupled
tcf =trillion cubic feet
UNS=Unified Numbering System
UOE = "U"ing and "O"ing Expansion

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20. ASTM G48, "Standard Test Method for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution"
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Tables and Figures

ALLOY (UNS No.)	Cr	Ni	Mo	Fe	Mn	C - Max	Cb+Ta	Other - Max
825 (N08825)	22	42	3	Bal	0.5	0.03		.9 Ti, 2 Cu
925 (N088925)	19/21.0	24/28.0	6/7.0	Bal	1.0 Max	0.02		1.5 Cu
725 (N088725)	21	58	8	Bal	0.25	0.02		
625 (N08625)	22	Bal	9	2	0.2	0.05		3.5Cb
G3 (N06985)	21/23.5	Bal	6/8.0	18/21.0	1.0 Max	0.015	.50 Max	2.5 Cu, 2.4 W
G30 (N06030)	28/31.5	Bal	4/6.0	13/17.0	1.5 Max	0.03	.3/1.5	4.0 W
G50 (N06050)	19/21.0	50.0 Min	8/10.0	15/20.0	1.0 Max	0.015	.50 Max	2.5 Co
C276 (N010276)	15	Bal	16	6	-	0.01		2 Co, 3.5 W

Table 1 – CRA Alloy Compositions

ALLOY TYPE	PRIMARY APPLICATION ENVIRONMENT
Ni	Caustic Solutions
Ni-Cu	Mild Reducing Solutions Especially Hydrofluoric Acid
Ni-Mo	Strong Reducing Media
Ni-Fe-Cr	Oxidizing Solutions
Ni-Cr-Mo	Versatile For All Environments

Table 2 – Application Environments

Temp $_0$C	H_2S - psi	CO_2 - psi	NaCl - g/L
140 to 160	.50 to 5.0	<1000	>100
120 to 180+	>50	<1000	>100
0 to 100	0.05	<1000	<100
120 to 160	.05 to .50	<1000	<100
60 to 80	.50 to 5.0	<1000	<100
100 to 120	5.0 to 50	<1000	<100
60 to 80	>50	<1000	<100

Table 3 – Field Experience with UNS N08825 (825 Alloy)[6]

Temp $_0$C	H_2S - psi	CO_2 - psi	NaCl - g/L
80 to 100	<.05	<1000	<100
60 to 80		>1000	<100

Table 4 – Field Experience with UNS N08925 (925 Alloy)[6]

Temp $_0$C	H_2S - psi	CO_2 - psi	NaCl - g/L	NOTE
80 to 100	<.05	<1000	<100	
80 to 140	.05 to .50	<1000	<100	
60 to 120	.50 to 5.0	<1000	<100	
0 to 80	50 to 50	<1000	<100	
140 to 160	.50 to 5.0	<1000	> 100	
80 to 100	5.0 to 50	<1000	> 100	
120 to 180+	>50	<1000	> 100	
100 to 120	.05 to .50	<1000	<100	Free Sulphur

Table 5 – Field Experience with UNS N08625 (625 Alloy)[6]

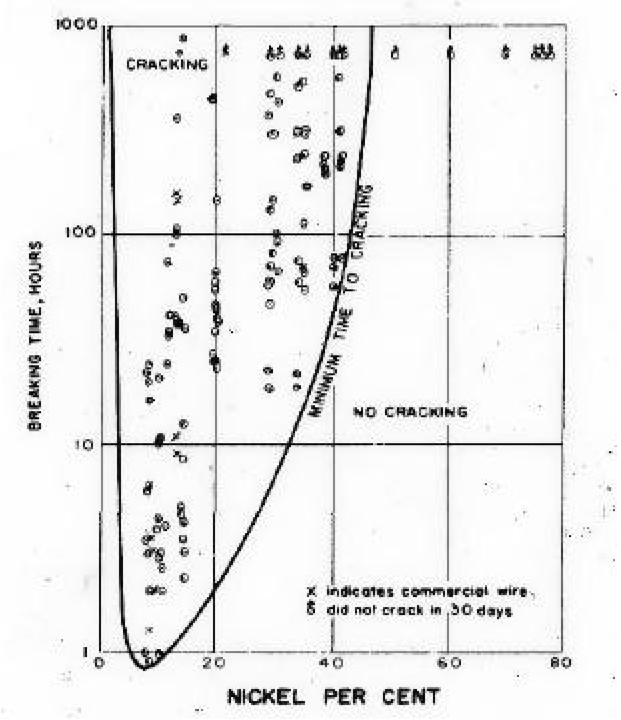


Figure 1 – Effect of Ni Content on Corrosion Cracking
42% Magnesium Chloride Test Solution

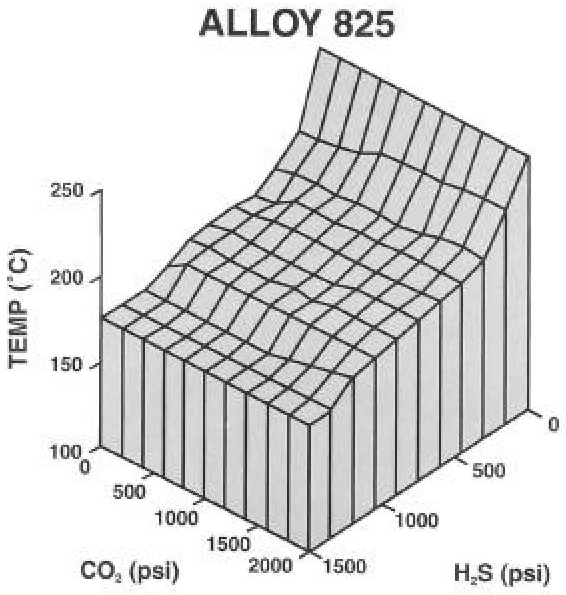


Figure 2 – Environmental Limits of Alloy 825 (UN08825)

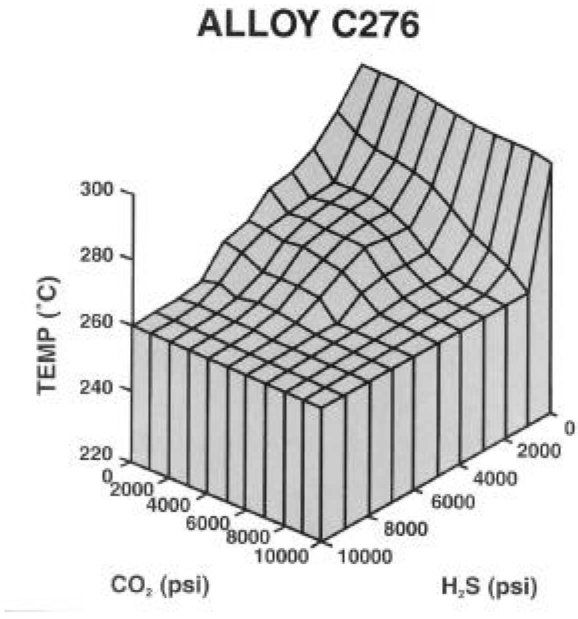


Figure 3 – Environmental Limits of Alloy C276 (UN10276)

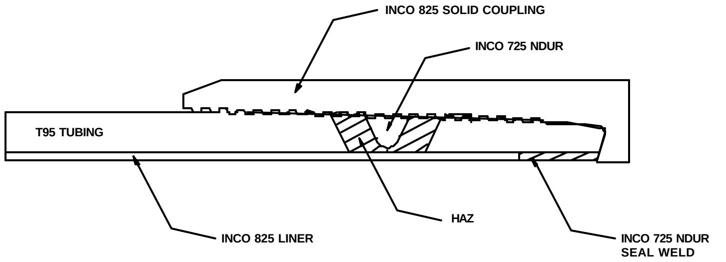


Figure 4 – Grant Prideco L.P. Downhole Tubular Product Components

Figure 5 – Butting Edelstahlrohre Hydroforming Equipment

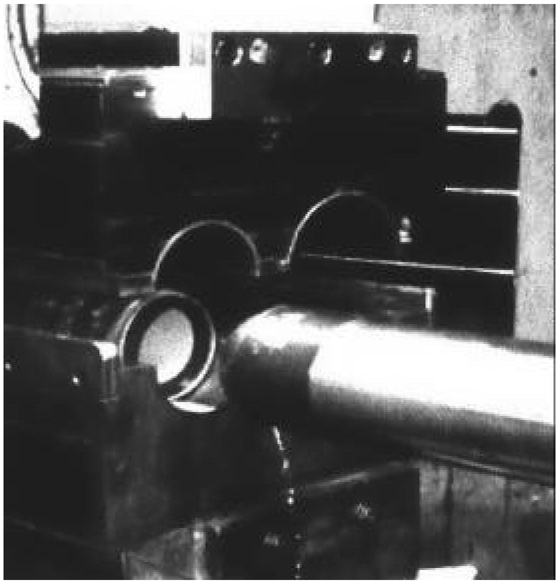


Figure 6 – Close Up of Ends
Butting Edelstahlrohre Hydroforming Equipment

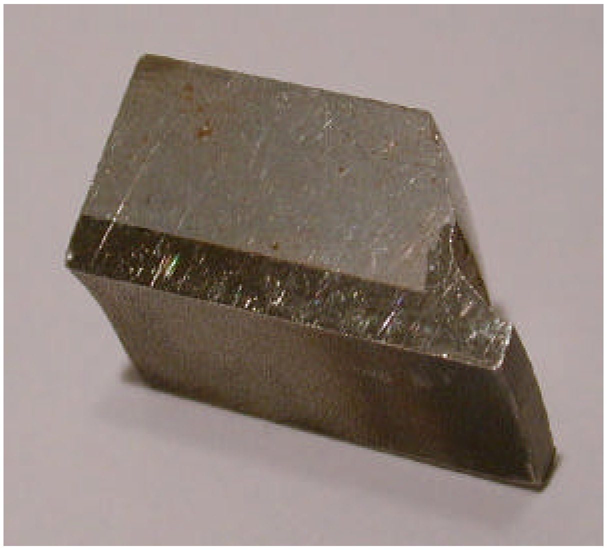
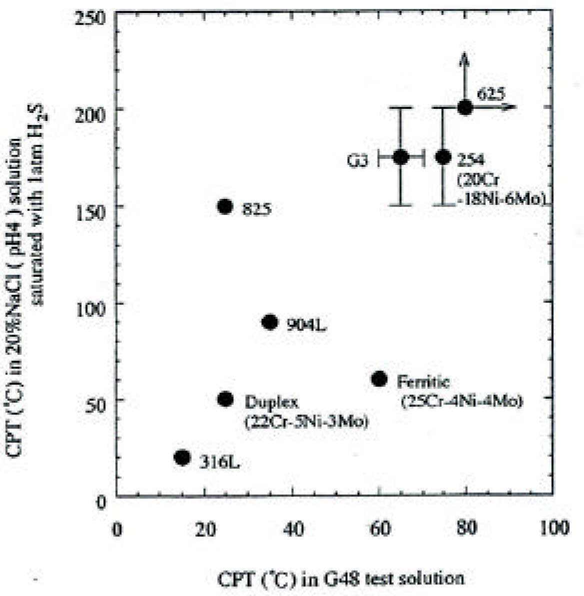


Figure 7 – TIG Seal Weld Between Carbon Steel and CRA Liner



…. Figure 8 – G48 Pitting Resistance of Several Ni Based CRA Alloys

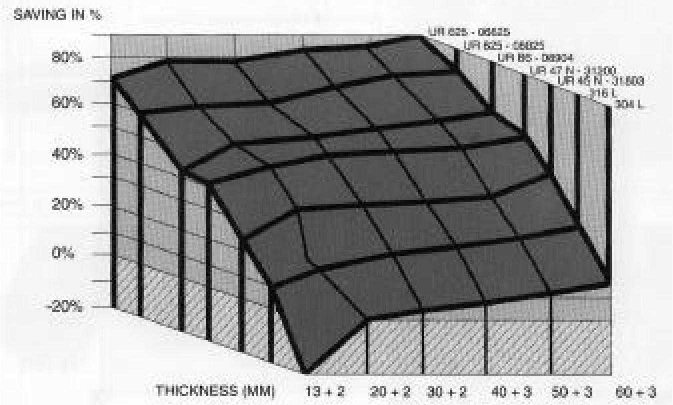


Figure 9 – Cost Savings of Various CRA Clad Plate Alloy Materials