Engineering with Clad Steel

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Engineering

with

CLAD STEEL

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ABSTRACT

Corrosion resistant alloy clad steel has been available in various forms for over 40 years and is being used increasingly in the oil and gas production industries. In the context of the specific requirements of this industrial sector, methods of manufacturing clad plate, pipe and fittings are given along with welding details and information on existing field applications of clad products.

Nevertheless, CRAs contain expensive alloying elements, particularly the more highly alloyed materials required for corrosive sour production systems. Clad steel is a composite product developed to provide effective and economic utilisation of expensive materials. The cladding layer which will be in contact with the corrosive fluids is made of the corrosion resistant alloy whilst the less expensive backing steel provides the strength and toughness required to maintain the mechanical integrity.

The cost saving from using clad steel rather than solid CRA is particularly valid when the total thickness increases or when the cladding grade becomes more complex and hence expensive. An indication of the sort of savings which can be made is illustrated for integrally bonded clad plates in Figure 1. Because high strength backing steel can be utilised, wall thicknesses can be reduced relative to solid CRAs thus reducing fabrication time and costs.

Clad steel plates have been utilised with great success in processing vessels, heat exchangers, tanks and a variety of material handling and storage facilities as well as for making longitudinally welded clad pipe. Clad steel has been available in various forms for more than 40 years and has been widely used in the chemical, oil refining and chemical transport industries and more recently in oil and gas production. Yet despite this there are still concerns regarding the use of clad steel. For some items, for instance vessels and pipe, the question is which kind of clad steel is cheapest or most appropriate for a given application. For other components, such as valves and fittings there are questions of availability and even the feasibility of cladding such components. Finally there are questions about the fabrication of clad steel, joint design and appropriate welding methods. This paper aims to address these matters relating to clad steel in order that it can be applied with confidence.


2. CLAD PLATE

Clad plates can be produced by hot roll-bonding, explosive bonding and weld overlaying. Table 1 lists some of the alloys which are available in clad form, which are of particular interest in oil and gas production. Typical product specifications are ASTM A264 (stainless chromium-nickel steel clad plate, sheet and strip) and ASTM A265 (nickel and nickel base alloy clad steel plate) and JIS G3602 (nickel and nickel alloy clad steels). Clad plate has been used extensively worldwide for many processing vessels, separators, contactors, heat exchangers and pipe etc (Figure 2). Table 2 lists a few recent examples of clad vessels as an indication of the scope.

2.1 Hot Roll Bonding

Hot roll-bonding accounts for more than 90% of clad plate production worldwide (@ 68,000 t/y). The normal manufacturing sequence requires separate preparation of the backing steel and clad material. The surfaces of the slabs which will be joined together are ground and chemically cleaned prior to assembly to prevent defects on the joint line. Depending on the cladding alloy manufacturers may electroplate the surface of the CRA slab with nickel or iron to prevent the formation of chromium oxides, aid bonding and increase the percentage of bonded area. Some manufacturing processes use a sheet of metal inserted between the CRA and backing material whilst certain material combinations can be directly bonded without a metal insert or electroplated layer.

The formation of the bond in hot rolled plate is dependent upon diffusion between the cladding and backing materials which can result, in certain combinations, in hardening at the interface due to precipitation of intermetallic phases or carbides. In the case where the initial slab is plated before hot rolling or insert metal is used such intermetallic phases do not form since the nickel or iron layer acts as a buffer. Careful control of the material chemistry, particularly the backing steel carbon content, can also reduce the risk of precipitates at the interface in the absence of an intermediate nickel or iron layer.

Once the cleaned surfaces of the cladding and backing materials are brought together it is normal to prepare a “sandwich” of two clad slabs with the clad surfaces together with a layer of a separating compound (such as CrI or ZrI powder) to prevent the surfaces sticking together. The two slabs are welded together around the edges to prevent separation during rolling. Surface oxidation of the cladding during rolling is prevented by some manufacturers, by evacuating this sandwich construction or replacing the air with argon.

The advantages of rolling the sandwich construction are primarily that the cladding layer does not contact the steel rolls during the rolling so that it is not contaminated. From a practical point of view, rolling two slabs together allows thinner plates to be produced and the sandwich does not distort as the tendency for the clad plates to curl due to differential elongation of the cladding and backing is compensated.

During rolling the increase in area of the slabs causes the surface oxides to break up which allows metal to metal contact between the cladding and backing metal so that a metallic bond is formed in the solid state.

The plate rolling sequence is normally followed by heat treatment which is usually required to restore the cladding to the solution annealed condition and to bring the backing material into the correct heat treatment condition (normalised or quenched and tempered etc).

The solution annealing temperature depends upon the clad alloy type and is normally in the range 950°C-1150°C. Alloys with lower annealing temperatures, such as UNS N08825 (alloy 825) and the 300 series austenitic stainless steels (950°C), as well as UNS N06625 (alloy 625) (980°C), are easier to handle because holding at higher temperatures encourages grain growth and subsequent loss of toughness of the backing steel. Most duplex stainless steels and UNS N08904 (alloy 904L) can be solution annealed at 1050°C, but UNS N08825 (alloy 28) requires 1150°C which can give problems in achieving the toughness of the backing material to which this is clad. Where required, further heat treatments may be carried out to optimise the mechanical properties of the backing steel.

After heat treatment the plates are separated, cleaned, cut to size and visually and ultrasonically inspected. The cleaning of the clad surface may be by grinding or pickling or both.

Quality control tests usually include ultrasonic checks on the plate and cladding thickness and cladding adherence. It is normal to achieve full bonding over >98% of the plate and repair (by welding) is rarely necessary. A typical inspection specification would be ASTM A578 (straight beam ultrasonic examination of plain and clad steel plates for special applications). Roll bonded clad plates are readily available in thicknesses from 6 to 200mm, width 1000-4400mm and length up to 14m or 20m, depending on supplier. Larger dimensions can be obtained in certain combinations. The thickness of the cladding layer is normally 2 to 4mm although thicker cladding layers are possible.
2.2 Explosive Bonding

Explosive bonding uses the very short duration high energy impulse of an explosion to drive two surfaces of metal together, simultaneously cleaning away surface oxide films and creating a metallic bond. The two surfaces do not collide instantaneously but progressively over the interface area. The pressure generated at the resulting collision front is extreme and causes plastic deformation of the surface layers. In this way, the surface layers and any contaminating oxides present upon them are removed in the form of a jet projected ahead of the collision front. This leaves perfectly clean surfaces under pressure to form the bond. Figure 3 illustrates the wavy interface which characterizes most explosive bonds.

The selection and quantity of the explosive charge are determined by the strength and thickness of the materials, the specific material combinations and the area which is to be bonded.

The upper limit to the amount of explosive which can be detonated depends upon the environmental considerations of the manufacturing site. Some manufacturers carry out explosive bonding in large vacuum chambers to cut down the noise level.

Bonding is harder to achieve in materials with low impact toughness (<20J) or low ductility (<15% elongation).

Nevertheless it is possible to clad most material combinations by adjusting the process. Explosive bonding is the preferred way of cladding refractory metals such as Titanium alloys and Zirconium directly onto steel, although they can be rollbonded with an interlayer material. Figure 4 shows a 1.4m diameter tube plate explosively clad with 14mm thick Titanium Gr.1 along with a 1m diameter tubeplate explosively clad with 10mm of AISI 321 stainless steel.

Incorrect bonding parameters can result in cracking between the refractory metal and substrate. This cracking is a result of residual stresses due to the differential elastic recovery between the cladding and substrate after the stretching which occurs during explosive cladding. Similar interface cracks may arise with explosively clad duplex stainless steels but this problem is eliminated if a ductile layer such as nickel is placed between the cladding and substrate.

Cladding thicknesses between 3 and 25mm are readily bonded. Very thin sheets pose a problem, particularly if reasonable areal dimensions are required. This is because the wave amplitude of the bonding line increases as a function of distance from the initiation point. Consequently a point is quickly reached where the wave amplitude is the greater part of the sheet thickness and failure occurs as a result of shear cracking emanating from the wave crests.

One way in which explosive bonding can be made more economic is by following the explosive bonding by a hot rolling procedure which increases the bonded area thus reducing the cost per unit area. The hot rolling process tends to smooth out the wavy interface (Figure 5).

Heat treatment is not necessary in most cases after explosive bonding so that almost any combination of cladding and backing materials can be chosen. Stress relieving is advised after cladding with Ti and Zr to improve bond ductility in any subsequent fabrication of the clad composite.

In terms of quality (percentage of bonded area and bond strength) there is very little difference between explosive and hot rolled clad plates. In the standard test explosive clad plate generally gives higher values than roll bonded whilst both comfortably exceed the specified minimum value of 140MPa shear strength.

2.3 Weld Overlaying

Clad plate for subsequent forming into vessel shells was produced by weld overlaying in the early development days, but nowadays overlaying is directly applied to the completed vessel shell, or to vessel dished ends, vessel cylinders or individual strakes, and this latter aspect will be referred to in this section. Overlaying of heavy vessels has been developed for nuclear vessels, oil refinery hydrocracker vessels and pulp digesters in the last 30 years and is now being applied increasingly in the oil and gas sector for separators, heat exchanger shells, end plates and tube plates.

Various welding methods have been adapted to overlaying.

The selection of any one technique is dependent upon:

(i) access
(ii) welding position (downhand or positional)
(iii) alloy type and dilution specified
(iv) economics

If access is difficult or if positional welding is required (for example for internal weld cladding on vessels which cannot be rotated) then GTA welding techniques are most likely to be selected. For example synergic GMAW with alloy 625 filler has been used for the in-situ refurbishment of corroded vessels by a North Sea operator.
A greater choice of techniques is available for downhand welding of plates or rotatable vessels and flanges etc. In this case the ability to achieve the required alloy composition at the required deposit thickness most economically has to be considered. For instance, a high deposition rate process may appear to be fast (therefore reducing the labour cost) but if the heat input is too high, excessive dilution with the underlying base metal may mean that a second layer is required. It may be possible to deposit two layers faster than a single layer with a lower heat input welding method but, if the final deposit depth is greater, then the material cost will be higher. Clearly there is a trade-off between different techniques and fabricators will also have their preferences.

Figure 6 gives a guide to the deposition rates achievable with different welding processes. For very large areas strip welding with submerged arc or electro-slag techniques will generally be the most economic although both these techniques can only be done in the downhand position [1]. In one North Sea project 3 separators were electro-slag clad with alloy 625 using 60mm wide strip. Figure 7 shows one of the 3.5m diameter, 1.4m long vessel after cladding. A further two towers for the same project were electro-slag clad with 316L stainless steel, the remaining low pressure separator used roll bonded 316L because the wall thickness was too thin (14mm) for this overlay welding technique [2].

Compared to subarc strip cladding which would have required two layers of weld deposit to meet the specified chemical composition requirements the electroslag process was faster and more economic. The electrically conductive flux and higher welding currents produce less dilution with the base metal which means the cladding can be welded with a single pass. In this case the dilution was typically 7% in terms of iron; dilutions less than 5% resulted in loss of fusion.

In general, vessel cladding by weld overlaying may be considered above 30-50mm thickness but is most appropriate for heavy wall thicknesses. In some cases it is selected because of easier availability compared to a mill product.

Where the process can be controlled to give the correct chemical composition after one layer deposit then it can be economic. Frequently unnecessarily stringent dilution requirements are specified which demand that two layers or more are deposited. A typical example is a maximum iron content of 5% in alloy 625 deposits (nominal iron content in wrought alloy 625, 5% and in typical filler wire 1-3%). This may be necessary in some applications but for most oilfield environments (i.e., seawater, aerated/deaerated brines, CO2 and H2S containing corrosive fluids) this is unnecessarily stringent. Test data on the influence of iron on the corrosion behaviour of alloy 625 clad layers in seawater and in CuCl2, showed very little effect with iron dilutions up to 20%. No iron-rich phases were detected, even with 20% Fe [3]. Rather than specifying a maximum iron content it would be better to specify minimum levels of those elements which confer corrosion resistance i.e. Cr and Mo.

Overlay welding processes which can meet the specified chemistry in one layer are particularly important for overlaying the high nickel alloys such as C276 and C22. These materials can suffer from heat liquation cracking of underlying deposits when additional layers are added. That is, a single deposited layer will be perfectly sound and crack free but with slightly lower melting point phases between the dendrites. When reheated by a subsequent weld pass these interdendritic regions may melt and produce cracks. If multiple layers are required then careful control of the heat input is necessary. In one project 12 layers of alloy C276 were welded to build a deposit of 25mm thickness for a heat exchanger tubeplate (Figure 8). Cracking was avoided by using hot wire GTAW with the heat input limited to 0.8 kJ/cm max.

Overlay deposits may require machining, which can be difficult, before final inspection with dye penetrant and possibly ultrasonic inspection. If the deposit is reasonably smooth so that dye penetrant inspection can be adequately carried out without machining, and if the ultrasonic inspection can be arranged from the backing steel side, final machining may not be necessary.

Heat treatment may be required after overlaying if the heat affected zone hardness of the backing steel exceeds specified limits. Dependant on the backing steel type a tempering treatment may be sufficient to soften the HAZ without affecting the corrosion resistance of the overlay.

2.4 Clad Plate Cutting and Forming

Clad plate can be cut using normal methods. For flame cutting it is advisable to cut from the base metal side with a slightly larger nozzle than is normal for cutting steel. Shearing (for thin plate), powder cutting and plasma arc cutting should all be started from the side of the cladding metal.

Cold and hot forming operations can be carried out on clad plate for the manufacture of heads and shells. In both cases the clad surface should be protected from damage or contamination. In cold forming, the procedure will follow that for the solid steel with intermediate stress relieving when the strain ratio
exceeds 5%. In hot forming, the procedure will follow that for the solid alloy with particular care to avoid holding the temperature in the sensitising range (for stainless steels and NiCrFeMo alloys, 600-850°C depending upon the cladding type) and the transformation zone for the base grades (700-830°C). Thus hot forming should be completed above 830°C or else followed by appropriate heat treatment.

3. CLAD PIPE

Clad pipe can be made in a number of ways, the different methods tending to be suited to specific size ranges. Whilst product lengths may vary most manufacturers will double joint to produce economic pipe lengths if required. Table 3 lists examples of applications of internally clad steel pipe.

A specification for CRA clad and lined steel pipe (API 5LD) is now available.

3.1 Longitudinally Welded Pipe

Longitudinally welded pipe is normally made from clad plate produced by hot rolling. The plate should be thoroughly examined for any surface defects before making into pipe. The edges of the plate are machined for welding and the plate is formed to pipe in a UOE, press bend or rolling mill [4]. The carbon steel portion of the longitudinal seam is usually welded with submerged arc welding. The inside surface should be backwelded to ensure adequate root fusion and to give a smooth profile (Figure 9).

The aim of the internal welding should be to give a continuous corrosion resistant layer of at least the thickness of the cladding layer right across the weld seam. Further details on welding are given in a later section. The pipe is then made circular by compression or expansion before being inspected (radiographic or ultrasonic weld seam examination, hydrostatic testing, dimensional inspection).

Longitudinally welded pipe has been made to a diameter as small as 100mm (4") but is normally available from 219mm (8") to 1016mm (40") outside diameter. The wall thickness range (cladding plus backing steel) is from 6mm up to 32mm. Single pipe lengths are available from 8m to 12.8m depending on supplier but double joints can usually be supplied. Figure 10 shows an order for a longitudinally clad flowline being prepared for transportation.

3.2 Seamless Pipe

Most standard methods of making seamless pipe have been adapted to the production of clad pipe.

Certain manufacturers also produce clad downhole tubing, the pipe ends being adapted and machined to form the necessary threaded connectors. An example of a threaded connection, designed to ensure no contact between the production fluid and the backing steel is shown in Figure 11. Example applications of internally clad production tubing are given in Table 4.

3.2.1 Lined Pipe

At its simplest a standard pipe can be internally lined by inserting a seamless or welded liner made of the CRA. The outer pipe may be heated before the liner is inserted. Concurrent with the thermal shrink the liner is hydraulically expanded outward against the steel shell. The liner is then held in place by the mechanical forces of the shrink-fit without forming an integral bond along the full length. If no heat is applied then the liner is simply hydraulically expanded inside the outer pipe. The liner is welded to the backing steel at the pipe ends to facilitate girth welding (Figure 12).

Lined pipe can also be made by explosive forming if the force is applied such that the outer pipe is only elastically deformed whilst the inner cladding is plastically deformed. As the outer pipe relaxes it contracts around the liner with the residual hoop stress forming the mechanical bond. Metallurgical bonding may be obtained on a limited portion (eg. the pipe ends).

Whilst lined pipes may be economic for straight pipe lengths they are not suitable for cold bends because of the risk of liner collapse. Methods for producing induction bends are being developed [5]. Care must be taken in welding lined pipes, particularly if welds have to be cut out and repaired. Early applications (1974) of this type of product failed because of defects in the longitudinal weld in the liner which allowed pressure rise between the liner and outer pipe. Such defects may now be more easily prevented or detected with advancements in manufacturing and inspection technology.
3.2.2 LIDB/Pipe Mill Products

The most common method of producing seamless pipe is the Liquid Interface Diffusion Bonding method in which a composite intermediate is made of a CRA pipe "nested" inside a carbon steel pipe. The surfaces of the CRA and carbon steel are separated by an electroless nickel plated layer applied before assembly. Other methods of composite intermediate production may be used, such as centricasting (see section 3.2.4) or the HIP technique (see section 3.2.5).

The CRA inner pipe may be fastened to the carbon steel outer pipe by welding prior to further processing through standard pipe mills such as a plug mill, mandrel mill or extrusion press to extend the length and bond the two pipes together.

In pipe which is produced from billet or bloom as described above the finished length is dependent upon the diameter and wall thickness since the volume of material is fixed by the billet or bloom size. Diameters can be as small as 50mm (2") and up to 225mm (9") or 400mm (16") dependent on supplier. Wall thickness varies from 6mm to 25mm. Seamless pipe made by these production routes is the most likely to suffer from lack of concentricity, variation in cladding layer thickness and a wider tolerance on circularity. This should be borne in mind when ordering the pipe to allow for a greater cladding thickness to cover the anticipated variation in thickness which may arise. Machining of the pipe ends has been carried out in some projects to improve the fit-up for welding.

3.2.3 Explosively Bonded Pipe

Currently there are developments in clad pipe produced by explosive bonding. In principal a CRA liner placed in a pipe can be explosively bonded by either expanding the pipe assembly outward in a die or by compressing it inward onto a mandrel. In these methods a full metallic bond is formed between the cladding layer and the pipe (Figure 13).

Unfortunately the plastic deformation which accompanies the explosive process tends to deform the pipe progressively along its length such that the end of the pipe may be smaller in wall thickness and diameter than the start which would lead to fit-up problems in field welding.

The maximum length which can be made by this approach is 3-5m.

This process is generally recognised to be labour intensive and would probably be uneconomic for long pipelines. Current developments will use the explosive bonding process to produce a semi-finished product which can then be further processed in standard pipe mills as described above. With this approach pipe of diameter 50-200mm, wall thickness 2-20mm, can be made in lengths from 6-12m. These products would be expected to have improved pipe end dimensional tolerances.

3.2.4 Centricast Pipe

An entirely different approach to clad seamless pipe production uses horizontal centrifugal casting technology. First, well refined molten steel is poured into a rotating metal mold with flux. After casting, the temperature of the outer shell is monitored. At a suitable temperature after solidification the molten CRA is introduced. The selection of flux, temperature of the outer shell when the molten CRA is introduced and the pouring temperature of the CRA are the most important factors to achieve a sound metallurgical bond. By controlling these various parameters it is possible to achieve minimum mixing at the interface and maintain homogenous cladding thickness and wall thickness.

Centrifugal casting is followed by heat treatment to solution anneal the cladding and normally quench and temper the outer pipe to achieve its required mechanical properties. Finally the pipe is machined externally and internally to remove the shallow interdendritic porosity in the bore and to achieve the required dimensions and surface finish. As a result of this step centri-cast pipe has excellent tolerance (+/-0.5mm) on diameter and wall thickness which is highly beneficial for achieving accurate fit-up for welding (Figure 14).

According to the ANSI/ASME B 31.3 Code for Pressure Piping a casting factor Ec of 0.8 is applied in computing maximum allowable design stresses irrespective of whether the casting is a complex static casting or a simple centrifugal cast pipe or cylinder. However, this factor Ec can be progressively increased to 1.0 if all surfaces are machined, dye penetrant inspected (to ensure all interdendritic porosity is removed) and the pipe is 100% radiographic or ultrasonic tested.

Centricast pipe is available with the outer steel strength up to grade API 5L X70 and internal cladding with alloys 316L, 825, 925 and C276. Sizes range from 100-400mm diameter, wall thickness 10-90mm (minimum 3mm cladding) and lengths typically 4-5m with longer lengths above 200mm diameter. Centricast pipe tends to be particularly economic at larger pipe diameters and heavier wall thicknesses.
Figure 15 shows a 6" diameter subsea manifold constructed in X52 steel with alloy 625 cladding manufactured by centricasting.

3.2.5 HIP-Clad Pipe

The hot isostatic pressing (HIP) technique is used as a diffusion bonding process for the production of clad components. The corrosion resistant alloy cladding may be in the form of powder or as a solid lining (a sleeve or foil), the choice depending on both technical and economic considerations. The surfaces to be bonded have first to be prepared and cleaned.

They are then brought into contact under pressure at elevated temperature so that asperities are smoothed out and a pore-free metallic bond is created by diffusion across the interface. The temperature is dependant upon the alloy type, for example alloy 625 is held at 1100°C. By controlling the temperature and holding time the diffusion zone depth can be controlled and limited, so there is no zone of dilution.

The final density achieved is 100% with no porosity. After hot isostatic pressing, heat treatment may be required to restore the mechanical properties of the backing steel although there is no “heat affected zone” in the conventional sense.

If powder coating is used then the powder has to be held in place by a can which is machined or chemically removed from the finished part. The gap between the backing steel and can is filled with powder and then evacuated and sealed prior to being hipped. Whilst the preparation is labour intensive several parts can be hipped simultaneously dependent upon the size and capacity of the equipment. Where powder is used, densification and diffusion bonding occur simultaneously. The use of powder leads to a fine homogeneous microstructure in the consolidated material which is relatively easy to machine.

HIP-clad tubes may be further processed through standard pipe mills to produce longer lengths.

4. CLAD FITTINGS

4.1 Fittings from Plate or Pipe

Fittings can be produced from clad plate or pipe by hot or cold forming processes. Bends with radius more than three times the outside diameter can be produced by high frequency induction heating (Figure 16). Short radius and long radius elbows are produced by the hot - die bending or the hot-mandrel bending process. Tees are produced by hot extruding or cold bulge forming. Heat treatment may be required after forming as previously discussed in section 2.4.

* trademark of Inco family of companies.

4.2 HIP-cladding of fittings

The HIP manufacturing method has been described in section 3.2.5. This method is particularly useful for small diameter tubular components, parts with complex geometry, small radius bends or with regions difficult to access by other cladding methods. It is most economic for more highly alloyed cladding layers such as nickel based alloys 825, 625, C276 etc. Figure 17 illustrates a 625 alloy powder HIP clad steel valve and Figure 18 shows a tee-piece made by HIP-cladding a solid lining onto the backing steel.

4.3 Overlay weld methods for fittings

Weld overlaying of large plates for vessels etc, was discussed in section 2.3 but various overlay processes are widely used for cladding fittings. Examples include:

a) Vessel fittings - extended weld neck flanges for nozzles, manways etc. Figure 19 shows 2", nominal bore long weld neck flanges internally weld overlaid with INCONEL® 625.

b) Wellheads - Xmas tree blocks (eg figure 20) and valves.

c) Valves and valve components - full bodies or seal areas, gates, balls etc. Figure 21 shows the internal double layer overlaying of a 40" subsea ball valve with INCONEL® 625 using a combination of automatic GMAW and automatic GTAW. Much smaller bores can also be weld overlaid such as the dual 3" nominal bore composite manifold valve body illustrated in Figure 22 in which all bores are hot wire GTAW overlaid with INCONEL® 625.

Pulsed GMAW of alloy 625 in single and double layers was used to overlay the 3/4" wing valve shown in Figure 23.

At very small sizes weld overlaid valves have to compete with solid alloy valves. However, above 4" in diameter many valve manufacturers prefer to supply clad (weld overlay or HIP clad) valves because the low alloy backing steel provides higher strength than the solid alloy can achieve.

d) Pipe fittings - flanges, elbows, tees and sphere tees, reducers, branches etc. Figure 24 shows a 30" nominal bore 90° elbow internally well overlaid with INCONEL® 625.

e) Pipes - external overlaying of riser penetrations into concrete structures and for pipeline sections in inaccessible shore approach tunnels. In one project a 22m length of API X60 line pipe was overlaid with 5mm deposit of alloy 625. Two passes were applied using synergic GMAW (Figure 25).
The preferred weld overlaying methods are usually pulsed or synergic GMAW and hot or cold wire GTAW [6]. These processes are suitable for positional welding and can be carefully controlled to meet dilution specifications. Approximate deposition rates were given in Figure 6 from which it can be seen that the deposition rate of hot wire GTAW is 5 times greater than cold wire GTAW and comparable to pulsed GMAW. GTAW is the most easily adapted for access down very small bores or areas of difficult access.

The limit on the length which can be overlaid is determined by the rigidity of the torch. Where access permits and the part can be rotated etc the other processes discussed for downhand welding (eg submerged arc) may be applied to fittings.

Manual welding is widely used for overlaying, particularly for ring grooves on flanges. Compared to automatic welding there will inevitably be less control of the process (particularly welding speed and distance overlap between weld beads) which may lead to more variable dilution.

Besides the greater repeatability of automatic welding there are other advantages such as easier access to difficult to reach areas; efficient use of consumables (no stub ends), and weld deposition for 100% of the duty cycle. In principle less skilled personnel are required for automatic welding although in practice there is generally some requirement for operator control of certain parameters within pre-set tolerance windows.

Flux covered arc welding and plasma transferred arc powder processes are generally used for deposition of hardfacing.

Weld overlay processes can be used on moderately thin components although it may be necessary to provide some heat sink or means of removing the heat build-up during welding otherwise distortion and metallurgical damage to the substrate may occur. Post welding heat treatment may be required after overlaying as discussed in section 2.3.

Most specifications (whether national eg API 6A, ASME or company specific) require dye penetrant inspection of the clad surface to detect any cracks. If cracks are detected some specifications require a ferroxyl test of the crack to detect whether it reaches down to the underlying steel. Such a test is really only appropriate to a single layer deposit. Other requirements usually depend upon ultrasonic inspection of the interface eg, to ASTM A578. If the geometry allows inspection from the backing steel side, this is preferred since then machining of the clad layer is not necessary.

4.4 Explosively Bonded Fittings

Explosive bonding as described in section 3.2.3 has been successfully applied to the production of fittings such as nozzles for pressure vessels.

5. WELDING OF CLAD STEEL

The aim of welding clad steel is to maintain a continuous fully corrosion resistant layer across the joint. In the case of single side welds in internally clad pipe the weld preparation is generally a ‘J’ bevel with the nose of the bevel being entirely within the clad layer (see Figure 26). Good cleanliness and dryness is essential to prevent contamination of the deposit with sulphur or hydrogen which could lead to cracking.

The root can then be welded entirely within the clad layer using GTAW with a filler of matching or overmatching corrosion resistance. For example for cladding of 304L or 316L a 309MoL filler would be preferred; for 904L, 825 or 625 cladding a 625 filler would be preferred.

Successful welding of this critical root weld is highly dependent upon good tolerance on the roundness of the pipe. If automatic GTAW with a closed root is to be used, the maximum hi-lo which can be tolerated is 0.5mm which therefore requires a very tight tolerance on the pipe internal diameter. Slightly wider tolerances may be allowed on larger size pipe where pipe clamps can be used to round the pipe before welding. Mismatch of the root can be more easily accommodated by manual GTAW where a root gap is used.

The use of GTAW with good back shielding with inert gas produces an inner bead free of flux or oxides and undiluted with steel, thus offering maximum corrosion resistance. The second pass (GTAW or GMAW), also with alloy filler, will be diluted by the carbon steel and therefore it is important that the heat input is not high enough to remelt the root pass entirely otherwise carbon steel may be mixed into the root. Heat inputs of 0.9 - 1.2 kl/cm are recommended. Internal gas shielding should be maintained to prevent oxidation of the hot root. Subsequent passes may be completed with the alloy filler using GTAW, GMAW or SMAW techniques.

Alternatively a buffer layer of pure iron can be deposited after which the weld can be completed with the appropriate steel filler. Direct change to steel filler without the intermediate iron buffer would result in a hard martensitic formation in the weld where the alloying elements from the alloy deposit are mixed into the higher carbon content steel deposit.
In many cases changing electrodes during welding is not felt to be practical and so the welds are completed with alloy filler. The economic benefit of using a buffer layer would be particularly felt for heavier wall thickness with many weld passes.

In the case where alloy fillers are used throughout the weld, the strength should be at least equal to the backing steel. The as-deposited weld yield strength of 309MoL is equal to X60 grade steel and 625 filler meets X65 requirements.

Where there is double sided access then the weld can be completed in the steel backing material (see typical preparation, Figure 27). The root can then be ground out from the inside surface and the clad layer completed using any overlay welding technique.

5.2 Possible Field Problems

It is sometimes found after making the weld preparation that the nose of the bevel does not lie entirely within the clad layer but includes some backing steel. This can be checked by etching the bevel with copper sulphate or copper ammonium chloride solution. It may be possible to grind off the carbon steel but if the nose is then too small the weld preparation will need to be built-up by initially weld overlaying the nose and then remachining.

Such on-the-spot repair techniques may be particularly relevant in the case of liner pipe if the pipe has to be cut outside the prepared end sections (eg due to a field weld cut-out). In that case the liner must be rewelded to the pipe and the end overlaid before remachining the bevel.

During a number of projects in different parts of the world fabricators have commented on a problem of arc blow whilst welding clad pipe. This problem arises with GTA welding, particularly with a 625 filler because the arc is fairly easily deflected by the magnetic field in the carbon steel. The problem is easily solved by demagnetising the pipe (which can be done on-site if necessary) to a level below 5 Gauss [7].

6. ENGINEERING WITH CLAD STEEL

The previous sections of this paper have described the wide range of products available in clad form and given examples of where clad steel has been applied. By utilising the full range of available clad products a project could be completely engineered in clad steel from the reservoir to the export line using production tubing, wellhead, valves, flowline, vessels, piping and heat exchangers made from steel clad by appropriate methods.

A summary of various methods for making clad products and their dimensional availability is given in Table 5. The sizes given are those which are readily available although some combinations of dimensions may not be possible. Equally, it may be possible to supply items outside the quoted ranges in certain cases.

Clad steel is clearly a practical option for handling corrosive environments whether it is to control CO₂ corrosion (where 316L cladding competes primarily with solid duplex stainless steels), corrosion in H₂S containing (sour) environments (where clad steel competes with the solid alloy) or marine corrosion.

It is worth noting that the backing steel for clad plate in sour service does not need to be resistant to hydrogen induced (stepwise) cracking since the alloy layer prevents corrosion (and therefore hydrogen generation) at the inner surface of the vessel or pipe.

Occasionally concern is expressed about the risk of hydrogen disbonding between the cladding and the backing steel. In the context of oil and gas production this is unlikely to occur since there should be no hydrogen produced at the inner surface. The alloy layer should be selected to be fully corrosion resistant in the expected environment so that there is no corrosion and therefore no hydrogen generated internally.

The outer surface, if buried or submerged, would normally be cathodically protected. If protected at the correct potential no hydrogen will be generated externally. Sacrificial anodes are self-regulating and therefore do not result in over protection. Impressed current systems need careful design to prevent overprotection near the drain point. In the event that some hydrogen generation would occur tests have shown that the threshold hydrogen concentration for disbonding to occur is very high (about 10 times higher than the hydrogen concentration anticipated).

Resistance to disbonding is particularly high where the backing steel chemistry is carefully controlled and there are no hard interfacial zones [8].

7. CONCLUSIONS

Corrosion resistant alloy clad steel has been available in various forms for over 40 years and is being used increasingly in the oil and gas production industries. There are successful applications of clad steel worldwide using a wide variety of product forms and there is a lot of experience in welding clad steel. For new projects there is a wide choice of product types to suit most sizes and components so that clad steel is an obvious engineering option for corrosive production systems.
NOMENCLATURE

CRAs – corrosion resistant alloys
EB – explosive bonded
GMAW – gas metal arc welding
GTAW – gas tungsten arc welding
HIP – hot isostatic pressing
HRB – hot roll bonded
SMAW – shielded metal arc welding
UOE – ‘U’ing, ‘O’ing, Expansion (pipe mill)
WO – weld overlaid

ACKNOWLEDGEMENTS

The author would like to acknowledge the support of the Nickel Development Institute in the preparation of this paper. Grateful acknowledgement is also given to many producers of clad products for providing information, illustrations and helpful comments on the text. Special thanks are due to George Swales for his help with this project.

REFERENCE


* trademark of Inco family of companies.
FIGURE 1. Cost comparison between clad and solid plates.

FIGURE 2. Gas separators made from clad plate for an offshore platform.

FIGURE 3. Micrograph of the bond line formed by explosively bonding titanium to steel showing the characteristic wavy interface of explosive bonds. Magnification x180.

FIGURE 4. Explosively bonded tube plates: 1050mm diameter x 52mm carbon steel +10mm AISI 321 stainless steel and 1410mm diameter x102 AISI 316L, stainless steel +14mm titanium grade 1.

Comparison of Deposition rates in kg/hour for different welding processes.

FIGURE 5. Comparison of deposition rates in kg/hour for different welding processes.

FIGURE 7. A view of the inside of a 3.5m diameter separator, 14m long after electroslag cladding with alloy 625.

FIGURE 8. Heat exchanger tubeplate with 25mm thick weld overlay of alloy C276.

FIGURE 9. Backwelding the longitudinal weld in clad pipe.

FIGURE 10. An order of longitudinally welded clad pipe being prepared for transportation.
FIGURE 11. Internally lined downhole tubing and connector for oil country tubular goods.

FIGURE 12. End pipe seal weld attaching liner to outer pipe in mechanically bonded lined pipe.

FIGURE 13. Explosively bonded pipes; from left to right, 6\% X52 clad with 3mm alloy 625, 4\% X60 clad with 3mm of AISI 316L, 2\% X60 clad with 3mm of alloy 625.

FIGURE 14. Centricast clad pipe showing accurate fit-up achievable for gr 11th welding.

FIGURE 15. Subsea manifold (6\% diameter piping) made of centricast clad pipe (X52 with 3mm alloy 625 clad layer) for a North Sea project.

FIGURE 16. High frequency induction bending of centricast clad pipe.

FIGURE 17. Steel valve HIP clad with alloy 625 powder.

FIGURE 18. X60 Tee piece (16\% x 8\%) HIP clad with a solid lining of alloy 825.
FIGURE 19. 2" nominal bore long weld neck flanges internally weld overlaid with alloy 625.

FIGURE 20. 4130 Xmas Tree block GTAW overlaid on all wetted internal surfaces with alloy 520.

FIGURE 21. Weld overlaying of a 40" subsea ball valve with alloy 625.

FIGURE 22. Dual 3" nominal bore composite manifold valve body with all bores clad with alloy 625.

FIGURE 23. Pulsed GMAW alloy 625 overlaid 33/8" wing valve.

FIGURE 24. 30" nominal bore 90° elbow internally weld overlaid with alloy 625.

FIGURE 25. Synergic GMAW overlaying of external pipe surface with two passes of alloy 625.
FIGURE 26. Typical welding sequence for clad steel with single-sided access.

1 GTAW - alloy filler
2 GTAW or GMAW - alloy filler
3 GTAW, GMAW, SMAW - alloy or pure iron buffer
4 - 7 etc. GTAW, GMAW, SMAW - alloy or backing steel filler

FIGURE 27. Typical welding sequence for steel with double-sided access.

1 - 6 etc. Any welding method - backing steel filler
7 - 8 Overlay welding - alloy filler
<table>
<thead>
<tr>
<th>NOMINAL COMPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNS designation</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Alloy 405</td>
</tr>
<tr>
<td>Alloy 410</td>
</tr>
<tr>
<td>Alloy 304L</td>
</tr>
<tr>
<td>Alloy 316L</td>
</tr>
<tr>
<td>22Cr duplex</td>
</tr>
<tr>
<td>25Cr duplex</td>
</tr>
<tr>
<td>Alloy 904L</td>
</tr>
<tr>
<td>Alloy 90C</td>
</tr>
<tr>
<td>Alloy 635</td>
</tr>
<tr>
<td>Alloy C22</td>
</tr>
<tr>
<td>Alloy C276</td>
</tr>
<tr>
<td>Alloy 685</td>
</tr>
<tr>
<td>Alloy 400</td>
</tr>
<tr>
<td>90% CuNi</td>
</tr>
<tr>
<td>70/30 CuNi</td>
</tr>
</tbody>
</table>

Other alloys may be cladded and also pure metals such as nickel, copper, titanium (and alloys) and zirconium.

### TABLE 1.

Typical Cladding Alloys

<table>
<thead>
<tr>
<th>Cladding Method</th>
<th>Backing Steel</th>
<th>Cladding Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMB</td>
<td>BSB301.3224.490</td>
<td>304L</td>
</tr>
<tr>
<td>HMB</td>
<td>SUPERELSO 590°</td>
<td>304L</td>
</tr>
<tr>
<td>WO</td>
<td>SUPERELSO 800°</td>
<td>304L</td>
</tr>
<tr>
<td>HMB</td>
<td>BS1 501.225.460</td>
<td>316L</td>
</tr>
<tr>
<td>WO</td>
<td>CMn</td>
<td>316L</td>
</tr>
<tr>
<td>HMB</td>
<td>SUPERELSO 590°</td>
<td>316L</td>
</tr>
<tr>
<td>EB</td>
<td>SUPERELSO 590°</td>
<td>Titanium G.1</td>
</tr>
<tr>
<td>HMB</td>
<td>BSB301.225.490</td>
<td>304L</td>
</tr>
<tr>
<td>HMB</td>
<td>STE 355</td>
<td>304L</td>
</tr>
<tr>
<td>HMB</td>
<td>AS16370</td>
<td>304L</td>
</tr>
<tr>
<td>EB</td>
<td>AS16370</td>
<td>304L</td>
</tr>
</tbody>
</table>

HMB = hot rolled bonded  WO = weld overlay  EB = explosive bonded  ° trademark of Creusot Loire Industries

### TABLE 2.

Examples of clad vessels
<table>
<thead>
<tr>
<th>Location</th>
<th>Service</th>
<th>Application</th>
<th>Material</th>
<th>Length</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-shore Netherlands</td>
<td>Gas</td>
<td>18&quot; Flowline long, welded</td>
<td>X52 pipe (10.7mm) with 2mm 316</td>
<td>5 km</td>
<td>laid 1978</td>
</tr>
<tr>
<td>On-shore Netherlands</td>
<td>Gas</td>
<td>4&quot; Flowline extruded seamless</td>
<td>X52 pipe (6.6mm) with 2mm 316L</td>
<td>3 km</td>
<td>laid 1979</td>
</tr>
<tr>
<td>On-shore Netherlands</td>
<td>Multi</td>
<td>8&quot; Flowline seamless</td>
<td>A106 pipe (8.3mm) with 2.3mm 316</td>
<td>1 km</td>
<td>laid 1979 NO longer in service</td>
</tr>
<tr>
<td>On-shore Netherlands</td>
<td>Sour Oil</td>
<td>10&quot; Flowline long, welded</td>
<td>X56 pipe (8.3mm) with 2mm 316</td>
<td>1.66cm</td>
<td>laid 1985</td>
</tr>
<tr>
<td>On-shore Netherlands</td>
<td>Gas</td>
<td>12&quot; Flowline long, welded</td>
<td>X52 pipe (11.7mm) with 2mm 316L</td>
<td>1.5cm</td>
<td>laid 1988 partly replaced in 1988</td>
</tr>
<tr>
<td>Off-shore Southern North Sea</td>
<td>Gas</td>
<td>3 x 12&quot; risers</td>
<td>X80 pipe with 3mm 625, 2.5mm 625, Spheres, 2.5mm 625 and flanges weld overlaid with 625</td>
<td>14 km</td>
<td></td>
</tr>
<tr>
<td>Off-shore Southern North Sea</td>
<td>Gas</td>
<td>8&quot; Flowlines</td>
<td>X80 pipe with 3mm 316L</td>
<td>1.3cm</td>
<td>laid 1988</td>
</tr>
<tr>
<td>Off-shore Southern North Sea</td>
<td>Sour Gas</td>
<td>12&quot; pipeline long, welded</td>
<td>X52 (8mm) with 2mm 625</td>
<td>3.3cm</td>
<td>laid 1988</td>
</tr>
<tr>
<td>Off-shore Southern North Sea</td>
<td>Sour Gas</td>
<td>8&quot; pipeline long, welded</td>
<td>X52 (8mm) with 3mm 625</td>
<td>5 km</td>
<td>laid 1989</td>
</tr>
<tr>
<td>Off-shore Netherlands</td>
<td>Sour Gas</td>
<td>4&quot; pipeline long, welded</td>
<td>X52 (6.5mm) with 2mm 825</td>
<td>1.4km</td>
<td>laid 1988</td>
</tr>
<tr>
<td>Off-shore North Sea</td>
<td>Oil</td>
<td>6&quot; Subsea manifold piping and bends on 36&quot; x 18&quot; x 10m template Centrifugally cast</td>
<td>X52 (8mm) with 3mm 625</td>
<td>approx 1000m</td>
<td></td>
</tr>
<tr>
<td>Off-shore Iranian Ocean</td>
<td>Sour Gas</td>
<td>24&quot; pipeline 20&quot; pipeline long, welded</td>
<td>X65 (14.3mm) and (17.5mm) with 3mm 826</td>
<td>9.5km</td>
<td></td>
</tr>
<tr>
<td>Off-shore New Zealand</td>
<td>Gas</td>
<td>20&quot; Flowline long, welded</td>
<td>X65 (19.1mm) with 3mm 316L</td>
<td>16 km</td>
<td>Constructed 1991/2</td>
</tr>
<tr>
<td>Off-shore Mobile Bay</td>
<td>Sour Gas</td>
<td>Flowline (Thermal Shrink Fit)</td>
<td>X70 (16.8mm) with 3mm 825 liner</td>
<td>5.8 km</td>
<td>approx. 1.3% H₂S 3% CO₂ Tmax 100° 120°C Constrained 1991</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.53&quot;</td>
<td>X70 (20mm) with 3mm 825 liner</td>
<td>1.1 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3&quot; Heat exchanger tubing (extruded seamless)</td>
<td>SAE 4130 (10mm) with 2mm 825</td>
<td>1 km</td>
<td></td>
</tr>
<tr>
<td>Off-shore Alabama Gulf of Mexico</td>
<td>Sour Gas</td>
<td>Tiepipe process piping (extruded seamless)</td>
<td>Grade B with 6&quot;, 2.5mm 825, 10&quot;, 12&quot; Pipe fittings weld overlaid with 625</td>
<td>260m</td>
<td>000 ppm H₂S 4% CO₂ Design T, 177°C Constructed 1991</td>
</tr>
<tr>
<td>Location</td>
<td>Service</td>
<td>Application</td>
<td>Material</td>
<td>Length</td>
<td>Remarks</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------</td>
<td>------------------------------</td>
<td>-----------------------------------------------</td>
<td>--------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Off-shore North Sea</td>
<td>Oil</td>
<td>36&quot; riser</td>
<td>X65 (27mm) with 3mm 316L.</td>
<td>520m</td>
<td></td>
</tr>
<tr>
<td>Off-shore Alaska</td>
<td>Flowline (Thermal Shrink Fit) 6&quot;</td>
<td>X60 (7mm) with 5mm 825 liner</td>
<td></td>
<td>300m</td>
<td>1991</td>
</tr>
<tr>
<td>Off-shore North America</td>
<td>Flowline (Thermal Shrink Fit) 6&quot;</td>
<td>X60 (7mm) with 3mm 825 liner</td>
<td></td>
<td>10.6km</td>
<td>1991</td>
</tr>
<tr>
<td>Off-shore North Sea</td>
<td>Gas</td>
<td>Riser 3&quot; external 4&quot; external 8&quot; external 12&quot; central shaft</td>
<td>X65 with 3mm 825</td>
<td>0.6mm</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.1mm</td>
<td>20.2mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25.9mm</td>
<td>220m</td>
<td>225m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>220m</td>
<td>220m</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>220m</td>
<td>230m</td>
<td></td>
</tr>
<tr>
<td>Off-shore Indonesia</td>
<td>Gas</td>
<td>Long welded flowlines 30°</td>
<td>X60 (12.7mm) with 2mm 825</td>
<td>9.4km</td>
<td>1993</td>
</tr>
<tr>
<td>Off-shore Indian Ocean</td>
<td>Gas</td>
<td>Long welded flowlines 18° and 22°</td>
<td>X65 with 825 cladding (15.9 + 3mm)</td>
<td>5.5km</td>
<td>1993</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(20.6 + 3mm)</td>
<td>3.3km</td>
<td></td>
</tr>
<tr>
<td>Off-shore North Sea</td>
<td>Gas</td>
<td>Hydraulically lined pipe 10° 10°</td>
<td>X66 (9.4mm) with 3mm 316L.</td>
<td>6.9km</td>
<td>1995</td>
</tr>
<tr>
<td>Off-shore Mobile Bay</td>
<td>Sour Gas</td>
<td>Hydraulically lined flowline 5&quot;</td>
<td>X66 (9mm) with 2.5mm 825 liner</td>
<td>5.25km</td>
<td>1995</td>
</tr>
<tr>
<td>Off-shore North Sea</td>
<td>Gas</td>
<td>Hydraulically lined flowline 6&quot; 10&quot;</td>
<td>X65 with alloy 825 liner (8.7 + 3mm)</td>
<td>12km</td>
<td>Installed as bundle low 12km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(14.3 + 3mm)</td>
<td></td>
<td>1996</td>
</tr>
<tr>
<td>Off-shore Indonesia</td>
<td>Sour Gas</td>
<td>Long welded flowline 18°</td>
<td>X60 (7.2mm) with 2mm 825</td>
<td>4km</td>
<td>1996</td>
</tr>
<tr>
<td>Off-shore North Sea</td>
<td>Gas</td>
<td>Hydraulically lined flowline 10&quot;</td>
<td>X65 (10.5mm) with 2.5mm 316L liner</td>
<td>41km</td>
<td>Installed as bundle low 1996</td>
</tr>
<tr>
<td>Offshore USA</td>
<td>Gas</td>
<td>Flowlines (mechanically lined) 5.668&quot;</td>
<td>X65 (9mm) with 2.5mm 825</td>
<td>7.9km</td>
<td>1997</td>
</tr>
<tr>
<td>Offshore Norway</td>
<td>Gas</td>
<td>Flowlines (mechanically lined) 10&quot; (both)</td>
<td>X65 (14.4mm) with 2.5mm 825 liner</td>
<td>5.25km</td>
<td>1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X65 (19.9mm) both with 2.5mm 825 liner</td>
<td>5.25km</td>
<td></td>
</tr>
<tr>
<td>Offshore UK</td>
<td>Gas</td>
<td>Flowlines (mechanically lined) 8&quot; 16&quot;</td>
<td>X65 (11mm) with 2.5mm 825 liner</td>
<td>5.8km</td>
<td>1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X65 (22mm) both with 2.5mm 316L liner</td>
<td>5.8km</td>
<td></td>
</tr>
<tr>
<td>Offshore UK</td>
<td>Gas</td>
<td>Riser (long welded) 16&quot;</td>
<td>X65 (11.9mm) with 3mm 316L.</td>
<td>503m</td>
<td>1997</td>
</tr>
<tr>
<td>Offshore USA</td>
<td>Gas</td>
<td>Flowline (mechanically lined) 8&quot;</td>
<td>X65 (12.7mm) with 2.5mm 825 liner</td>
<td>34km</td>
<td>1997</td>
</tr>
<tr>
<td>Offshore Netherlands</td>
<td>Gas</td>
<td>Flowline (mechanically lined) 16°</td>
<td>X65 (11.2mm) with 2.5mm 316L liner</td>
<td>7km</td>
<td>1996</td>
</tr>
<tr>
<td>Offshore Philippines</td>
<td>Gas</td>
<td>Flowlines (long welded) 16&quot; 16&quot;</td>
<td>X65 (15.9mm) with 3mm 316L.</td>
<td>29km</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X65 (17.9mm) both with 2.5mm 825</td>
<td>27km</td>
<td></td>
</tr>
<tr>
<td>Offshore Malaysia</td>
<td>Gas</td>
<td>Flowline (long welded) 18&quot;</td>
<td>X65 (9.5mm) with 3mm 316L.</td>
<td>9.1km</td>
<td>2001</td>
</tr>
<tr>
<td>Offshore Malaysia</td>
<td>Gas</td>
<td>Flowline (long welded) 14&quot; 14&quot;</td>
<td>X65 (14.3mm) with 3mm 316L.</td>
<td>8.6km</td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X65 (20.7mm) with 3mm 316L.</td>
<td>1.6km</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Service Conditions</td>
<td>Remarks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------------------</td>
<td>---------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 Cr (1.9mm) clad L80 (5mm) 2(\frac{1}{4})&quot; diameter</td>
<td>Rod pumped oilwell 50 bbls oil/day 250 bbls water/day 1.4% H(_2)S 2.2% CO(_2), 43°C 35 psi. Batch treating with corrosion inhibitor.</td>
<td>Examined after 20 months, severe pitting near the pin end to pit depth of 3mm. Previous J55 tubing had failed in 3 months [9].</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 joints run in top of tubing string</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>625 clad tubing 3(\frac{1}{4})&quot; diameter</td>
<td>Sour gas 9% H(_2)S 130°C</td>
<td>inspected after 2 years. No corrosion and no problems at joints. Tubing replaced and still in service.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete tubing string @ 3400m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 Cr duplex clad tubing</td>
<td>Oil well, 20m(^3) oil/day, 160m(^3) water/day. 30ppm H(_2)S 1.2% CO(_2), 83g/l NaCl, 43°C, FTHP 5.5 bar G1BHP 90 bar</td>
<td>Oil field abandoned after 2 years in service. Tubing to be pulled and inspected.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete tubing string</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

**TABLE 4.** Applications of internally clad production tubing

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>Wall Thickness (mm)</th>
<th>Width/Diameter (mm)</th>
<th>Max Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll bonded plate</td>
<td>6 - 200, Cladding 1.5mm to 40% of total thickness</td>
<td>1000 - 4400</td>
<td>12 to 16.5 depending on supplier</td>
</tr>
<tr>
<td>Explosive bonded plate</td>
<td>Cladding 1.5 - 25mm, Minimum base thickness 3x cladding thickness, no limit to max thickness of base</td>
<td>50 - 3500</td>
<td>6</td>
</tr>
<tr>
<td>with hot rolling</td>
<td></td>
<td>1000 - 4400</td>
<td>14</td>
</tr>
<tr>
<td>Overlay welded plate</td>
<td>Base metal &gt; 5mm clad layer &gt; 2.5mm</td>
<td>limited only by access of equipment</td>
<td>limited only by equipment access</td>
</tr>
<tr>
<td>Longitudinally welded pipe</td>
<td>6 - 34</td>
<td>100 - 1016</td>
<td>8 or 12.8 depending on supplier</td>
</tr>
<tr>
<td>Lined pipe</td>
<td>7-20 Total wall Liner 0-20mm</td>
<td>100 - 760</td>
<td>12 depending on diameter</td>
</tr>
<tr>
<td>Lined pipe (explosive mechanical joint)</td>
<td>Outer pipe &gt; 5 Liner &lt; 5 (depending on diameter)</td>
<td>50 - 500</td>
<td>12</td>
</tr>
<tr>
<td>Seamless pipe</td>
<td>6 - 25</td>
<td>60 - 400, depending on supplier</td>
<td>12.8 depending on diameter</td>
</tr>
<tr>
<td>- extruded</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- plug / mandrel mill</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seamless pipe</td>
<td>6 - 20</td>
<td>200 - 250</td>
<td>3 or 5 depending on supplier</td>
</tr>
<tr>
<td>- explosive metallurgical joint</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- after cold rolling</td>
<td>2 - 20</td>
<td>50 - 200</td>
<td>6 - 12</td>
</tr>
<tr>
<td>Centricast pipe</td>
<td>10 - 93 Clad layer minimum 3mm</td>
<td>100 - 400</td>
<td>4 - 6</td>
</tr>
<tr>
<td>HIP clad pipe or fittings</td>
<td>&gt; 5 Clad layer minimum 2mm</td>
<td>25 - 400</td>
<td>2</td>
</tr>
<tr>
<td>Weld overlay fittings</td>
<td>Base metal &gt; 5mm clad layer &gt; 2.5mm</td>
<td>25 minimum</td>
<td>For small diameters limited by torch length eg 1 m for diameter 50mm. No limit on large diameter.</td>
</tr>
</tbody>
</table>

**TABLE 5.** Summary of Clad product production methods and dimensional availability.

**Notes:**
1) Not all combinations of wall thickness/diameter/length may be possible.
2) Readily available sizes are quoted; exceptional sizes may be possible.
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