

Engineering with CLAD STEEL

By Liane Smith



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Environmental Note:

Stainless steels and nickel alloys offer important environmental benefits. Properly selected, they permit safe containment of oil and gas process fluids. Their durability ensures long life: replacement, and the resource demand that makes, is minimized as operating efficiencies are improved. At the end of the life of the structure, the nickel alloys are completely recyclable. Overall, stainless steels and nickel alloys are exceptional life cycle performers in both the environmental and economic senses.

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Cover Photo: Partially completed vessels made from roll-bonded clad plate. *Courtesy of Verbundmetalle GmbH.*

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ABSTRACT

Corrosion resistant alloy clad and lined steel has been available in various forms for over 50 years and is widely applied 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 some field applications of clad and lined products.

1. INTRODUCTION

The use of corrosion resistant alloys (CRAs) for the control of corrosion in oil and gas systems has a number of benefits. Production systems constructed of correctly selected CRAs (based on appropriate laboratory testing or previous field experience in similar environments) will provide a safe, leak-free system for the full duration of a project. Whilst the initial capital expenditure often appears to be higher for a CRA system there are great savings to be made in reduced processing requirements through the safe handling of wet corrosive fluids. If well fluids can be transported to shore or to an existing platform without drying then the cost savings in equipment, weight and space can

be more than sufficient to cover the expense involved in the CRAs needed to handle the fluid from the well to the processing facility.

Additional savings can be made in operating costs since corrosion inhibitor injection is not required and inspection and maintenance costs are greatly reduced compared to a carbon steel production system (with or without internal organic linings). Thus if a life-time costing approach is taken CRAs can often be shown to be an economic corrosion control option for oil and gas production systems.

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. Because high strength backing steel can be utilised, wall thicknesses can be reduced relative to solid CRAs thus reducing fabrication time and costs.

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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.

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. Various forms of clad, weld overlaid and lined steel have been widely used in the chemical, oil refining and chemical transport industries and for about 50 years in oil and gas production. The term “clad” steel is often taken to be generic, covering also weld overlaid and lined products.

The selection of clad steel requires decisions to be made regarding:

- **the optimum choice of CRA/backing steel combination**
- **the selection of manufacturing method appropriate to the part which is clad**
- **the approach to the fabrication.**

This paper aims to address the concerns 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 1**). **Table 2** lists a few 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 (@ 130,000 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

TABLE 1. Typical cladding alloys used in oil industry applications

NOMINAL COMPOSITION (Weight %)							
	UNS Designation	C _{max}	Cr	Ni	Mo	Cu	Other
Alloy 304L	S30403	0.030	18-20	8-10	-	-	-
Alloy 316L	S31603	0.030	16-18	11-13	2-3	-	-
Alloy 904L	N08904	0.020	20	25	4.5	1.5	-
Alloy 825	N08825	0.020	21	42	3	2	-
Alloy 625	N06625	0.030	21.5	58 min	9	-	Nb 3-6
Alloy C22	N06022	0.01	20-22.5	bal	12.5-14.5	-	Fe 2.6, W 3
Alloy C276	N10276	0.01	15.5	bal	16	-	Fe 4-7, W 3.75
Alloy 400	N04400	-	-	63 min	-	31	Fe 2.5
90/10 CuNi	C70600	-	-	10	-	bal	Fe 1.5, Mn 1
70/30 CuNi	C71500	-	-	30	-	bal	Fe 0.6

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

FIGURE 1. Partially completed vessels made from roll-bonded clad plate.



Courtesy of Verbundmetalle GmbH.

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 to carbon and other alloy diffusion. 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.

TABLE 2. Examples of clad vessels to illustrate typical dimensions and cladding alloys

Cladding Method	Backing Steel		Cladding Alloy	
	Type	Thickness (mm)	Type	Thickness (mm)
HRB	BS 1501.224.490 (~A516 Gr. 70)	15,43,63,16,29	904L	3, 3.5
HRB	Proprietary high strength grade (500MPa yield)	34,37,60,64,73	904L	3
WO	Proprietary high strength grade (500MPa yield)	83 (x4)	625	3
HRB	BS 1501.224.490 (~A516 Gr. 70)	71,60,36,18,11,10	316L	3
WO	CMn	120 (x2)	625	3
HRB	Proprietary high strength grade (500MPa yield)	43,27,14	316L	3
EB	Proprietary high strength grade (500MPa yield)	287	Titanium Gr.1	8
HRB	BS 1501.224.490 (~A516 Gr. 70)	72,82	625	3
HRB	STE 355 / A516 Gr. 60	15,36	904	3
HRB	STE 355 / A516 Gr. 60	28,31,71,57	825	3
EB	ASTM A516 Gr. 70	100 Head 2x50 Shell	825	

HRB = hot roll-bonded WO = weld overlaid EB = explosive bonded

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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 Cr_2O_3 or ZrO_2 powder) to prevent the surfaces sticking together. The two slabs are welded together around the edges to prevent separation during rolling. An alternative method of preventing surface oxidation on the cladding during rolling, rather than electroplating, is to evacuate this sandwich construction or replace 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 for.

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 of the corrosion resistant alloy depends upon the 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 easiest 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) are solution annealed at 1050°C , and this can be managed with some care but UNS N08028 (Alloy 28) requires 1150°C which can give problems in achieving the toughness of the backing material to which this is clad. For this reason, manufacturers may be unable to offer plates clad with certain alloys if the backing steel mechanical properties specification require good toughness properties. Where required, further

heat treatments may be carried out to optimise the mechanical properties of the backing steel.

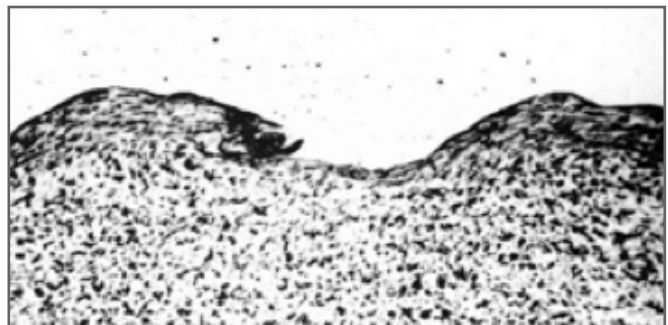
After heat treatment the plates are separated, cleaned, cut to size and visually and ultrasonically inspected. The cleaning of the clad surface may be by grinding or pickling or both.

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

FIGURE 2. Micrograph of the bond line formed by explosively bonding titanium to steel showing the characteristic wavy interface of explosive bonds. Magnification x80.



Courtesy of Dynamic Materials Corp.

bond. **Figure 2** 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.

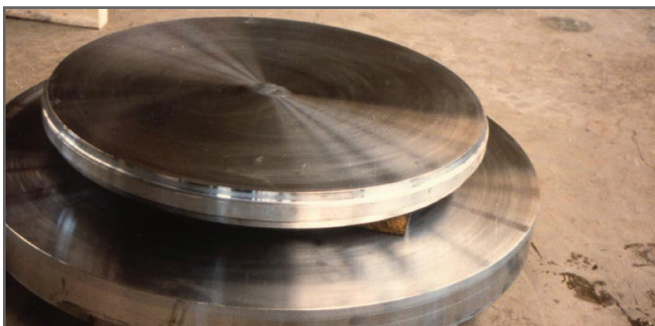
The upper limit to the amount of explosive which can be detonated depends upon the environmental considerations of the manufacturing site. Some manufacturers carry out explosive bonding in large vacuum chambers to cut down the noise level.

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 roll-bonded with an interlayer material. **Figure 3** shows a 1.41m diameter tubeplate explosively clad with 14mm thick titanium Gr.1 along with a 1m diameter tubeplate explosively clad with 10mm of Type 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.

FIGURE 3. Explosively bonded tube plates; 1050mm diameter x 52mm carbon steel +10mm Type 321 stainless steel and 1410mm diameter x102 Type 316L stainless steel +14mm titanium grade 1.



Courtesy of Verbundmetalle GmbH.

Cladding thicknesses between 3 and 25 mm 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 wave interface (**Figure 4**).

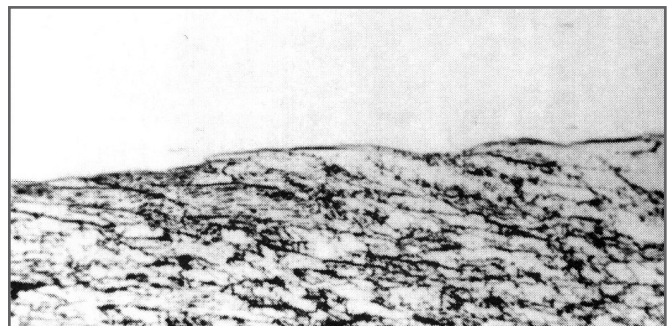
Heat treatment is not necessary in most cases after explosive bonding so that almost any combination of cladding and backing materials can be chosen. Stress relieving is advised after cladding with Ti and Zr to improve bond ductility in any subsequent fabrication of the clad composite.

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 shear 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

FIGURE 4. Micrograph of explosively-bonded stainless steel onto carbon steel after onward rolling. Magnification 200X.



Courtesy of Dynamic Materials Corp.

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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 40 years and is now applied 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:

- **access**
- **welding position (downhand or positional)**
- **alloy type and dilution specified**
- **economics**

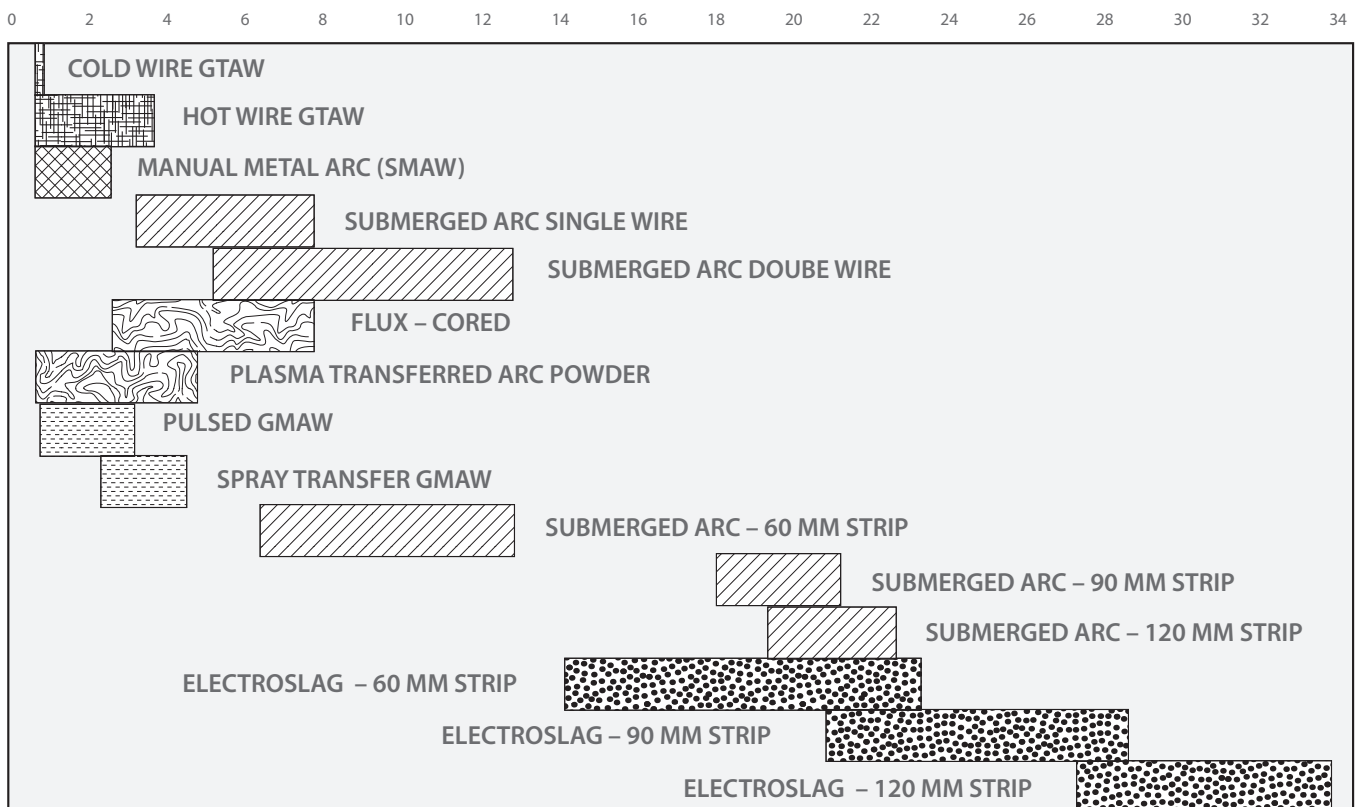
If access is difficult or if positional welding is required (for example for internal weld cladding on vessels which cannot be rotated) then GTAW or GMAW techniques are most likely to be selected. For example synergic GMAW with Alloy 625 filler is to be used for the in-situ refurbishment of corroded 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 slower low 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 5 gives a guide to the deposition rates achievable with different welding processes. For very large areas strip welding with submerged arc or electroslag 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 electroslag clad with Alloy 625 using 60mm wide strip. Figure 6 shows one of the 3.5m diameter, 14m long vessels after cladding. A further two towers for the same project were electroslag clad

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



With acknowledgement to Soudometal

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 submerged arc strip cladding which would have required two layers of weld deposit to meet the specified chemical composition requirements electroslag 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 25mm 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 (e.g., 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, however, this policy is rarely followed. A practical approach, which balances the requirement to control iron pickup against the need to ensure good fusion of the cladding to the base metal, is to specify 10% iron content maximum in Alloy 625 overlay. This value rarely causes concern to the fabricator and yet ensures there is not excessive heat input and alloy dilution.

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 reheat 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 up a deposit of 25mm thickness for a heat exchanger tubeplate (Figure 7). Cracking was avoided by using hot wire GTAW with the heat input limited to 0.8 KJ/cm max.

In some cases deposits may be specified to be machined 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,

FIGURE 6. A view of the inside of a 3.5m diameter separator, 14m long, after electroslag cladding with Alloy 625.



Courtesy of Soudometal and NEI International Combustion Ltd.

FIGURE 7. Heat exchanger tubeplate with 25mm thick weld overlay of Alloy C276.



Courtesy of Head Robinson Engineering Ltd.

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and if the ultrasonic inspection can be arranged from the backing steel side, final machining may not be necessary, with obvious cost benefits.

2.4 Post-Welding Heat Treatment (PWHT)

Heat treatment may be required after overlaying if the heat affected zone (HAZ) 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. **Figure 8** gives an indicative Time -Temperature-Transformation diagram for Alloy 625. It can be seen that tempering conditions for normal carbon or low alloy pressure vessel steel between 580-620 °C would not result in Cr/Mo carbides precipitating even with heat treatment times up to 20 hours and there is no impact of heat treatment upon the corrosion properties.

Tempering higher alloy steels like 2¼ Cr - 1 Mo requires a higher tempering temperature, around 720 °C. Alloy 625 weld overlay heated at this temperature for a few hours could result in carbide precipitation in the clad layer ^[4]. The % carbon in the Alloy 625 consumables is very low, but the amount of diffused carbon from the underlying steel will depend upon the number of layers

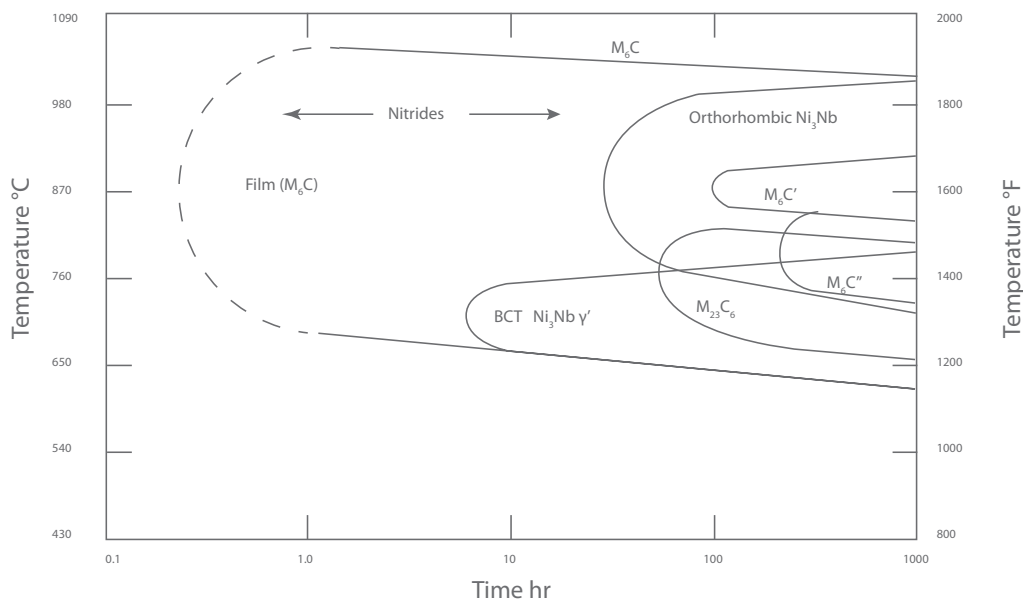
and the heat input used in the overlaying procedure. Normally the outermost layer of weld overlay has a composition comparable to the consumable and so the carbon content will be very low. As a consequence, the volume fraction of carbides formed is low and there is little impact upon the bulk Cr or Mo content near the surface, which is controlling the cladding corrosion properties. Nevertheless, some amount of sensitization may occur, although it has never been recorded that sensitized material has actually resulted in intergranular corrosion in oil and gas producing conditions.

2.5 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

FIGURE 8. Schematic time-temperature-transformation diagram for Alloy 625 (derived from data published by Special Metals and Krupp VDM)



Time-temperature-transformation diagram for solution-treated Alloy 625

Courtesy of Japan Steel Works

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 sensitizing 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 850°C or else followed by an appropriate heat treatment.

2.6 Hard Zones and Their Significance

The interface between the austenitic deposit and the ferritic steel is complex. Depending upon the exact composition of the materials joined, a range of microstructures can be formed in the diluted zone and often there is potential to form a martensite phase, whose hardness, to a large extent, will be dictated by the carbon content diffusing from the base steel.

The effect of local hard zones has been studied in detail for weld overlays on pressure vessel steels. For example, Gittos and Gooch investigated several stainless steel weld consumable deposits on a BS 1501-224 Gr. 430 steel (0.20%C, 0.9-1.5Mn, 0.25Cr, 0.1Mo, 0.3Cu, 0.1-0.4Si, 0.03S and 0.03P) and on a 2¼ Cr – 1 Mo steel ^[5]. The extent of martensite varied depending upon the composition of the steels used, but similar features were found in all the samples, irrespective of base steel, stainless steel consumable or welding process. PWHT of 690°C for 30 minutes resulted in some decarburisation of the backing steel HAZ, giving a softened zone adjacent to the fusion line. The hardened part of the weld zone is softened by the heat treatment, falling from about 440Hv to 300Hv as a result of carbide precipitation from the carbon-enriched martensite. However, further out from the fusion line the hardness is raised again to similar high values (approaching 500Hv).

Thus, PWHT at normal stress-relieving or tempering temperatures is not guaranteed to reduce the hardness. The reason is, whilst some carbide precipitation takes place, some carbon also diffuses further into the weld metal and, on cooling, there can be re-formation of untempered martensite. The only way to remove the hard zone entirely is by a second heat treatment below the Ac1 temperature (based on the composition in the metal). Such a two stage heat treatment is not normally specified and prediction of the Ac1 and Ms temperatures can be difficult as the composition is variable in different parts of the weld.

Gittos and Gooch also tested nickel-based alloy

cladding (ERNiCr-3 and Alloy 625). They found a carburised zone with martensite formation inside the fusion line, but only extending for a distance of about 10 microns (less than the width in the stainless steel overlays). The hardness of this zone was similarly around 450Hv. Post weld heat treatment resulted in some carbide precipitation, but not forming a continuous band, even at the longest heat treatment times (up to 10 hours at 650°C). PWHT did not remove the hard zone, but as with stainless steels, just shifted its location.

These high hardness zones may evidently be present in the HAZ of most weld overlays and also in the HAZ of austenitic weld deposits in ferritic steels such as welds in clad and lined pipelines. It is thus important to address the question of the significance of these small high hardness zones.

From a mechanical point of view for room temperature applications, the hard zone does not present a great worry. The tensile strength is high and so, even with samples notched in the hardened region, failure does not occur consistently in this region. However, with the hardness measured there is a risk of hydrogen embrittlement of this hardened zone at the interface of the weld metal and the backing steel.

Under the normal conditions of the oil and gas industry, where there is a complete cladding of the surface, the risks associated with this narrow hard zone are negligible. The cladding material is selected to be inert to the service environment so there is no corrosion expected and so no hydrogen generated. If there should be (short term) upset conditions which cause corrosion of the alloy, then hydrogen will be generated, but at the typical service temperatures it is unlikely that the hydrogen will diffuse into the carbon steel. The solubility of hydrogen in the austenitic cladding is very high, and the diffusion rate is low, so the risk of hydrogen entering the hard zone is low unless corrosive conditions were sustained for a long period. (Only in the case of a refinery situation with high temperature service does the hydrogen diffuse rapidly into the backing steel.)

Of greater concern is the situation of partial cladding, where there is an interface between the cladding and the backing steel exposed in the environment, as happens in many partially clad valves. In such cases, there is a risk that the hardened zone is exposed to the producing environment. In hydrogen sulphide

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containing (sour) producing environments this hardened region may then be at risk of sulphide stress corrosion cracking, particularly if the critical region corresponds to a stress-concentrating notch in the design. To avoid this risk it is recommended to avoid partial cladding in sour conditions and to use fully clad components, or ensure that the hardened zone is not exposed by a careful design approach.

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 and lined steel pipe. Considering all the pipe laid since the early 1970s, approximately 50% by length is metallurgically clad (longitudinally welded and seamless) and 50% is lined. There is a specification for CRA clad and lined steel pipe (API 5LD).

3.1 Longitudinally Welded Clad Pipe

Longitudinally welded pipe is made from clad plate produced by hot rolling or explosive bonding followed 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.^[6] The longitudinal seam is usually welded with submerged arc, gas tungsten arc or plasma 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 girth 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).

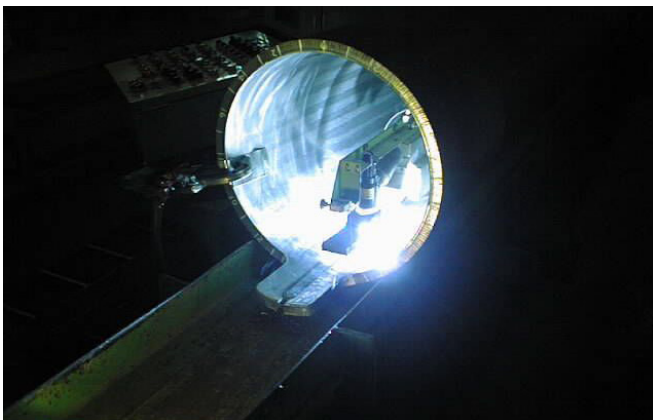
Longitudinally welded pipe has been made to a diameter as small as 100mm (4") but this is exceptional and it is normally available from 219mm (8") to 1016mm (40") outside diameter. The wall thickness range (cladding plus backing steel) is from 6mm up to 32mm. Single pipe lengths are available from 8m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

3.2 Lined Pipe

Lined pipe can be produced from 100mm (4") to 1016mm (40") but this is exceptional and it is normally available from 219mm (8") to 558mm (22") outside diameter.

At its simplest a standard pipe can be internally lined by inserting a seamless or welded liner made of the CRA (**Figure 11**). If no heat is applied, the liner is simply hydraulically or mechanically expanded inside the outer pipe. The liner is then held in place by the mechanical forces of the shrink-fit without forming an integral bond

FIGURE 9. Backwelding the longitudinal weld in clad pipe.



Courtesy of Japan Steel Works

FIGURE 10. An order of longitudinally welded clad pipe being prepared for transportation.



Courtesy of Japan Steel Works

TABLE 3. Example applications of internally clad and lined steel pipe illustrating various production routes and typical dimensions

Location	Service	Application	Material	Length	Remarks
On-shore Netherlands	Gas	Flowline (long. welded) 18"	X52 pipe 10.7mm with 2mm 316	5 km	Laid 1978
On-shore Netherlands	Gas	Flowline (extruded seamless) 4"	X52 pipe 8.6mm with 2mm 316	3 km	Laid 1979
On-shore Netherlands	Sour Gas	Pipeline (long. welded) 8"	X52 6mm with 2mm 825	5 km	Laid 1988
Off-shore North Sea	Oil	6" Subsea manifold piping and bends on 36m x 18m x 10m template. Centrifugally cast	X52 9mm with 3mm 625	Approx 1000 m	Manifold tees solid 625, weld neck flanges overlaid with 625, constructed 1988
Off-shore Indian Ocean	South Bassein gas field	Pipeline 24" & Pipeline 20" (long. welded)	X65 14.3mm with 3mm 825 17.5mm	6.5 km, 4.4 km	6-8% CO ₂ 0.12% H ₂ S 1988
On-shore Netherlands	Sour Gas	Pipeline (long. welded) 6"	X52 pipe 5.1mm with 2mm 825	3 km	1990
Off-shore New Zealand	Gas	Flowline (long. welded) 20"	X60 19.1mm with 3mm 316L	16 km	1991/2
Off-shore Mobile Bay	Sour Gas	Flowline (Thermal Shrink Fit) 5.73" 6.53" 3" Heat exchanger tubing (seamless) Risers and misc. piping	X70 15.8mm with 3mm 825 liner X70 26mm with 3mm 825 liner SAE 4130 with 3mm 825, C90 casing 27mm, 825 clad	5.8 km 1.1 km 1 km	Approx. 1.2% H ₂ S 3% CO ₂ T _{max} 100-120 °C 1991
On-shore North America		Flowline (Thermal Shrink Fit) 6"	X60 7mm with 3mm 825 liner	10.6 km	1991
Off-shore North Sea	Gas	Risers 3" extruded 4" extruded 8" extruded 12" centricast	X65 with 3mm 825 9.6 mm 13.1 mm 20.2 mm 25.8 mm	228 m 225 m 220 m 230 m	1992
On-shore Indonesia	Gas	Flowlines (long. welded) 30"	X60 12.7mm with 2mm 825	9.4 km	1993
Off-shore Indian Ocean	South Bassein gas field	Flowlines (long. welded) 18" and 22"	X65 with 825 15.9 + 3mm 20.6 + 3mm	5.5 km 3.3 km	1993
Off-shore North Sea	Gas	Flowline (hydraulically lined) 10 ³ / ₄ "	X65 9.3mm with 3mm 316L	6.9 km	1995
Off-shore North Sea	Gas	Flowline (hydraulically lined) 6" 10 ³ / ₄ "	X62 with 825 liner 8.7 + 3mm 14.3 + 3mm	12 km 12 km	Installed as bundle tow 1996
Off-shore North Sea	Gas	Flowline (hydraulically lined) 10"	X52 15.5mm with 2.5 mm liner	41 km	Installed as bundle tow 1996
Off-shore UK	Gas	Flowlines (hydraulically lined) 8" 18"	X65 11mm with 2.5mm 316L liner X65 22mm with 2.5mm 316L liner	5.8 km 5.8 km	1997
Off-shore USA	Gas	Flowlines (hydraulically lined) 8"	X65 12.7mm with 2.5mm 825 liner	34 km	1998
Off-shore Philippines	Gas	Flowlines (long. welded) 16" 16"	X65 15.6mm with 2.5mm 825 X65 17.0mm with 2.5mm 825	29 km 27 km	2000
Off-shore Malaysia	Gas	Flowline (long. welded) 14" 14"	X65 15.6mm with 2.5mm 825 X65 17.0mm with 2.5mm 825	8.6km 1.6km	2001
Off-shore Mediterranean	Gas + condensate	Flowlines (hydraulically lined) 8" (long. welded) 22"	X60 8.7mm with 2.5mm 825 liner X60 21.0mm clad with 2.5mm 825	24.2 km 24.5 km	2004
Off-shore North Sea	Gas	Flowline (long. welded) 8"	X65 16.3mm with 3mm of 316L	45 km	2004
Off-shore Indonesia	Gas	Flowline (mechanically lined) 4"	X52 6.4mm with 1.8mm 825 liner	49 km	2005
On-shore Mid-East	Gas	Flowlines (mechanically lined) 14" 16" 20"	X65 8.0mm X65 8.0mm X65 9.5mm All with 2.5mm 825 liner	8 km 7 km 14 km	2006
Off-shore Malaysia/Thailand	Gas	Flowlines (long. welded) 20" 26"	X65 10.4mm X65 13.5mm with 3mm of 316L	24.4 km 18.1 km	2007
Off-shore Norway	Gas	Flowline (long. welded) 16"	X60 21mm with 3mm of 316L	17 km	2008

All pipe diameters are nominal bore in inches, other measurements in metric units.

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along the full length. The outer pipe may also 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 seal welded to the backing steel at the pipe ends to prevent moisture ingress during transportation and pipe coating.

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. A metallurgical bond may be obtained on a limited portion (e.g. the pipe ends). In general, explosively-lined pipe production has not been considered economic relative to other production routes.

Lined pipes are not normally considered for bends because of the risk of liner collapse. However, methods for producing induction bends are being developed and so may become available in specific D/t ratio pipe sizes in the future.

Occasionally concerns have been expressed about the possible risk of liner collapse due to the generation of hydrogen on the external surface of the pipe as a result of cathodic over-protection. A theoretical study of this subject based on hydrogen permeation and the thermodynamics of hydrogen in steel has shown that when the cathodic protection potential is properly controlled there is no risk of liner collapse. A kinetic investigation of the time required for hydrogen gas pressure to build-up at the interface indicated that even under the worst case conditions imagined it would take more than a hundred years for the hydrogen pressure to

reach the liner collapse pressure.^[7]

3.3 Seamless Clad Pipe

Most standard methods of making seamless pipe have been adapted to the production of clad pipe, however there is no doubt that this is technically very challenging.

3.3.1 Extruded/Pipe Mill Products

Most commonly, seamless pipe is produced by making a composite billet of a CRA pipe 'nested' inside a steel pipe. The two may be welded together or, in one innovative process, partly brazed together by means of an electroless nickel plated layer applied to the outside of the CRA pipe before assembly (so-called liquid interface diffusion bonding). Other methods of composite billet production may be used such as the HIP technique (see section 3.2.5) or weld overlaying.

The composite billet can be processed through standard pipe mills such as a plug mill, mandrel mill or extrusion press. Considerable skill is required to optimize the temperature of the metal and the deformation rate involved since the cladding alloy and backing steel exhibit a difference in hot strength. The challenge is to ensure an even distribution of the cladding alloy relative to the backing steel along the finished pipe length and around the pipe circumference.

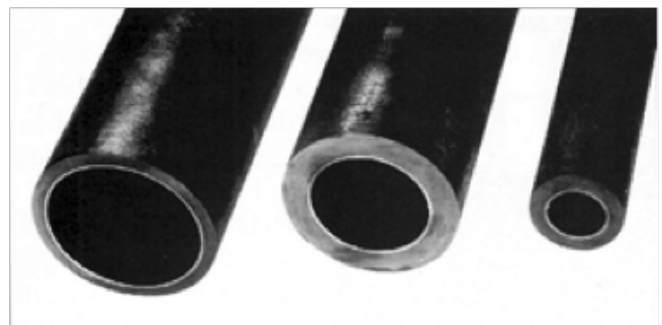
In pipe which is produced from billet or bloom as described above, the finished length is dependent upon the diameter and wall thickness since the volume of material is fixed by the billet or bloom size. Diameters can be as small as 50mm (2") and up to 225mm (9") or

FIGURE 11. Telescopic alignment of liner and outer pipe prior to hydraulic expansion to form lined pipe.



Courtesy of Butting GmbH

FIGURE 12. Explosively bonded pipes; from left to right, 6⁵/₈" X52 clad with 3mm Alloy 625, 4" X60 clad with 3mm of Type 316L, 2" X60 clad with 3mm of Alloy 625.



Courtesy of Japan Steel Works

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.

3.3.2 Explosively Bonded Pipe

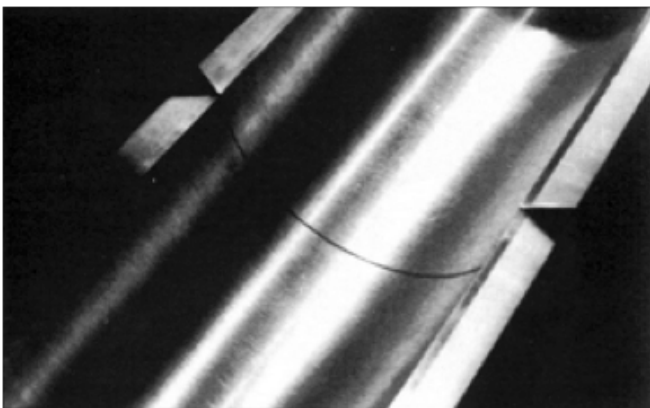
In principal a CRA liner placed in a pipe can be explosively bonded by either expanding the pipe assembly outward in a die or by compressing it inward onto a mandrel. In these methods a full metallic bond is formed between the cladding layer and the pipe (**Figure 12**).

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. The explosive bonding process may be used to produce a semi-finished product which can then be further processed in standard pipe mills. With this approach pipe of diameter 50-200mm, wall thickness 2-20mm, can be made in lengths from 6-12m.

FIGURE 13. Centricast clad pipe showing accurate fit-up achievable for grith welding.



Courtesy of Kubota.

These products would be expected to have improved pipe end dimensional tolerances and better overall economics.

3.3.3 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 controlled to achieve a sound metallurgical bond with minimum mixing at the interface. Whilst such pipe has been produced and used in oil and gas service (**Figure 13**) it is not currently produced, primarily due to high cost.

Figure 14 shows a 6" diameter subsea manifold constructed in X52 steel with Alloy 625 cladding manufactured by centricasting.

3.3.4 HIP-Clad Pipe

The hot isostatic pressing (HIP) technique can be 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

FIGURE 14. Subsea manifold (6" diameter piping) made of centricast clad pipe (X52 with 3mm Alloy 625 clad layer) for a North Sea project.



Courtesy of Kubota and Marathon Oil UK Ltd.

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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 a powder coating is used then the powder has to be held in place by a can which is either 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 hot pressed. Whilst the preparation is labour intensive, several parts can be hot pressed 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 homogenous 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.

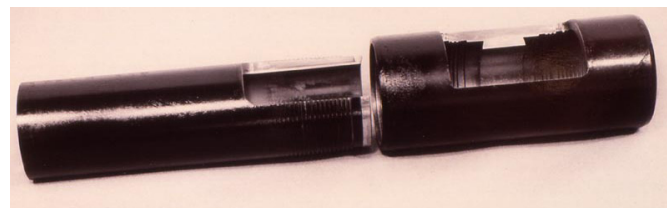
4. CLAD PRODUCTION TUBING

Certain manufacturers also produce clad downhole production 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 15**. Example applications of internally clad production tubing are given in **Table 4**.

Analysing why clad tubing has not seen wider application may be explained by the following key points ^[8]:

- **there is a risk of damage to the cladding or lining if wireline operations are required;**
- **if the connection is damaged and has to be re-cut there is a risk of not reproducing the same high integrity joint as in the original product;**
- **the additional 2-3mm of CRA inside clad tubing reduces the internal diameter relative to a tubing manufactured from solid CRA which may restrict throughput and increase pressure losses;**
- **solid CRAs can be cold worked to achieve much higher strength levels (120-140ksi) than typical backing steels and thus a solid CRA tubing would have a thinner wall for the same depth/pressure rating;**
- **economically it seems that clad tubing can only compete with solid alloys in certain sizes and particularly where there is a corrosion need for rather highly alloyed CRAs.**
- **The potential for clad tubing may increase in future in response to a demand for larger diameter production tubing for high production rate gas fields ^[9].**

FIGURE 15. Internally lined downhole tubing and connector for oil country tubular goods



Courtesy of Nippon Steel

TABLE 4. Example applications of internally clad production tubing

Material	Service Conditions	Remarks
13 Cr (1.9mm) clad L80 (5mm) 3 joints run in top of tubing string	Rod pumped oilwell 50 bbls oil/day 250 bbls water/day 1.4% H ₂ S 2.2% CO ₂ , 43 °C 35psi. Batch treating with corrosion inhibitor.	Examined after 20 months, severe pitting near the pin end to pit depth of 3mm. Previous J55 tubing had failed in 3 months. ^[11]
625 clad tubing 3 1/2" diameter Complete tubing string @ 3400m	Sour gas 9% H ₂ S 130 °C	Inspected after 2 years. No Corrosion and no problems at joint. Returned to service.
22 Cr duplex clad tubing Complete tubing string	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 CIBHP 90 Bar.	Oil field abandoned after 2 years in service.

5. CLAD FITTINGS

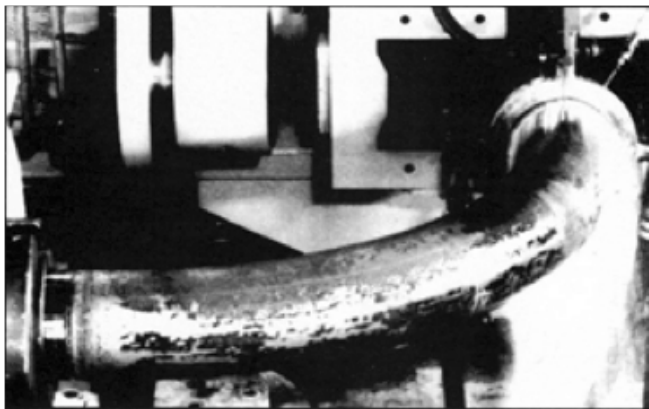
5.1 Fittings and Bends From Pipe

Fittings can be produced from clad pipe by hot or cold forming processes. Bends with a 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. Some pipe manufacturers will also supply fittings produced from their pipe products. Heat treatment may be required after forming as previously discussed in section 2.4.

5.2 HIP-cladding of fittings

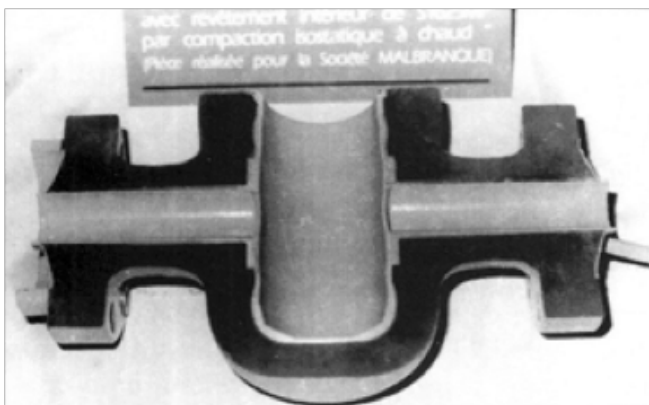
The HIP manufacturing method has been described in section 3.3.4. This method is particularly useful for small

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



Courtesy of Kubota.

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



Courtesy of Aubert et Duval Tecphy

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.

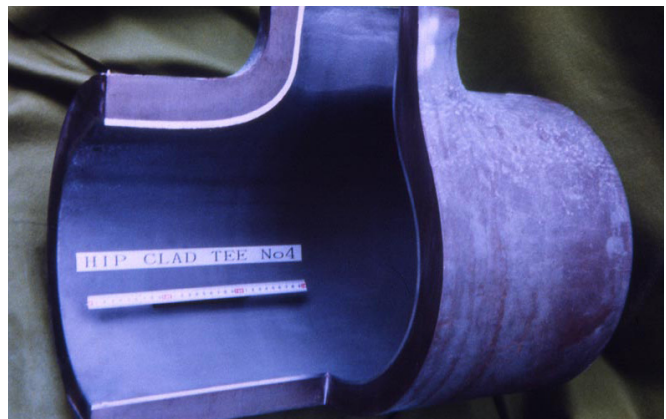
Figure 17 illustrates a 625 alloy powder HIP clad steel valve and **Figure 18** shows a tee-piece made by HIP cladding a solid lining onto the backing steel.

5.3 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:

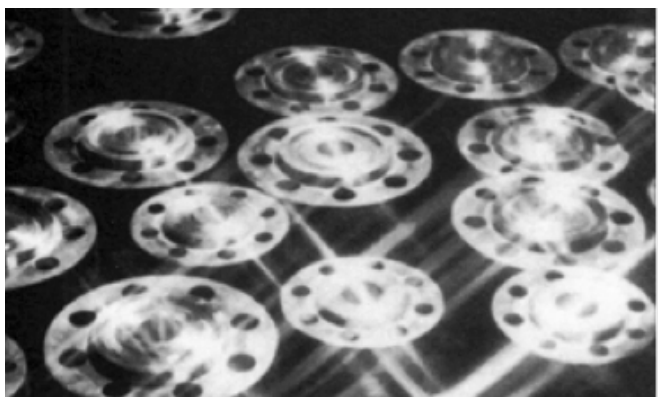
- **vessel fittings – extended weld neck flanges for nozzles, manways etc. Figure 19 shows 2” nominal bore long weld neck flanges internally weld overlaid with Alloy 625**

FIGURE 18. X60 Tee piece (16” x 8”) HIP clad with a solid lining of Alloy 825.



Courtesy of Kubota.

FIGURE 19. 2” nominal bore long weld neck flanges internally weld overlaid with Alloy 625.



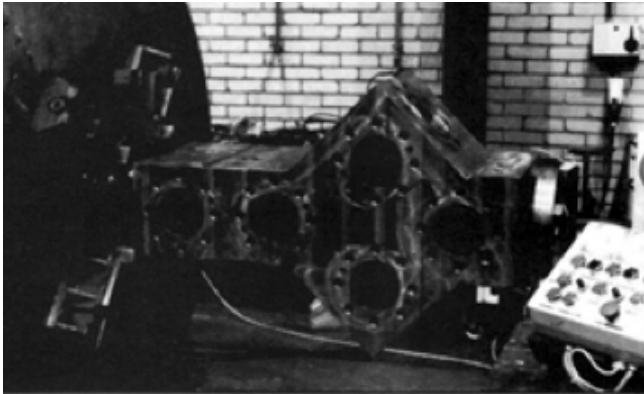
Courtesy of Head Robinson Engineering Ltd.

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- wellheads – Xmas tree blocks (e.g. **Figure 20**) and valves
- 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 Alloy 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 Alloy 625. Pulsed GMAW of Alloy 625 in single and double layers was used to overlay the 3 1/8" 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
- pipe fittings – flanges, elbows, tees and sphere tees, reducers, branches etc. **Figure 24** shows a 30" nominal bore 90° elbow internally weld overlaid with Alloy 625
- 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 a 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. These processes are suitable for positional welding and can be carefully controlled to meet dilution specifications. Approximate deposition rates were

FIGURE 20. AISI 4130 Xmas Tree block GTAW overlaid on all-wetted internal surfaces with Alloy 625.



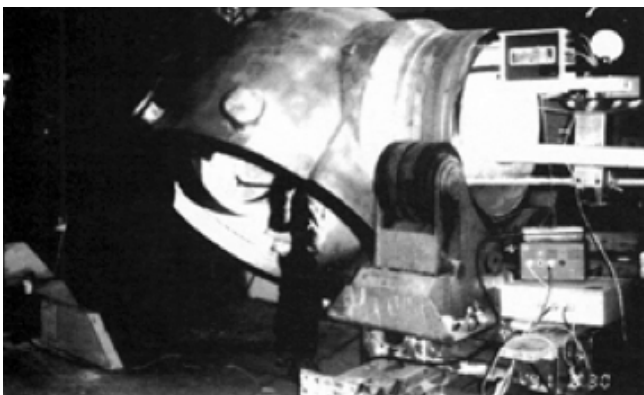
Courtesy of Forth Tool and Valve Ltd

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



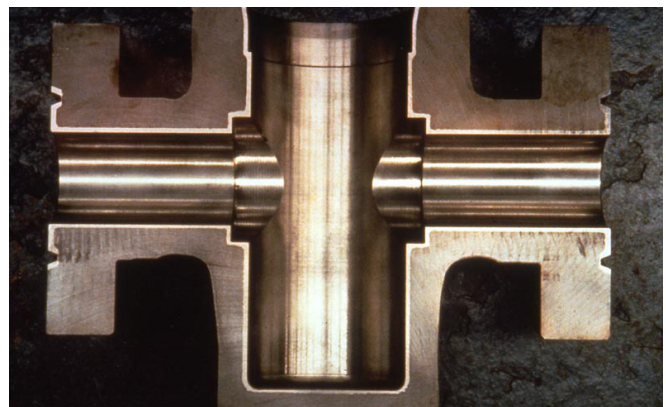
Courtesy of Cameron Iron Works Ltd

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



Courtesy of Weir Strachan and Henshaw Ltd and Borsig Valves

FIGURE 23. Pulsed GMAW Alloy 625 overlaid 3 1/8" wing valve.



Courtesy of ABB Vecto Gray UK Ltd.

given in **Figure 5** 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 (e.g. submerged arc) may be applied to fittings.

Manual welding is sometimes used for overlaying, particularly for small areas such as 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 cored 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 sinks or means of removing the heat build-up during welding, otherwise distortion and metallurgical damage to the substrate may occur.

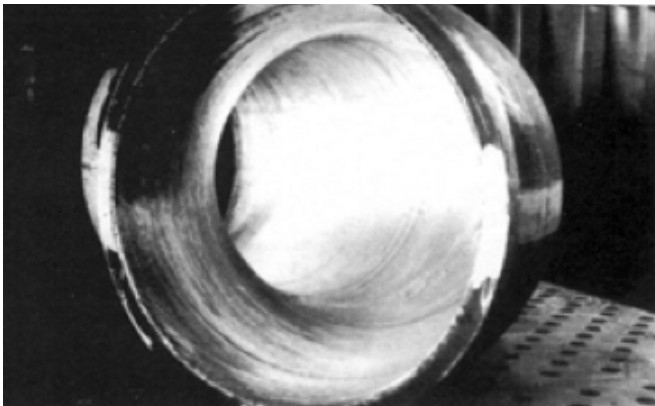
Post-welding heat treatment may be required after overlaying as discussed in section 2.4.

Most specifications (whether external e.g. API 6A, ASME Section IX, VIII, V or internal) 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 e.g., to ASTM A578. This is usually done from the backing steel side if the geometry allows since machining of the clad layer is then not necessary.

5.4 Explosively Bonded Fittings

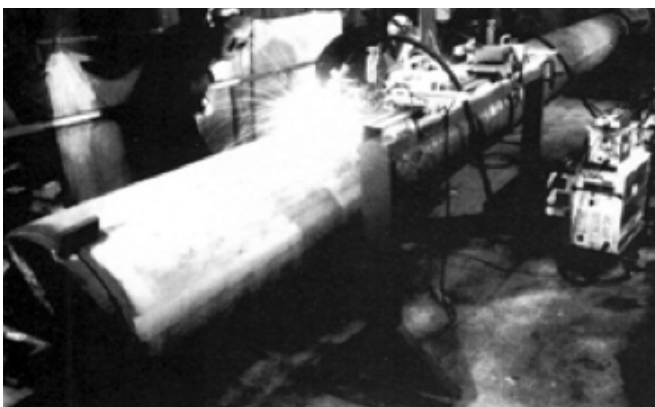
Explosive bonding as described in section 3.3.2 has been successfully applied to the production of fittings such as nozzles for pressure vessels.

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



Courtesy of Head Robinson Engineering Ltd.

FIGURE 25. Synergic GMAW overlaying of external pipe surface with two passes of Alloy 625.



Courtesy of Scomark Engineering Ltd.

6. WELDING OF CLAD STEEL

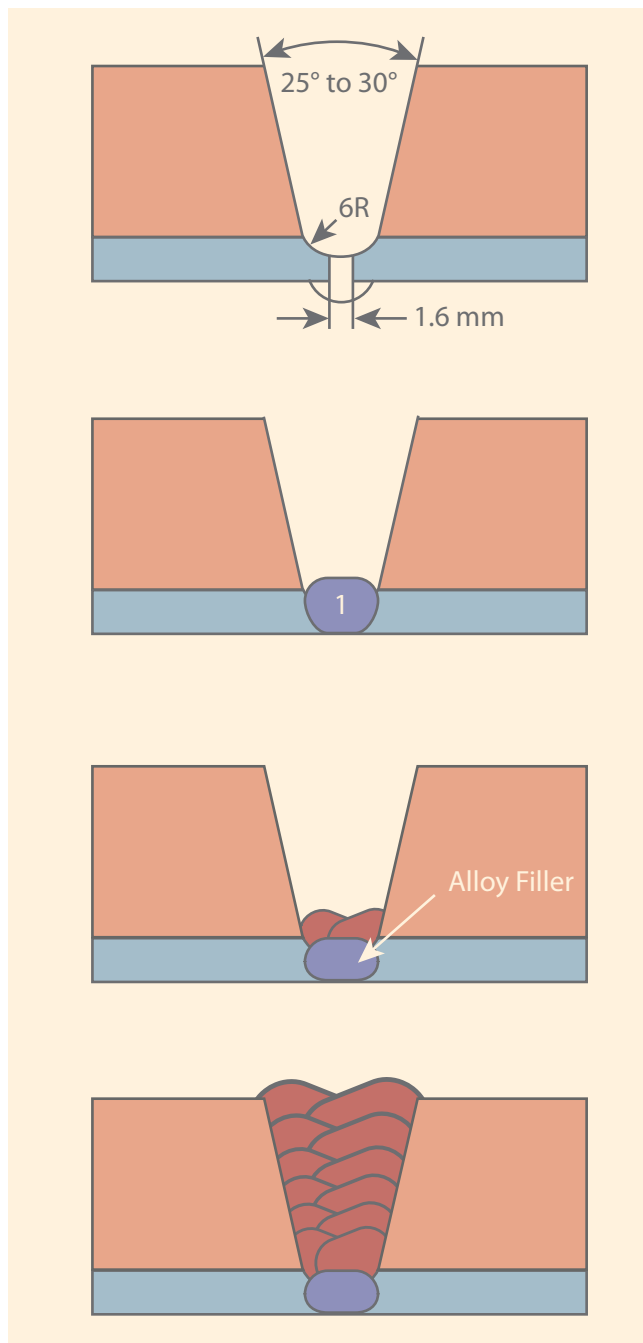
The aim of welding clad steel is to maintain a continuous fully corrosion resistant layer across the joint. In the case of single side welds in internally clad pipe, the weld preparation is generally a "J" bevel with the nose of the bevel being entirely within the clad layer (see **Figure 26**). Good 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 metal of matching or over-matching corrosion resistance. For example, for cladding of 304L or 316L, a 309MoL filler metal would be preferred; for 904L, 825 or 625 cladding, a 625 filler would be preferred.

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Successful welding of this critical root weld is highly dependent upon a good tolerance on the roundness of the pipe. If automatic GTAW with a closed root is to be used, the maximum misalignment, often called "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 diameter pipe where pipe clamps can be used to round the pipe before welding. Mismatch of the root can

FIGURE 26. Schematic bead sequence for welding of clad steel with single-sided access.



be more easily accommodated by manual GTAW where a root gap in 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, 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 kJ/mm 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 martensite 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 advantageous 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 Alloy 625 will meet the 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.

6.1 Field Welding Challenges

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.

Early lined pipe installation always required the lining to be rewelded to the pipe following the cut-out of girth welds. More recent project experience indicates that where the repair weld is made quickly after rebeveling the pipe end (so there is no risk of moisture getting into the gap) the repair girth weld can be easily done without the re-attachment of the liner.

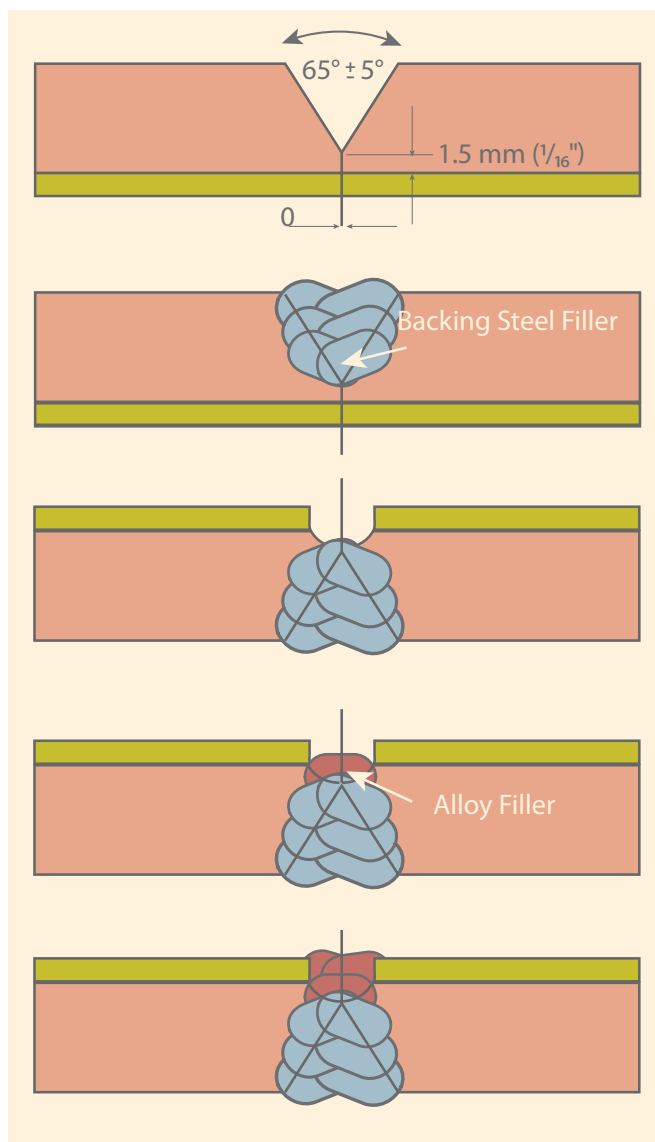
During a number of projects in different parts of the world, fabricators have commented on a problem of arc blow whilst welding clad pipe. Arc blow is a much more acute problem for welding clad and lined pipe than when welding carbon steel pipe. It is therefore considered to be primarily a problem related to the use of an austenitic (non-magnetic) filler material, in a magnetic

steel pipe. As the joint is filled with austenitic material, the lines of magnetic flux have to deflect around the deposited metal, causing distortion to the magnetic field.

The extent to which these problems can arise is dependent upon many parameters:

- **The joint design.**
- **The joint gap.**
- **The inherent magnetism of the pipe ends and the way they interact when brought together at the joint.**
- **The selected welding process (some having a stronger or stiffer arc and therefore less susceptible to deflection).**
- **The welding parameters which influence arc characteristics.**
- **The type of welding power source.**

FIGURE 27. Schematic bead sequence for welding of clad steel with double sided access.



Notwithstanding this phenomenon, pipelines have been laid without excessive repair rates in most cases. Steps which help are to purchase pipe with residual magnetism below 20 Gauss and also to dynamically remove the magnetic field whilst welding using specialist demagnetizing equipment.

The ultrasonic inspection of clad welds presents a challenge because of the refraction of the beam as it passes from the ferritic backing steel into the austenitic weld metal (in a typical fully-austenitic weld deposit). This results in some error in interpretation of any defect dimensions and location. Confidence in identifying the critical root defects is not as high as in welds with a homogeneous composition. Specialist inspection methods can overcome these problems but it is advised to use the weld qualification trials as an opportunity to calibrate any system for use in the production phase.

7. 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

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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. Type 316L clad steel can have an advantage over solid 316L because the exterior surface is not susceptible to stress corrosion cracking.

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 is 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 is generated internally.

The outer surface, if buried or submerged, would normally be cathodically protected. If protected at the

TABLE 5. Summary of clad production method and dimensional availability

Product	Wall thickness (mm)	Width/Diameter (mm)	Max Length (m)
Roll-bonded plate	6 –200. Cladding 1.5mm to 40% of total thickness	1000-4000	14 or 20 depending on supplier
Explosive bonded plate	Cladding 1.5 – 25mm. Minimum base thickness	50 – 3500	5
Explosive bonded plate with hot rolling	3x cladding thickness, no limit to max. thickness of base	1000 – 4400	14
Overlay welded plate	Base metal > 5mm Clad layer >2.5mm	Limited only by access of equipment	Limited only by access of equipment
Longitudinally welded pipe	6 – 32	219 – 1016	12.8 depending on supplier
Lined pipe	7 – 24 Total wall Liner 2 – 20 mm	219 – 1016	9.6 or 12 depending on diameter
Seamless pipe extruded plug/mandrel mill	6-25	60 – 400 depending on supplier	Depending on diameter
Seamless pipe -explosive metallurgical joint	6-20	200 – 250	3 or 5 depending on supplier
Seamless pipe -after cold rolling	2-20	50 – 200	6 – 12
HIP clad pipe or fittings	> 5 Clad layer min. 2mm	25 – 1000	2
Weld overlay fittings	Base metal >5mm Clad layer > 2.5 mm	25 minimum	For small diameters limited by torch length e.g. 1m for diameter 50 mm. No limit on large diameter.

correct potential, some 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 over-protection 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. ^[10]

8. CONCLUSIONS

Corrosion resistant alloy clad steel has been available in various forms for over 50 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 a proven engineering option for corrosive production systems.

NOMENCLATURE

CRAs -corrosion resistant alloys

EB -explosive bonded

GMAW -gas metal arc welding

GTAW -gas tungsten arc welding

HRB -hot roll-bonded

SMAW -shielded metal arc welding

UOE -'U'ing, 'O'ing, Expansion (pipe mill)

WO -weld overlaid

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