DISSIMILAR METAL WELDING

Noel F Herbst

Presented To The Welding Technology Institute Of Australia - Victorian Branch
February 4th 1998

Dissimilar Metal Welding

1 INTRODUCTION

All welding processes have a component of dissimilar metal welding about them

The fact that metals have to be joined is an admission that they are most probably from two different sources. By far the greatest tonnage of welding would be in joining the same general type of material— perhaps the most common situation would be in structural steel where two low-medium carbon steel components are welded together. Even in this simple case there can still be a problem if one piece is at the high end of the carbon range and the other is at the low end.

A more demanding case is where there are two quite different materials that have to be joined. This paper is designed as a review of the practice of dissimilar metal welding of this latter class of join.

2 PREQUALIFICATION

One aspect of dissimilar metal welding that needs stressing is that recommendations in this area are largely recommendations of the first material with which to start the pre-qualification test with. Because of the large number of permutations possible, it is essential that any combination of parent metals, fillers and welding variables must be given a pre-qualification test to ensure that the system is able to meet the design requirements.

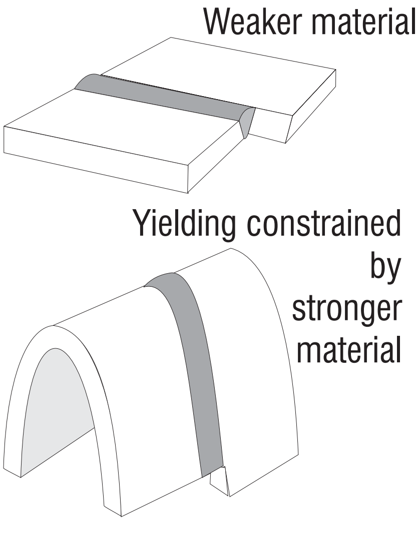

Figure 1 Transverse bend

3 DISSIMILAR WELD STRENGTH

The strength of a weld between dissimilar metals must be considered as lower than either of the components.

There will be the added complexity that the properties of the weld will vary across the weld more than would be expected with a conventional single metal weld.

When one metal is significantly weaker than the other overall flow in the weaker component will be constrained by the stronger one and there will be a lack of overall ductility. This can be easily illustrated by considering a transverse bend of a welded selection, Figure 1

4 NON-FUSION JOINTS

The simplest case of a non fusion join is one made with adhesives, or by bolting. These topics will not be covered in this paper.

Brazing and soldering are generally regarded as non-fusion joins but there can often be some metallurgical interaction at the brazing-alloy metal interface and there can certainly be other problems related to expansion, conductivity and corrosion. For this reason these joints will not

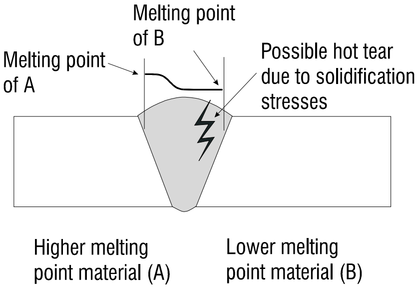

Figure 2 Variation in melting point in a weld with a wide variation in component melting points

ALLOY	Approx Liquidus Temp. (°C)	Approx Solidus Temp. (°C)	Specific Heat (20°C) (J/kg.°C)
0.2% carbon steel	1500	1490	480
0.4% carbon steel	1500	1490	480
Nickel-chrome-molybdenum steel (4140)	1500	1490	495
Stainless steel type S30400	1450	1405	500
Stainless steel type S30403	1440	1395	500
Stainless steel type S43000	1510	1510	460
Stainless steel type S31803	1445	1385	470
N08800	1385	1350	460
N06600	1410	1355	445
N04400	1350	1300	430
Copper	1095	1065	390
C71000 (80-20 Cupro-nickel)	1200	1150	375
C26000 (70-30 brass)	955	915	400
Aluminium	660	660	1000
A96063 Aluminium extrusion alloy (Mg: 0.7; Si: 0.4;)	655	615	900
A04430 Al-5% Si casting alloy	575	630	960

Table 1 Melting ranges and specific heats for a number of common materials

NOTEBOOK

Dissimilar metal welding has the variables of the metals being welded, the filler and the welding process. All can affect the quality of the final weld.

The principal factors that have to be considered in relation to the materials *are:*

Physical Properties: melting point; thermal expansion; thermal conductivity.

Metallurgical Properties: Microstucture - undesirable phases; thermal stability - ageing.

Chemical Properties: Corrosion - particularly galvanic corrosion.

The first two of these can dictate the welding operation in relation to the amount of dilution of the weld pool that can be accommodated and the need for pre- and post- weld heating. The third controls the service environment that the joint can be expected to withstand be specifically segregated from fusion joints for the purpose of this paper.

Other non-fusion type joints - explosive and friction welds - will be dealt with later, Sections 7 and 8.

5 CONTROLLING FACTORS IN DISSIMILAR METAL WELDING

5.1 Melting temperatures

It is clear that a difference in melting temperatures can present a problem in fusion joints. A table of the melting temperatures of a range of common alloys that could be welded together is given in Table 1.

The effect of dissimilar metal welding can depend on whether the joint is a fusion or non-fusion join. It is clear that the lower melting point alloy will form a greater part of the weld pool than the higher melting point one. Where there is not a great deal of difference, the welder can help this distribution to some extent by the direction of his arc.

The problem can be illustrated when a joint is such that considerably more of one metal is melted compared to the other. As this joint solidifies contraction stresses are more likely to cause a hot-tear to develop in the low melting point alloy at or close to the parent - weld interface since this will be the last section to solidify. A plot across the weld junction would show the solidification temperature generally decreasing as the amount of the lower melting point metal increased in the alloy, Figure 2. The wider area of the lower melting point material will be constrained on both sides and thus the solidification contraction and stresses are likely to generate a crack.

Where there is a wide divergence in melting temperatures, and this can be as low as 100 C °, then it may be necessary to include a material with an intermediate melting temperature as an interface between the two. This will most usually be one of the brazing alloys. The melting ranges of some of the common brazing alloys are given in Table 2. This process is known as buttering and is a common solution for a lot of dissimilar metal welding problems, see Section 5.2.

Brazing-Soldering Alloy	Liquidus (°C)	Solidus (°C)
50-50 Sn-Pb solder	421	361
60-40 Sn-Pb solder	374	361
60-40 Cu-Zn brazing alloy (AWS A5.27 RBCu-ZnA)	900	890
Silver solder (Ag:45; Cu: 30; Zn: 25) [AWS A5.8 BAg5]	843	743
BNi1 Nickel brazing alloy (B:3.4; C: 0.7; Cr:14; Fe: 4.5; Ni: Bal; Si:4) [AWS A5.8 BAg5]	1040	970

Table 2 Melting ranges of some common brazing alloys

ALLOY	Coefficient of thermal expansion μm/m/°C	Applicable temperature range (°C)
0.2% carbon steel	13.37	0-1000
0.4% carbon steel	13.59	0-1000
Nickel-chrome-molybdenum steel (4140)	13.86	0-1000
Stainless steel type S30400	20.0	0-1000
Stainless steel type S30403	20.0	0-1000
Stainless steel type S43000	11.9	0-650
Stainless steel type S31803	18	0-300
N08800	18.0	0-800
N08330	17.64	0-800
N06600	16.4	0-900
N04400	17.64	0-900
Copper	17.7	0-350
C71000 (80-20 Cupro-nickel)	16.38	0-350
C26000 (70-30 brass)	19.9	0-350
Aluminium	25.5	0-300
A96063 Aluminium extrusion alloy (Mg: 0.7; Si: 0.4;)	25.6	0-300
A04430 Al-5% Si casting alloy	24	0-300

Table 3 Thermal expansion coefficients of a number of common materials

5.2Expansion

5.2.1 Fusion welds

Differential thermal expansion over a dissimilar metal weld can introduce stresses additional to those normally accompanying welding. It is possible that these stresses could be sufficient to induce a crack either during cooling, after welding or in service

The coefficients of thermal expansion for a number of common materials are shown in Table 3.

Differential expansion can also produce a problem during service. The following example illustrates this:

Metal A: S30400 stainless steel - expansion coefficient = 20.0 m/m.°C

Metal B: 0.2% carbon steel - expansion coefficient = 13.4 m/m.°C

If an assembly containing these two materials, Figure 3 is heated, the before and after conditions would be:

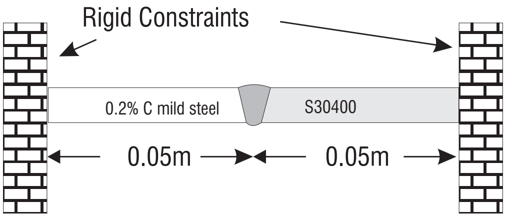

Figure 3 Expansion stresses in a welded joint

NOTEBOOK

Variation in the expansion coefficients of the components of a dissimilar weld cannot only produce distortion in the weld but, more particularly, can initiate fatigue failure in components subjected to thermal cycling.

If the component is likely to have to accommodate this type of service stressing then it may be necessary to provide an intermediate, buttering, layer with an expansion coefficient midway between each of the parent metals.

Metal A: ....cold length = 0.05m
.....................hot length = 0.05050m[1]
.....................expansion = 0.00050m
Metal B: ....cold length = 0.05 m
.....................hot length = 0.05033 m
.....................expansion = 0.00033m

This will mean that there will be a compressive internal stress, induced in the component. This can be calculated from the expansion, ie strain, and the elastic modulus, E, as:

= E x strain

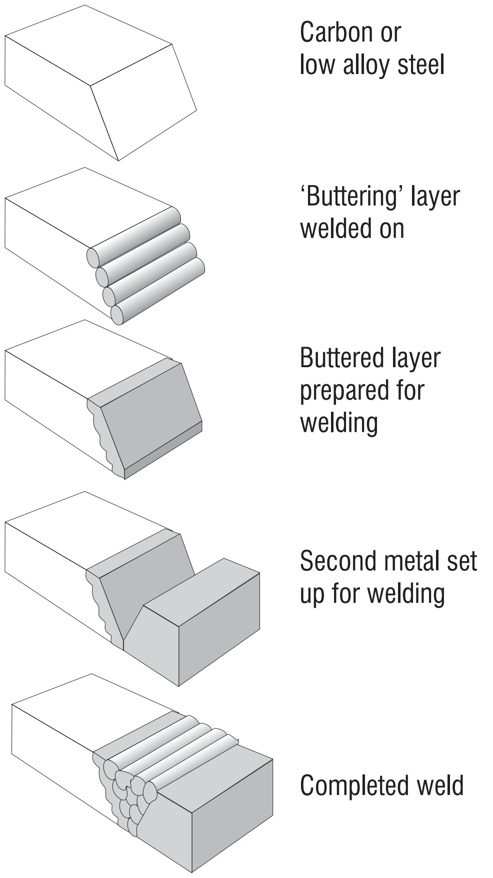

Figure 4 Buttering with an intermediate expansion coefficient alloy

It is possible to consider the difference in strain on either side of the weld, assuming the weld to be a 'fixed' point

The strain in the mild steel component will be:

$_{MS}$ =211.9 x 0.00033
= 69 MPa

and in the stainless steel it will be

$_{SS}$ = 215.3 x 0.00050
= 107 MPa

It must be appreciated that there have been several approximations in these calculations, not the least being the temperature distribution selected. The main point to be made is that there will be expansion, it will be different to that expected with homogeneous welds and it will generate internal stressing, distortion or both.

Stress analysis of joints between the chrome-molybdenum steels used in steam service and either S30400 or S31600 austenitic stainless steels shows that the thermal expansion stresses occurring across the joint are nearly double that caused by the operating pressure.[2]

Where this stress produces a fluctuating load—as it would in a thermal cycling situation—it is possible that fatigue loading could occur. The welding of boiler tubes to minimise in cost by using the higher alloyed stainless steels only where these are necessary has led to failures that can be related in part to the differential expansion from dissimilar metal welds[3].

It is for this reason that the operating stress on dissimilar metal weld joints between stainless and carbon steels should be kept at a minimum.

To avoid undue stressing the weld metal should, if possible, have an expansion coefficient intermediate between the two parent alloys, ie providing a *buttering* layer, Figure 4 . If this path is chosen, the high nickel alloys, N08800 or N08330 are likely materials for the buttering layer.

ALLOY	Coefficient of thermal conductivity W/mK	
	At 100°C	At 500°C
0.2% carbon steel	51.1	39.1
0.4% carbon steel	50.7	37.9
Nickel-chrome-molybdenum steel (4140)	42.7	36.4
Stainless steel type S30400	16.3	21.5
Stainless steel type S30403	16.3	21.5
Stainless steel type S43000	24.9	28.8
Stainless steel type S31803	15	18 (300°C)
N08800	13.0	19.5
N06600	15.9	22.1
N04400	21.7	29.3
Copper	387.6	375.5 (300°C)
C71000 (80-20 Cupro-nickel)	36	- - -
C26000 (70-30 brass)	121	147 (200°C)
Aluminium	239	- - -
A96063 Aluminium extrusion alloy (Mg: 0.7; Si: 0.4;) Annealed	218	- - -
A04430 Al-5% Si casting alloy	159	- - -

Table 4 Thermal conductivity coefficients for a number of common materials

A table of expansion coefficients for some common structural materials is given in Table 3

Thermal expansion can be altered by alloying. Nickel is a particularly interesting

NOTEBOOK

Thermal conductivity variations in the components of a dissimilar weld can give problems with over-heating one component and/or under-heating the other. Directing the arc to the lower conductivity component may assist to minimise this problem.

---

[1] To calculate expansion: $L_1 = L_0(1 + \alpha t)$ where α is the coefficient of thermal expansion and t is the temperature rise. Assuming an average temperature rise over the 5 cm of 500°C, $L_1 = 5(1+20.0*10^{-6}*500)) = 5.05$ cm

[2] American Welding Society *Welding Handbook 7th Ed Vol 4, Chapter 12 Dissimilar Metal Welding* p523 (1982)

[3] Avery R E *Pay attention to dissimilar welds - Guidelines for welding dissimilar metals* Chemical Engineering Progress May 1991. Reprinted as NiDI publication 14018

NOTEBOOK

Pre- or post-heating is often necessary in hardenable steels or alloys requiring an ageing heat treatment. If one component of a weld requires either pre- or post-heating then the whole weld will probably have to have the same treatment. This could usually be expected to generate considerable difficulties.

example since alloying with copper increases its thermal expansion but iron, chromium and molybdenum will reduce the expansion coefficient

5.2.2 Brazing

When dissimilar metals with differing expansion coefficients are brazed, the clearance required for correct capillary action during brazing must be calculated. For example if a tube with a high thermal expansion is a press fit at room temperature around another with low thermal expansion, it is probable that the clearance at the brazing temperature will be too much to permit the correct capillary action. If the reverse arrangement of tubing is used, the clearance will be too small.

If two solid components of differing expansion coefficients are being brazed, the brazing alloy should have an intermediate brazing coefficient.

5.3 Thermal conductivity

The effect of thermal conductivity variation is similar to both melting point and thermal expansion problems. The problems arise when one half of a joint has a markedly different coefficient of thermal conductivity compared to the other. Directing the welding heat source can qualitatively allow for this, preheating the high conductivity metal can also assist this.

Thermal conductivity changes with temperature. A tabulation of some metallic thermal conductivities with the applicable temperature range are given in Table 4 .

It is interesting to note that conductivity increases with increasing temperature for some metals, eg UNS S30400, but decreases with others, eg carbon and low alloy steels.

Components where distortion is critical may require procedures to counteract the effect of a thermal conductivity that could cause problems. This may require heat input on some occasions - or extraction on others.

5.4 Pre- and post-heating

If pre-heating or post-heating is required on one half of a joint for metallurgical reasons, this must also be the case for the whole of a dissimilar metal joint containing that alloy.

Pre-heating is frequently important for higher carbon and/or restrained plain carbon steels to prevent post-weld cracking. This will not present a serious problem with most dissimilar metal joints although in some cases where pre-assembly or jigging is required, there may be some handling difficulties.

Post-weld heating is not as simple. It is conceivable for example that a carbon steel welded to a UNS S30400 stainless steel may accentuate the possibility of sensitisation corrosion due to the combination of welding heat input plus the post weld heating. Sensitisation is the decrease in aqueous corrosion resistance due to carbide precipitation.

Heat treatment can be considered as a post weld heating operation.. If one side is to be heat treated by, say ageing, then the effect on the other side must be considered, eg two different age hardening alloys may have different ageing treatments. Clearly other types of heat treatment could cause concern.

5.5 Choice of Welding Process

The main points that must be considered when selecting the basic process for completing a dissimilar metal weld is a need for precision location of the arc to permit differential heat transfer between either side of the weld.

Other factors relating to pre-heat, post-weld heat treatment, shielding gases etc depend on the most sensitive side of the weld, eg in welding a hardenable carbon steel to an austenitic stainless steel, a pre-heat must be given to ensure there is control over martensite formation in the weld pool and the heat affected zone of the carbon steel.

As mentioned above, the effect a necessary treatment on one side of the weld would have on the other side - or the weld pool - must always be considered.

5.6 Weld pool properties

5.6.1 Metal mixing

Metal mixing is essentially a mechanical process and for any mixing to occur, the metals must be wetted by the filler metal. This could require specialised fluxes.

The normal considerations in mixing that apply to all welding operations will also apply to dissimilar metal joints.

Six zones are usually identified, Figure 5[4]:

Composite zone where there has been complete mixing

Unmixed zone where the parent plate has melted but not mixed with the metal of the composite zone. This zone can give phases that might not be present in the overall structure and that could markedly alter the weld structure.

Fusion line

Partially melted zone: This can give corrosion problems due to dendritic solidification on cooling but also can have penetration by the weld metal into the parent plate - ie liquid metal corrosion.

Heat affected zone. The normal area of the parent plate where heat from the weld can affect the parent plate structure

Unaffected base material

It is probably the composite zone and the partially mixed zone that can give unexpected results in a dissimilar metal weld. The reasons for this are essentially related to the effect of mixing on the phases that will be present, see Section 5.6.3

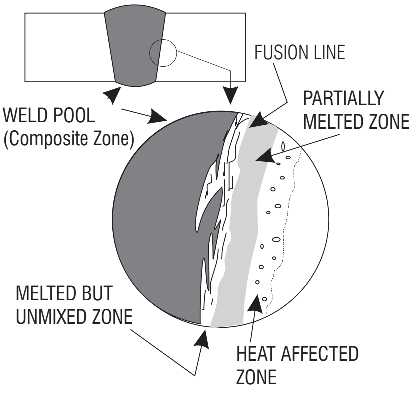

Figure 5 Zones in a welded deposit

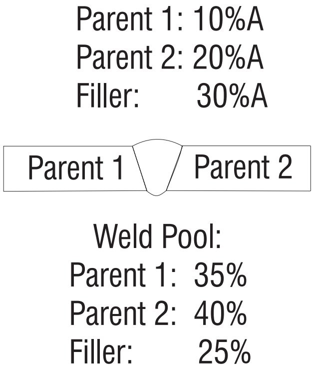

Figure 6 Weld pool dilution calculation

---

[4] Taylor JS *The fusion welding of dissimilar metals* The Welding Technology of Stainless Steels WTIA Seminar Melbourne 1995

NOTEBOOK

The composition of the weld metal in a dissimilar metal weld can be approximately calculated from the lever rule.

This process requires an estimate to be made of the amount of each constituent that ends up in the weld pool. It is usually assumed that there are no losses from oxidation during the weld.

There are also some structural factors that can affect dilution: component thickness, location relative to the weld face, weld run placement relative to the previous run, factors that alter penetration.

5.6.2 Dilution calculation

The basic concept behind calculation of weld pool composition relies on the lever rule so familiar to metallurgical calculations.

If it is assumed, as a simple situation, that a weld pool between two dissimilar metals, A and B, contains half of metal A and half of metal B then the composition of the pool must be an equal mixture of each alloy.

In the case of a three component system, it will be remembered that the composition of the weld pool will depend on the ratio of each metal. On the phase diagram the three alloy lever rule is used for graphical calculation of the weld pool composition.

Referring again to a binary alloy. If it contains one quarter of metal A and three quarters of metal B, the composition must reflect this.

If there is a third alloy introduced as a filler material then the composition of the weld pool will be controlled by the amount of filler present. As an example of this, the effect of the ratio of parent metals and filler metal for a mild steel/UNS S30400 weld with and without S30900 filler is shown in Table 6.

For example, assume that each component has the following composition of metal A.

Parent 1:	10%
Parent 2:	20%
Filler wire:	30%

Also assume that the weld pool contains the following proportion of each component, (See Figure 6):

Parent 1:	35%
Parent 2:	40%
Filler wire:	25%

The amount of metal A in the weld pool will therefore be:

$$(0.35\ x\ 10\%)+(0.4{*}x\ 20\%)+(0.25\ \ x\ 30\%)=19\%$$

This calculation assumes the unlikely situation that there has been no loss by oxidation during welding. If necessary, an estimated correction could be made for this.

All of the above assumed relatively simple ratios of each of the contributing materials. There are a number of factors that will affect these proportions:

Thin materials: The low heat input required to melt for thin materials together with the low cross sectional area to conduct heat away will be expected to generate a higher proportion of these in the weld pool.

Location relative to the weld face: The closer the weld run is to the parent metal face, the greater will be the contamination from the parent. Root runs will have the most contamination.

Weld run placement: Placing a second run on top, rather than between previous runs should produce less contamination from underlying runs.

Penetration: Factors that would normally be expected to give more penetration can be expected to give more dilution, eg GTAW, higher current, slower travel rate.

5.6.3 Microstucture determination

When metals are mixed, they will either mutually dissolve in each other, form a mixture of phases or appear as a mechanical mixture of the two metals with virtually no mutual solubility. The structure after ‘mixing’ will depend on the actual zone in the weld, Figure 5. These considerations are illustrated in the phase diagrams for three systems:

Copper - nickel, Figure 7: These alloys have similar crystal structures and each is soluble in the other.

Lead-tin, Figure 8: Each of these alloys has a limited solubility for the other but at room temperature it would be found that all alloys, other than those at the extreme ends, would consist of a mixture of the two solid solutions.

Aluminium - Iron, Figure 9: Apart from their widely differing melting points, each of these metals is virtually insoluble in the other. In the molten state they react to form brittle intermetallic phases etc. These will give the weld unsatisfactory properties.

A further example of the third type, perhaps of more industrial significance, is the iron-copper system, Figure 10: Like iron-aluminium, iron has very limited solubility for copper so that the two metals virtually form a mechanical mixture. Unlike aluminium-iron the phases formed are more ductile, but do have the disadvantage that there is the likelihood of corrosion in the mixture due to the galvanic effect between the copper- and iron-rich phases. There is also the wide solidification range that would almost certainly give hot cracking problems.

Where brittle phases are likely to be a problem, it may be that low temperature - non-fusion - brazing will have to be resorted to. Even in this case it could be that care

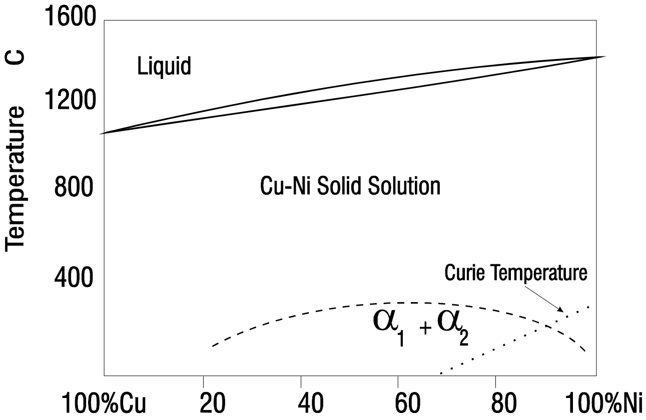

Figure 7 Copper-nickel phase diagram

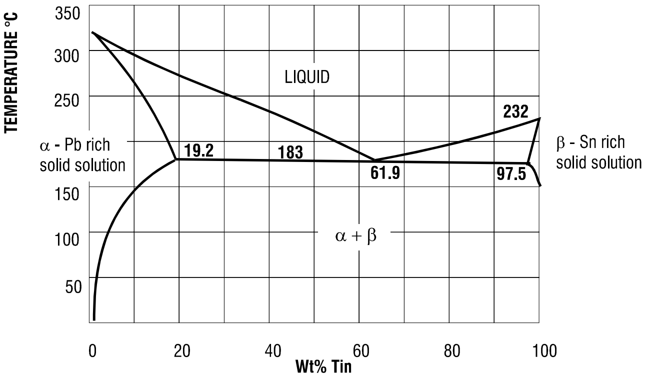

Figure 8 Lead tin phase diagram

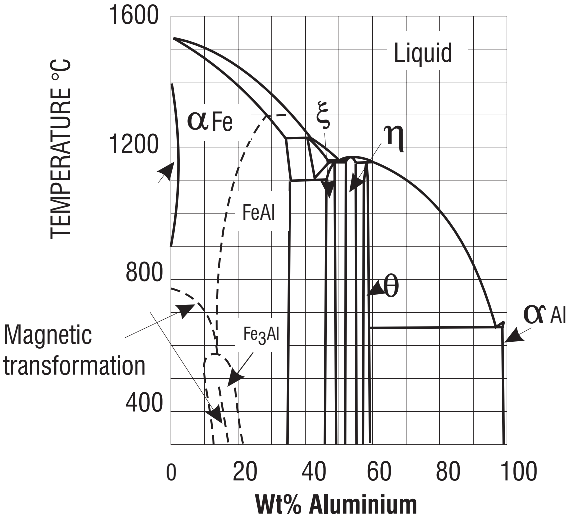

Figure 9 Aluminium-iron phase diagram

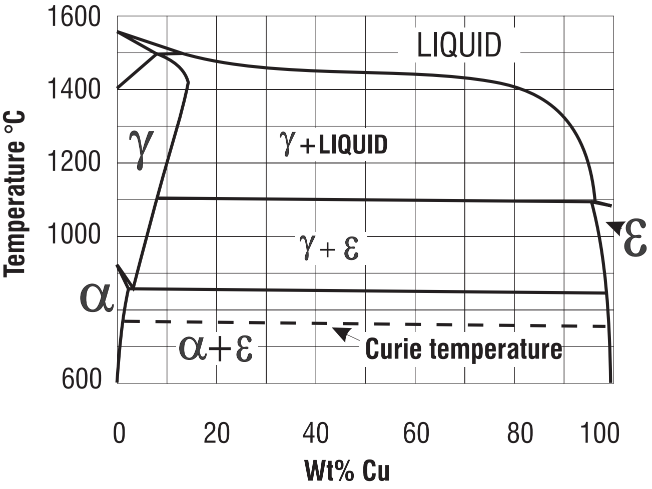

Figure 10 Copper-iron phase diagram

will have to be taken to ensure that there is no phase reactions.

If melting of the base materials can be eliminated, these reactions can only occur by the much slower solid state diffusion and thus the problem is less likely to arise.

5.6.3.1 Consumables

Taylor has summarised the effect of various elements in filler materials on the microstructure:[5]

Nickel fillers: These are tolerant to a wide range of diluting elements. The main problem areas are lead, sulphur and phosphorus

High nickel (Monel®) type fillers: High nickel-copper type fillers, because of their mutual solubility, can be deposited over copper, nickel, Monel® or cupro nickels

Dilution with up to 10% iron or 5% chromium will lead to cracking although this can depend on the process (see Table 8)

Copper Nickel type fillers: Again these can be diluted with any amount of nickel and copper because of the mutual solubility

Dilution with more than around 5% of iron or 5% of chromium can lead to solidification cracking. Weldable grades of cupronickel also have close limits placed on carbon, phosphorus, silicon, sulphur and zinc to minimise cracking

These fillers also can form brittle intermetallic compounds with aluminium magnesium and titanium when solubility limits for these alloys are exceeded.

Aluminium, magnesium and titanium fillers: These fillers cannot tolerate iron, chromium or copper without generating an unacceptably brittle weld

Carbon and low alloy steel fillers:

These are not normally recommended for dissimilar metal welding.

The addition of alloys from stainless or high nickel alloys increase the hardenability with probable post weld cracking

Nickel, chromium and copper can increase the probability of post weld cracking

Aluminium, magnesium and titanium alloys will generate brittle intermetallic compounds

Austenitic stainless steel fillers: These have been studied extensively and there is quite a lot of information on the tolerance for many elements, see Section 6.1

Aluminium, magnesium and titanium will again lead to brittle intermetallic compounds

High nickel-chromium alloy fillers:

These are dealt with later, see Section 6.3.

In general chromium should not exceed around 35%. This is a sufficiently high value that it would seldom lead to problems.

Copper should not exceed 30%, although some authorities limit this to 15%

Aluminium bronze fillers: These fillers can withstand dilution from both iron and copper and are often recommended for the dissimilar metal welding of carbon and low alloy steels, stainless steels and copper base alloys

These items will be discussed further for specific metal combinations in Section 6

5.6.4 Microstructure stability

A dissimilar metal weld could have unusual phase structures that may give problems, for example if the weld is required to have long term stability at elevated temperatures.

The common problem of sensitisation with stainless steels is an example. If a stainless steel is welded to a medium carbon steel and both are then subjected to elevated temperatures, it is possible that the stainless steel will have its carbon content increased by diffusion from the carbon steel. This can then lead to sensitisation corrosion.

An extension to this is that there will also be a following stage where more extensive carbides will form in the austenitic steel, thus making the weld zone more brittle and likely to crack under the design stresses plus, in this case of elevated temperature service, the thermal stresses that will be present.

There is a further potential problem in that the lowering of the carbon content of the low alloy steel will decrease its strength. The lower carbon steel is also more susceptible to grain growth with a further possibility of a decrease in mechanical properties.

There is also the possibility of martensite formation, see Section 4.2.

Other than lowering the amount of heat input, there is not a great deal that can be done to avoid these problems - it is probably better to avoid the situation where this type of welding is required.

5.6.5 Corrosion

The most likely problem with a dissimilar weld in a corrosive environment is the generation of a galvanic couple. This can occur on the macro scale between one of the parent plates and the mixed weld pool as well as be-

---

[5] Taylor JS *The fusion welding of dissimilar metals* The Welding Technology of Stainless Steels WTIA Seminar Melbourne October 1995

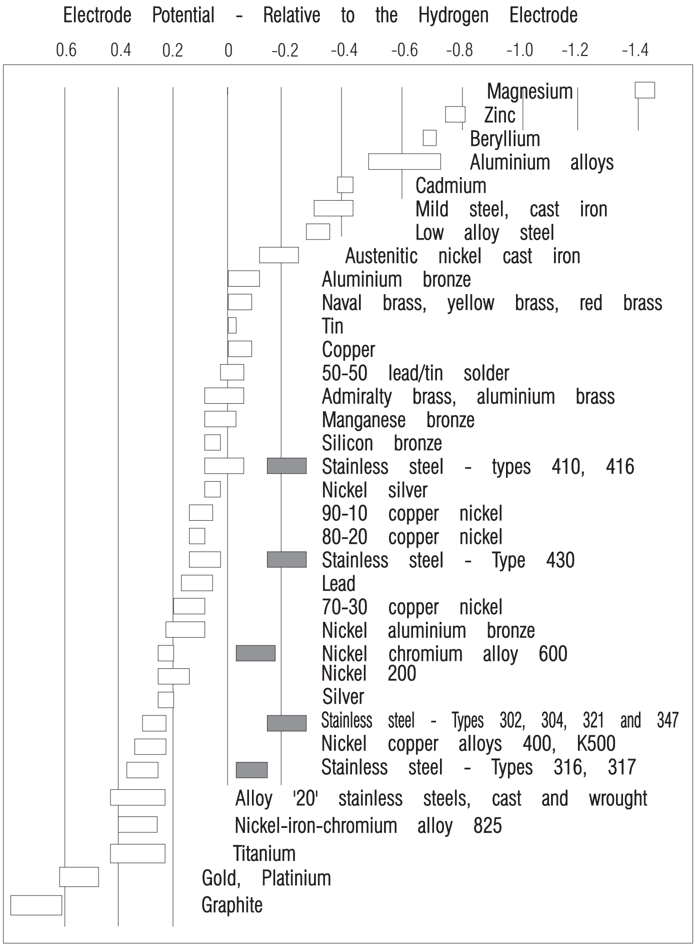

Figure 11 Galvanic series in sea water

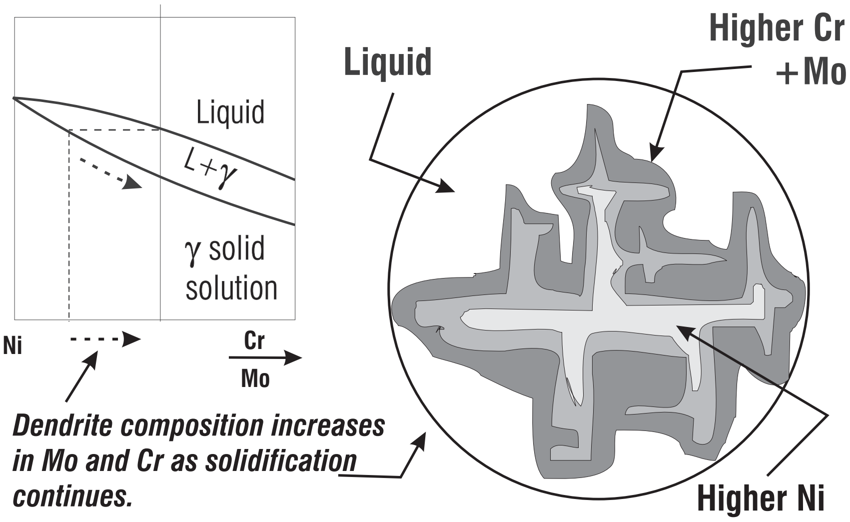

Figure 12 Segregated areas in the dendrites forming in a highly alloyed Ni-Cr-Mo weld.

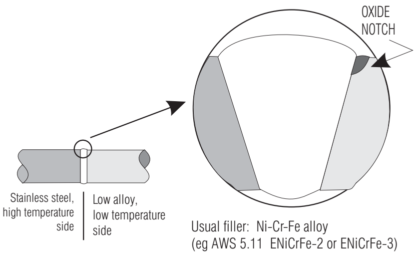

Figure 13 Differential oxidation generating an oxide notch.

NOTEBOOK

The type of alloy microstructure obtained in the solidified weld pool will control the weld properties. The microstructure can be predicted to a large extent from the phase diagram for the two alloys.

The types of structure found are:

1. Complete mutual solubility
2. Mixtures of two solid solutions
3. A solid solution or solutions with a intermetallic phase or phases. These phases are generally brittle but there are many cases where they are not.

Another problem that can arise with unusual alloy additions is a major alteration in the melting range. Iron copper alloys show this.

Microstructure stability is also important, eg carbides can form with prolonged heating at intermediate temperatures in stainless steels that have been contaminated with a plain carbon steel. These carbides can then result in undesirable mechanical properties or accelerated corrosion due to sensitisation.

NOTEBOOK

Galvanic corrosion is an ever present possibility with dissimilar metal welds.

Area relationships become significant if the weld is anodic, ie likely to corrode.

Carbon or low alloy steels welded to stainless steels are a likely site for this type of corrosion.

A common, but not particularly successful, preventative measure is to paint the carbon or low alloy steel plus the weld zone and to continue the paint film over the stainless steel for about 1cm.

This procedure will not help the carbon steel if the film is damaged - and may, in fact, accelerate corrosion if the damaged area is small and also close to the stainless steel.

Stainless Steel	Consumable	Also known as
S30400	S30900	309
S30403	S30983	309L
S31000	S30900	309
S31600	S30903	309L
S31603	S30986	309MoL
S32100	S30982	309Mo
S34700	S30900	309
S31803	W39209	2209
S32750		2510 or 25.10.4
S43000	S30900	309
S44400	S30982	309Mo
S41000	S30900	309

Table 5 Filler materials for stainless - carbon steel dissimilar welds

WELD POOL RATIO			WELD POOL COMPOSITION.		
Parent Metal A	Parent Metal B	Filler Metal C	C	Cr	Ni
0.00	1.00	0.00	0.06	19.00	10.00
0.25	0.75	0.00	0.10	14.25	7.50
0.50	0.50	0.00	0.13	9.50	5.00
0.75	0.25	0.00	0.17	4.75	2.50
1.00	0.00	0.00	0.20	0.00	0.00
0.50	0.50	0.00	0.13	9.50	5.00
0.45	0.45	0.10	0.13	10.85	5.85
0.40	0.40	0.20	0.12	12.20	6.70
0.35	0.35	0.30	0.12	13.55	7.55
0.30	0.30	0.40	0.12	14.90	8.40
0.25	0.25	0.50	0.12	16.25	9.25
0.20	0.20	0.60	0.11	17.60	10.10
0.15	0.15	0.70	0.11	18.95	10.95
0.10	0.10	0.80	0.11	20.30	11.80
0.05	0.05	0.90	0.10	21.65	12.65
0.00	0.00	1.00	0.10	23.00	13.50

Table 6 Variation in weld pool composition with varying amounts of parent metal A, parent metal B and filler metal C.Compositions:
Parent metal A: Mild steel: C: 0.2%; Cr: 0%; Fe Bal; Ni: 0%
Parent Metal B: S30400 stainless steel: C: 0.06; Cr: 19.0%; Fe: Bal; Ni: 10%
Filler Metal: S30900: C: 0.10; Cr: 23.0%;Fe: Bal; Ni: 13.5

tween the mixed weld pool and the other parent plate.

The galvanic series, indicating which metals are likely to corrode is shown in Figure 11. Metals higher on the chart, ie the more electro-negative ones, will corrode when in contact with those lower down, ie the more electropositive ones.

There is a compounding effect in that galvanic corrosion can be markedly affected by area. If the anodic, ie corroding, half of the couple is small in area relative to the supporting cathodic, ie non-corroding half, then galvanic corrosion will be markedly accelerated.

A weld bead is usually relatively small compared to the surrounding parent metal. If the bead is anodic to either of the parents, it would therefore be expected to corrode relatively quickly. It may be that it could be partially protected by the other parent metal but this may be inadequate.

Where corrosion of either the weld bead or the more anodic parent metal is a possibility, eg in a carbon steel - stainless steel weld, one solution commonly used is to paint over the carbon steel and the weld, extending the paint film about 1cm over the stainless steel. This is done in the hope that moisture will be excluded from the interface and thus eliminate the corrosion problem.

The area relationship can sometimes be an advantage, ie if the anodic area is large compared to the cathodic area then the galvanic effect can virtually be ignored. This point can be illustrated with fasteners. It is not unusual to employ stainless steel fasteners to fix aluminium sheeting. The large aluminium area is well able to support the galvanic action of the smaller stainless steel fastener area without any deleterious effect.

Galvanic corrosion can also occur on the micro scale between different phases in the weld metal or, more usually, in segregated areas within the weld pool. Highly alloyed welds, particularly those involved with the nickel-chrome-molybdenum corrosion resistant alloys, can exhibit molybdenum segregation in the weld dendrites, Figure 12.

Apart from the general dissolution aspect of galvanic corrosion, there is the secondary effect of hydrogen evolution at the cathodic half of the galvanic cell. If this cathode happens to be a high strength steel

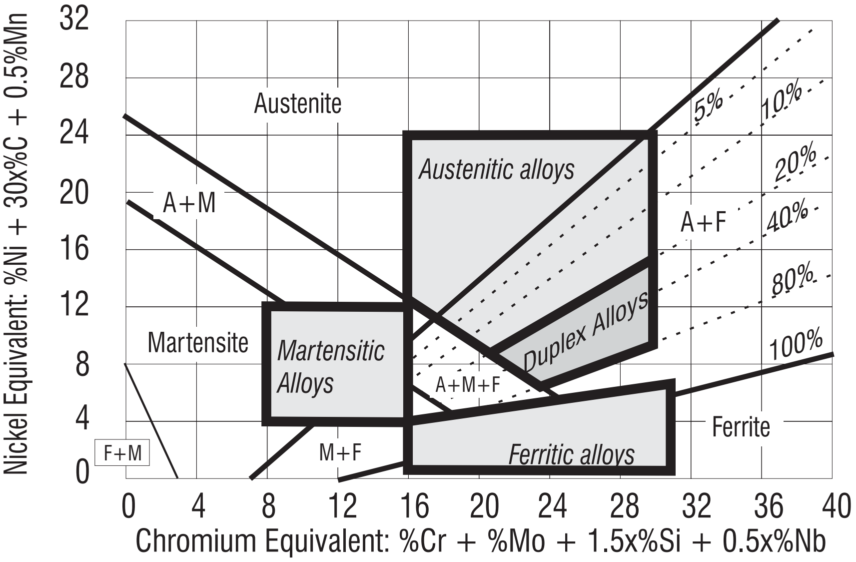

Figure 14 Schaeffler constitution diagram for stainless steels

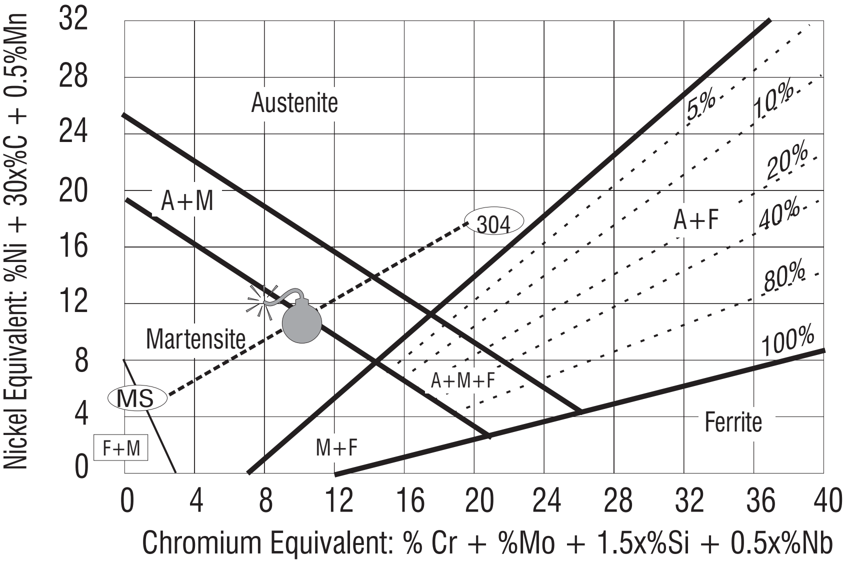

Figure 15 Probable weld pool composition from a mild steel-S30400 weld with no filler material, ie within the martensite range and hence there will be a high probability of cracking

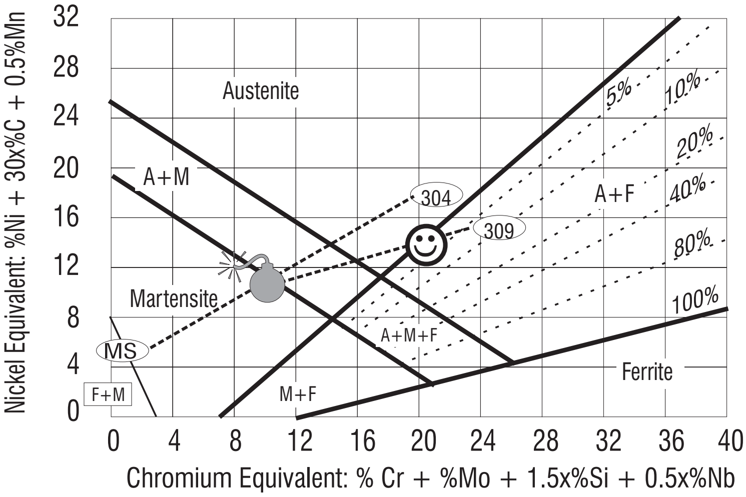

Figure 16 Probable weld pool composition from a mild steel-S30400 weld with no filler material. In this case the structure is within the austenite range so that cracking is improbable

then there is a strong possibility that this hydrogen will be absorbed into the lattice generating conditions where hydrogen embrittlement may result.

High temperature oxidation can also occur at the junction between dissimilar metals with oxidation occurring preferentially in one of the metals right at the interface. This will generate an oxide 'notch', Figure 13, that will act as a stress concentrator

5.6.6 Magnetic effects on dilution

The effect of the magnetic characteristics of metals on welds is well known . Where only one of the metals is magnetic, a DC arc can be deflected towards that metal with excess melting of that half of the joint. This can occur when welding carbon steels to nickel alloys or austenitic stainless steels. It can be minimised by operator action or overcome by using an AC arc

6 JOINT DESIGN

The major considerations with dissimilar metals are related to correct filler material and eventual joint serviceability, However, because many dissimilar metal welds are associated with one of the stainless steels, it is recommended that reference be made to AS 1554.6 for indications of appropriate physical joint designs

6.1 Austenitic stainless steel - carbon steel

The choice of consumable with these alloys is largely related to the effect of contamination of the weld pool by the carbon steel.

6.1.1 Low temperature applications:

For low to moderate temperature service it is usual to use a stainless steel filler. Prequalified fillers are listed for most stainless steels in AS 1554.6 (p45) with 309 type stainless steel being the most common. A listing of the grades suggested for some of the more common steels adapted from this Standard is given in Table 5 .

Consumable selection can be understood by reference to the Scaeffler DeLong diagram, Figure 14

It is possible to predict the type of alloy that will be obtained in the weld pool by relating these to the approximate ranges of the particular alloy groups superimposed on this diagram.

For example, Figure 15 shows what type of alloy would be expected in a weld pool with equal amounts of S30400 and mild steel present in the pool, a condition that would be expected in an autogenous weld. .

This condition would not usually be acceptable since it can be seen that a martensitic structure with its attendant undesirable properties would occur.

If a higher alloyed consumable, such as UNS S30900, were used and it was assumed that it would form 1/3 of the weld pool then the final structure would be as shown in Figure 16.

These conditions are also demonstrated in Table 6 where it can be seen that the composition of the weld pool approaches a satisfactory combination with progressively higher proportions of the higher alloyed consumable - alloy "C" in this table.

The Schaefller diagram does not accurately display the 'real' situation since it deals only with the room temperature result. The solidification pattern is considerably different.

There have been a series of modifications to the Schaeffler diagram to allow for this with the WRC 1992 diagram, Figure 17 , being the most recent.

This diagram does not include manganese as an alloying addition and as such is unable to predict the possibility of martensite formation. Manganese has little effect on the high temperature formation of ferrite or its transformation to austenite and therefore is of little significance in the fundamental use of the WRC diagram, ie the prediction of room temperature ferrite.

NOTEBOOK

The Schaeffler diagram was an attempt to describe the solidification of stainless steel in order to calculate the composition that would give the required amount of ferrite in the solidifying weld pool to inhibit hot cracking. In effect it, and the subsequent De Long modification, described the final structure achieved. This makes these diagrams useful in determining what type of consumable will be needed to give a particular microstructure in the weld pool - in particular, whether martensite will be present. The role of predicting free ferrite has been assumed by the WRC-1992 diagram which is more appropriate to the solidification stage.

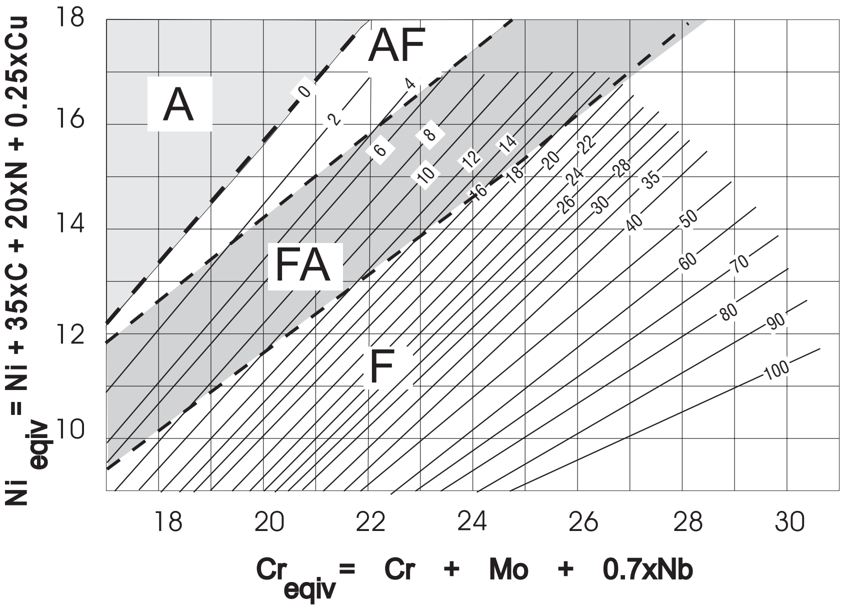

Figure 17 WRC 1992 diagram

Manganese does, however, have an effect on the lower temperature transformation of austenite to martensite and thus the inclusion of this element in the diagram can allow prediction of martensite regions. It is for this reason that the original Schaeffler diagram still finds application in dissimilar weld structure prediction[6].

One particular area of usefulness of the Schaeffler diagram is to indicate the type of behaviour that can be expected with welds of various compositions, Figure 18[7]

6.1.2 High temperature applications

Because of the problems with microstructure stability, it is usual to use one of the high nickel alloys in joints expected to operate over around 400°C. This is because of the higher tolerance to carbon and their favourable coefficient of thermal expansion as discussed in Section 5.2

These alloys also have a higher inherent creep strength and oxidation resistance to assist their survival at these higher temperatures.

The consumables usually employed are AWS 5.14 ERNiCr-3 or 5.11 ENiCrFe-3

6.2 Ferritic/martensitic stainless steels - carbon steel

The principal point of concern here is the hardenability of the combined joint

There are a large number of possible combinations but almost all will generate a hardenable steel through the combination of chromium and carbon that w in the weld pool

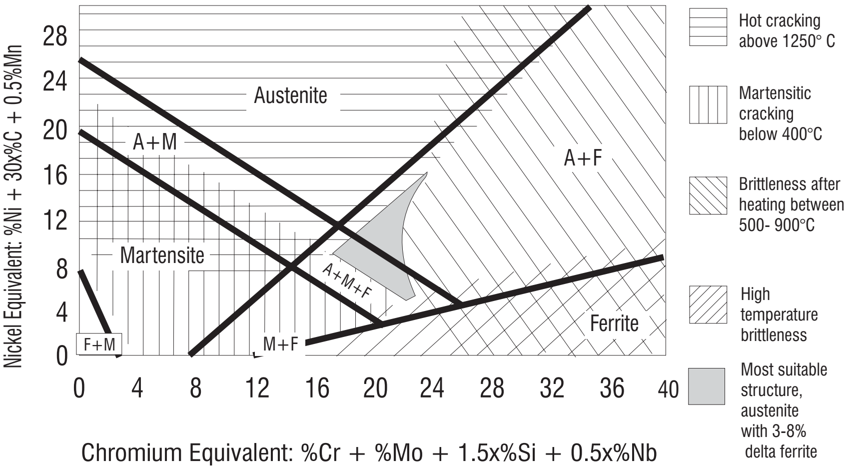

Figure 18 Modified Schaeffler diagram showing composition regions prone to brittleness and cracking

High nickel alloy	Welded to	
	Carbon or low alloy steel	Stainless steel
N02200	ERNi-1 ERNiCr-3	ERNi-1 ERNiCr-3 ERNiCrFe-6
N04400	ERNi-1	ERNiCr-3 ERNiCrFe-6
N06600	ERNiCr-3 ERNiCrFe-6	ERNiCr-3 ERNiCrFe-6
N08825	ERNiCrMo-3	ERNiCrMo-3
N10665	ERNiMo-7	ERNiMo-7
N10276	ERNiCrMo-4	ERNiCrMo-4

Table 7 Suggested TIG/GMAW filler materials for dissimilar nickel alloy welds to carbon and stainless steels

NOTEBOOK

In the welding of high nickel alloys the concern with maximum limits of iron and/or chromium means that special care must be taken in consumable selection.

It is also important to eliminate the normal nickel contaminants, lead, sulphur, phosphorus and zinc Tables have been prepared with suggestions on maximum values that can be accepted.

Again, as with all dissimilar metal welds, it is advisable to conduct test welds to check the ability of the weld to meet specification requirements.

---

[6] ASM Speciality Handbook - Stainless Steels p 342 (1994)

[7] American Welding Society *Welding Handbook 7th Ed Vol 4, Chapter 12 Dissimilar Metal Welding* p526 (1982)

This can be minimised by using a filler metal with the same composition as the carbon/low alloy steel but it is still probable that there will be sufficient chromium pickup from the stainless steel to give a martensitic weld pool

If hardenability is a problem, then it may be better to use a buttering layer of high nickel stainless steel on both components. Types 309 or 310 can be used . These may then be heat treated to obtain the desired properties. The weld can then be completed with an austenitic alloy such as type 308 stainless steel

The following general rules have been proposed for joining the 4xx series stainless steels[8]

> For welding one hardenable chromium steel to another with a higher chromium content, filler material with chromium content equal to that of either steel may be used. Furthermore, any filler material whose chromium content lies between these limits is equally satisfactory provide the weldment is properly heat treated.
>
> A general rule for welding any chromium steel to any low alloy steel is to use a filler metal that has the same composition as the low alloy steel, provided that it meets the service requirements of the application. With any low alloy steel filler metal, the chromium that is picked up by the dilution with the chromium steel base metal must be considered.
>
> For welding any chromium steel to a carbon steel, carbon steel filler metal can alternatively be used, but it is preferable to use a less hardenable filler metal.

6.3 High nickel alloys

The principal problems here are associated with contamination of the nickel alloy.

Nickel alloys are particularly sensitive to sulphur because of a low melting point eutectic that gives cracks and later failure in high temperature service.

Other contaminants that must be avoided are phosphorus, lead and zinc.

The major alloying elements can also give problems and it is usual to use the dilution calculations explained in Section 5.6.2 to determine the weld pool composition and then relate this to tabulations of generally acceptable impurity levels such as that shown in Table 8.

An alternative way of presenting this information for iron and chromium is given by the American Welding Society[9], Figures 19 and 20 They state that this information is based more on practical experience than fundamental metallurgy .

A listing of some suggested filler materials for dissimilar nickel welds for bare wire welding processes are given in Table 7[10]. Readers are also referred to trade publications in this area[11,12] and the appropriate AWS Standards[13],[14]

6.4 Copper alloys

6.4.1 Dissimilar fusion welds

Copper and its alloys can be welded to carbon and stainless steels as well as high nickel alloys

Copper and steel are virtually insoluble in the solid state and a weld pool between the two will be a mixture of two phases, refer Figure 10. This diagram also shows the wide freezing range that can occur with these alloys. This can point to the possibility of hot cracking.

Thermal conductivity also presents a problem with the copper alloy frequently requiring manipulation of the heat source to give a uniform temperature in the weld zone.

Pre-heating, particularly of the copper, is necessary to also help overcome conductivity problems

GTAW and MMAW are usually preferred for this type of junction because of the better control that can be achieved over heat input and placement. Oxy-acetylene welding would not normally be used because of the lack of control.

Where dilution can generate problems, eg by iron pick up in the copper giving a wide solidification range and subsequent solidification cracks, buttering may be necessary, particularly on thicker sections, ie greater than about 3 mm.

Iron can give hot cracking problems over a reasonably well defined composition range, Figure 21 .

Phosphorus is a problem with cupro-nickels because of the formation of brittle nickel phosphides.

Buttering can be done by a deposit of a brazing material or by a weld deposit. A common buttering material is nickel because of the total mutual solubility of copper and nickel, Figure .7 The weld can then

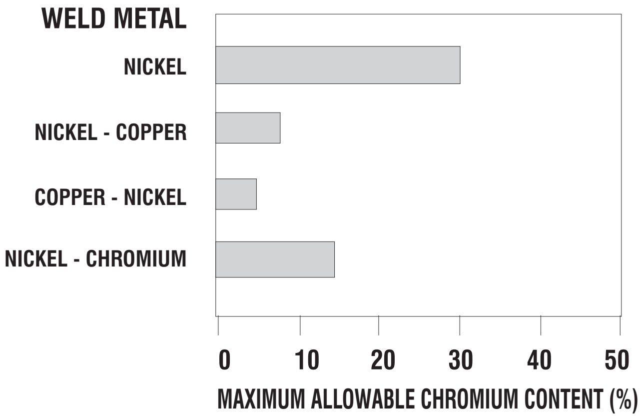

Figure 19 Tolerance for chromium in nickel alloy welds

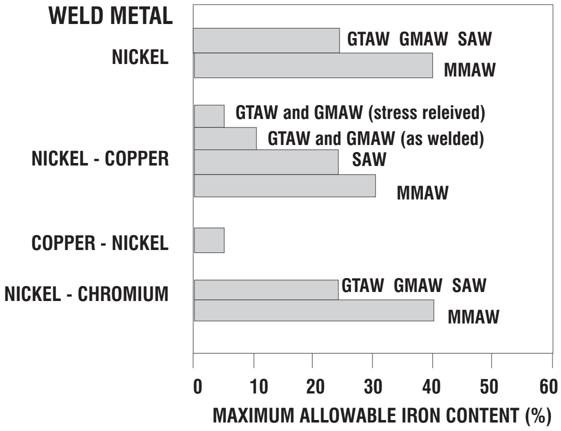

Figure 20 Tolerance for iron in nickel alloy welds

---

[8] American Welding Society *Welding Handbook 7th Ed Vol 4, Chapter 12 Dissimilar Metal Welding* p528 (1982)

[9] American Welding Society *Welding Handbook 7th Ed Vol 4, Chapter 12 Dissimilar Metal Welding* p531 (1982)

[10] American Welding Society *Welding Handbook 7th Ed Vol 4, Chapter 12 Dissimilar Metal Welding* p532 (1982

[11] INCO Alloys International *Nickel based welding products* p3 (1991)

[12] VDM Australia Pty Ltd, *Welding the VDM high nickel alloys* (undated)

[13] American Welding Society. Standard AWS 5.11 *Specification for nickel and nickel alloy welding electrodes for shielded metal arc welding*

[14] American Welding Society. Standard AWS 5.11 *Specification for nickel and nickel alloy bare welding electrodes and rods*

FILLER GROUP	TYPICAL FILLER MATERIALS		ALLOYING ELEMENT			
	AWS 5.11	AWS 5.14	Fe [see Note]	Ni and Cu	Cr	C,Si and Mn
NICKEL BASED FILLERS	ENI-1	ERNI-1	Cracking commences at about 25-40%Fe with ERNi1 being more susceptible	No limits	About 30-35%. Above this value sigma phase can form	Levels normally found in commercial practice can usually be tolerated
NICKEL-COPPER BASED FILLERS	ENiCu-7	ERNiCu-7	ENiCu7 can take up to 30% before hot cracking, ERNiCu7 commences to crack at 10-15%. Flux control available with SAW can allow even more iron. With the gas shielded processes values between 5 and 10% have been suggested	No limits	6-8% is the acceptable upper limit. Hot cracking can occur above this value	C: Values above about 0.4 can give graphitisation Si: values greater than about 1%give unacceptable weld ductility. Mn: Increases weld ductility. Some fillers use up to 9% to help prevent cracking
NICKEL-IRON-CHROMIUM-MOLYBDENUM FILLERS	ENiCrMo-3	ERNiCrMo-3	Can accept up to 10-15% but above that level becomes similar to an austenitic stainless steel and susceptible to hot cracking	Ni: satisfactory to all levels Cu: Can accept up to about 15% copper before hot cracking occurs	30% Cr is about the maximum level. This is the is the approximate composition of the filler. Problems will therefore arise if welding high chromium materials	Apart from silicon, which should be limited to 1%, values found in normal commercial products should not be a problem
NICKEL-CHROMIUM-IRON FILLERS	ENiCrFe-3	ERNiCr-3	Up to 50% iron can be tolerated with MMAW but only 25-30% with non coated filler materials	Ni: satisfactory to all levels Cu: Can accept up to about 15% copper before hot cracking occurs	Maximum level is 30-35% without cracking or problems associated with second phases	Apart from silicon, which should be limited to 1%, values found in normal commercial products should not be a problem
PLAIN CARBON OR LOW ALLOY FILLERS	VARIOUS	VARIOUS	All values of iron can be tolerated since the filler is essentially iron	The structure should be calculated from the Schaeffler-DeLong diagram to avoid martensite formation	Cu can cause hot shortness in the weld pool so that carbon and low alloy steel fillers should not be used for welding high copper nickel base alloys	The structure should be calculated from the Schaeffler-DeLong diagram to avoid martensidte formation
AUSTENITIC STAINLESS STEEL FILLERS	VARIOUS	VARIOUS	The structure should be calculated from the Schaeffler-DeLong diagram. The aim should be to avoid martensite and end up with about 4-10% ferrite to avoid hot cracking	The structure should be calculated from the Schaeffler-DeLong diagram. The aim should be to avoid martensite and end up with about 4-10% ferrite to avoid hot cracking	Cu can cause hot shortness in the weld pool so that austenitic stainless steel fillers should not be used for welding high copper nickel base alloys	The structure should be calculated from the Schaeffler-DeLong diagram. The aim should be to avoid martensite and end up with about 4-10% ferrite to avoid hot cracking
COPPER NICKEL FILLERS	5.6 - ECuNi	5.7 - ERCuNi	70-30 cupro-nickels have a limit of 5-10% before cracking occurs	No limits	5% maximum before hot cracking occurs	Not normally present in the usual applications where these alloys are welded but substantial quantities would be harmful.

Table 8 Weld pool composition limits for some grades of nickel alloys and welding electrodes.
Note: Iron is often limited to 5% maximum in the surface layer of high alloy welds to minimise corrosion problems

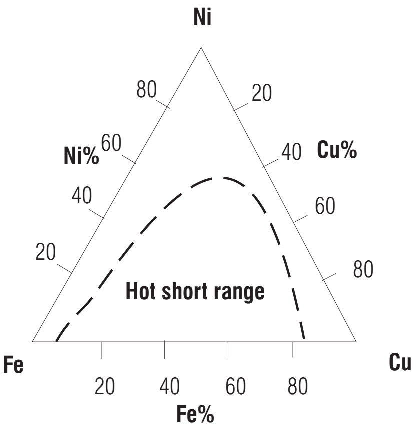

Figure 21 Hot short range in cupro nickel alloys caused by iron contamination

be completed with a filler suitable for the nickel buttering layer.

Brasses can be welded to steel if the zinc is less than about 20% and the brass is not directly heated by the arc. It is usual to use a copper tin buttering layer (ERCuSn-A) and then use this same material as a filler.

There is a wide range of filler materials specified for this type of junction. These will vary according to the type of copper alloy and the welding procedure. Some examples for GTAW, with suggested pre-heats, are given in Table 9[15]. Probably the most common filler for steel junctions is aluminium bronze (CuAl-A2). Silicon bronze CuSi-A and phosphor bronze (CuSn-A) are also used for non-nickel bearing materials.

6.4.2 Copper penetration.

One of the most important considerations with copper welding on steel is the potential for grain boundary penetration by the copper into the steel. This is sometimes referred to as liquid metal corrosion.

Molten copper has a low surface tension on iron and will quickly penetrate down grain boundaries. Internal stress accelerates this type of corrosion.

Because of this, care must be taken when welding or brazing copper materials to steel to ensure that the conditions are such that liquid metal attack does not occur.

This defect is also sometimes known as *infiltration*

6.4.3 Dissimilar metal brazing

Because of the tendency of the copper nickel alloys to hot cracking, Figure 21 and stress cracking (ie copper infiltration) the silver brazing alloys are preferred for this type of operation. Phosphorus is a particu-

METAL A	METAL B				
	Copper	Phosphor bronzes	Aluminium bronzes	Silicon bronzes	Cupronickels
Low zinc brasses, eg C23000	ERCuSn-A 540°C				
Phosphor bronzes eg C51000	ERCuSn-A 540°C				
Aluminium bronzes, eg C61400	ERCuAl-A2 540°C	ERCuAl-A2 200°C			
Silicon bronzes, eg C65500	ERCuSn-A 540°C	ERCuSi-A 65°C max	ERCuAl-A2 65°C max		
Cupronickels, eg C70600	ERCuAl-A2 540°C	ERCuSn-A 65°Cmax	ERCuAl-A2 65°Cmax	ERCuAl-A2 65°Cmax	
Nickel, eg N02200 and nickel-copper, eg N04400 alloys	ERCuNi or ERCuNi-7 540°C	These combinations not usually welded			ERCuNi or ERCuNi-7 65°C max
High nickel alloys, eg N08800, N06600	ERNiCr-3 540°C				ERNiCr-3 65°C max
Low carbon steels	ERCuAl-A2 540°C	ERCuSn-A 200°C	ERCuAl-A2 150°C	ERCuAl-A2 65°C max	ERCuAl-A2 65°C max
Low alloy steels	ERCuAl-A2 540°C	ERCuSn-A 260°C	ERCuAl-A2 260°C	ERCuAl-A2 200°C	ERCuAl-A2 65°C max
Stainless steels, eg S30400	ERCuAl-A2 540°C	ERCuSn-A 200°C	ERCuAl-A2 65°C max	ERCuAl-A2 65°C max	ERCuAl-A2 65°C max

Table 9 Suggested fillers and pre-heat temperatures for GTAW welding dissimilar welds with copper alloys

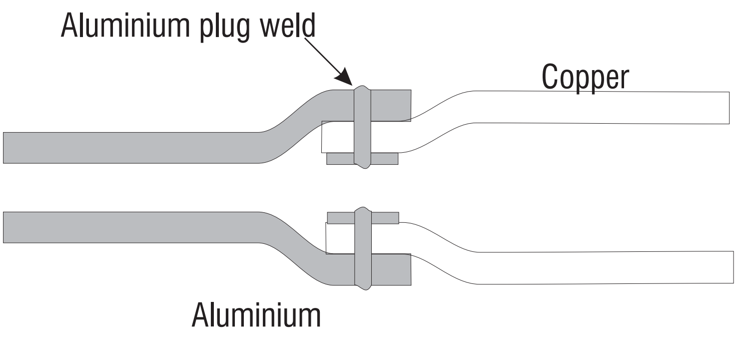

Figure 22 Plug welded aluminium copper joint

NOTEBOOK

Dissimilar welds containing copper base alloys can be made between copper alloys as well as with high nickel alloys, carbon and low alloy steels and stainless steels.

In many cases iron pick up can lead to hot cracking but buttering can be a way of minimising this problem.

Silicon bronze, aluminium bronze and phosphor bronze are common filler/buttering alloys.

Copper infiltration is a potential danger with steels. This is penetration of copper along the grain boundaries of the steel. Internal stress in the steel can promote this type of liquid metal embrittlement

---

[15] ASM International ASM Handbook Vol 6 Welding Brazing and Soldering (1993), p769

lar problem and fillers with phosphorus must not be used.

To minimise hot cracking, nickel silvers should be stress relieved prior to brazing

6.5 Aluminium alloys

6.5.1 Aluminium/copper welds

Aluminium and copper form brittle intermetallic compounds that restrict the application of dissimilar metal welding between these two alloys

Some success has been achieved by coating the copper with silver and then welding the aluminium in such a way that the weld does not penetrate through the silver layer.

Soft solders using high zinc solder of eutectic composition (Zn:95; Al:5). This alloy has a melting point of 382°C and is used in some heat exchanger applications

Ultrasonics have also been used to provide an initial coat of zinc or other low melting point solders onto aluminium for subsequent joining to other alloys

There are ways of mechanically fixing aluminium to copper, or placing a plug weld through a composite aluminium copper junction, Figure 22.

Friction or explosive welding has also been used. see Sections 7 and 8. A less violent form of welding can also be obtained by cold pressure welding at relatively high pressures. This is used for joining copper to aluminium for electrical conductors

6.5.2 Aluminium/steel welds

Apart from the wide difference in melting points, Table 1 , aluminium forms a series of brittle intermetallic compounds with iron, Figure 9. This makes fusion welds between these metals brittle.

The variations in thermal conductivity, Table 4 and thermal expansion, Table 3 would also give problems.

If it is necessary, aluminium can be welded to steel if the steel component is first coated with aluminium. This is usually done by dipping an abraded steel part into molten aluminium at around 690-705°C immediately after abrading. Friction welding can also be used to provide the coating, Section 7. The steel can then be joined to aluminium *provided the steel is not melted.*

Subsequent diffusion between the two metals can cause problems by the formation of the problem phases at the aluminium-iron interface so that the weld is usually restricted to service temperatures of less than 250°C.

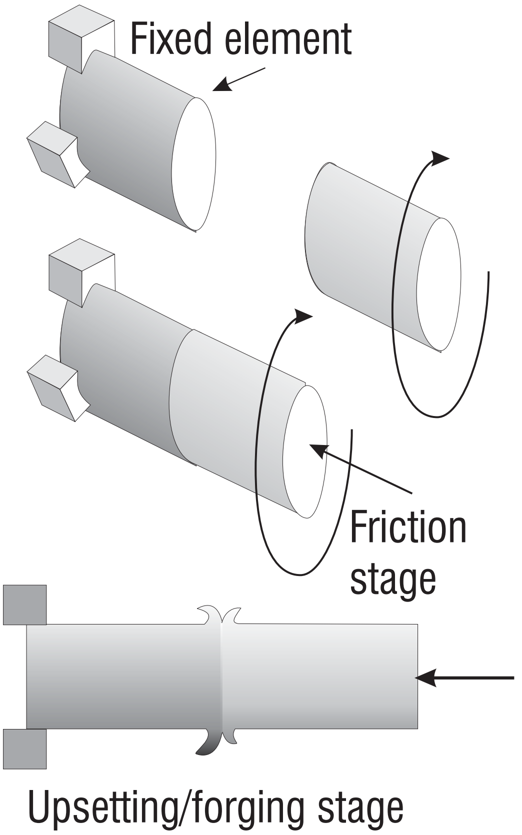

Figure 23 Friction welding stages

NOTEBOOK
Friction welding is a type of forge welding where the heating zone is very small. There should be no, or very little molten metal hence microstructure problems should be non-existent. The process is used for difficult joins, eg tool steel/mild steel; aluminium/copper.

6.6 Titanium welds

Titanium forms unsatisfactory intermetallic compounds with iron, nickel and chromium - the three metals most likely to require dissimilar metal welds.

It is possible to make satisfactory titanium-vanadium welds and vanadium is also compatible with iron so there is potential to use a vanadium interface for a titanium-steel weld, provided fusion did not extend through the vanadium interface.

In the case of nickel alloys, a satisfactory interface has been developed using niobium and copper as the transition layers. The titanium is welded to the niobium and the nickel alloy is welded to the copper

7 FRICTION WELDING

Friction welding relies on producing a narrow heating range followed by an 'upsetting' or forging stage, Figure 23

Although often cited as a method of producing dissimilar metal welds, it is still possible to obtain problems at the interface but since there is no molten zone and there is a relatively short time at temperature for diffusion to occur, the problems associated with intermetallic phases are minimised.

Should the energy input be too much, a liquid phase would form and problems associated with intermetallic phases could arise.

Satisfactory welds have been obtained between high hardenability steels, eg tool steels, and lower carbon varieties. This application is used in the joining of hardened tool steels to mild steel shanks In some cases a post weld temper may be required to soften the tool steel heat affected zone

The process is also used for the production of aluminium to stainless steel and copper base alloys. It finds particular application in coating steel with aluminium prior to fusion welding, Section 6.5.2.

8 EXPLOSION WELDING

This is a solid state welding operation similar to friction welding. The weld is accomplished in a fraction of a second, Figure 24.

There is some heat input associated with the energy of the explosion. The weld is essentially accomplished by solid state con-

NOTEBOOK
Aluminium has two principal difficulties when attempting dissimilar metal welds.
The first is its very high thermal conductivity, the second is the strong possibility that it will form brittle intermetallic compounds with the other metal.
This usually means that a brazed layer is used as a buttering interface or a mechanical type join is used.

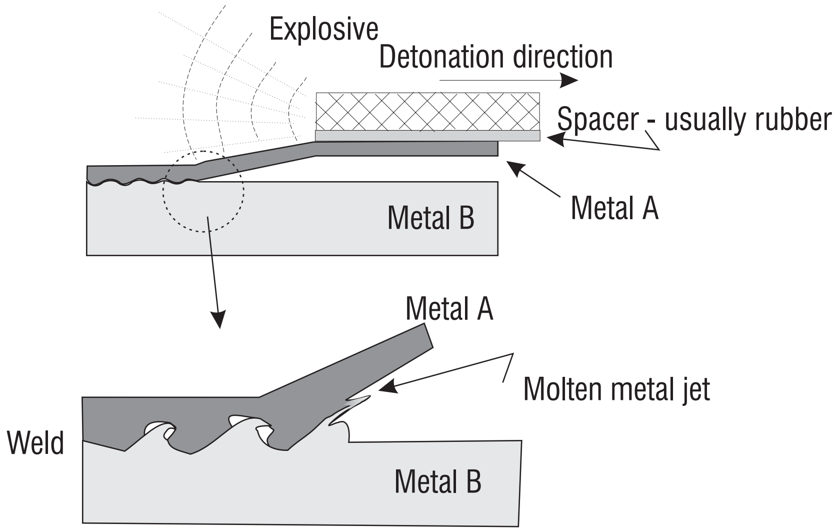

Figure 24 Explosion welding

NOTEBOOK
Explosion welding is a type of forge welding where metal movement is particularly fast.. There is a small amount of molten metal formed during the process but the majority of the bond would be a solid state weld.
The process is used extensively in the production of clad plate although the majority of this product is produced by another type of forge welding - *roll bonding*.

tact but there is some melting in the 'jet' component of the weld.

The weld is initiated from one end of the assembly with the two components being placed at an angle of around 2~4°. The explosive must ensure that the weld is made progressively along the length of the join

This process is used in the production of clad plate. It is also the normal method of titanium or zirconium cladding steel with the titanium ranging from 3 to 25mm[16]

It should be mentioned that explosive forming is only a small part of clad plate production, over 90% is produced by roll bonding the two materials.

9 ROLL BONDING

Roll bonding is the preferred method of producing clad plate.

Clad plate is used extensively for vessels where the interior surface must be corrosion resistant but the cost of the corrosion resistant alloy is very high.

The initial stage in producing a roll bonded joint is to clean both components and, perhaps, nickel plate the corrosion resistant alloy to minimise the possibility of chromium oxidation during rolling

The rolling process is then done usually with a sandwich approach, ie two sets of plate are rolled at once with the corrosion resistant alloy in the middle. This also helps to minimise surface oxidation of the corrosion resistant alloy

In some cases explosion bonded plate is hot rolled after cladding to reduce the thickness of the clad component.

10 ACKNOWLEDGEMENT

This paper has drawn on various publications of the American Welding Society. ASM International, the Nickel Development Institute and technical literature provided by the various alloy manufactures.

---

[16] Smith L M *Engineering with clad steel* Offshore Technology Conference, Houston, 1992. Reprinted as NiDI 10064

MATERIAL	ALSO KNOWN AS	Al	C	Cr	Cu	Fe	Mn	Mo	N	Ni	Nb	P	Pb	S	Si	Sn	Ti	W	Zn	Other
A04430	Al-Si casting alloy	Bal		0.25	0.60	0.80	0.50								4.50-6.00		0.25		0.50	Mg: 0.05; others total 0.35 max.
A96063	6063	Bal		0.10	0.10	0.35	0.60 - 1.10						0.500		0.90-1.80		0.20		0.25	Mg: 0.45-0.90; Others each 0.05 ma x, total 0.15 max
C23000	Red Brass (85%)				84.00-86.00	0.05							0.050						Bal	Cu+sum of named elements 99.8 min
C26000	Cartridge Brass (70-30)				68.00-71.50	0.05							0.070						Bal	Cu+sum of named elements 99.7 min
C51000	Phosphor Bronze 5% A				Bal	0.10						0.03-0.35	0.050			4.20-5.80			0.30	Cu+sum of named elements 99.5 min
C51800	Phosphor Bronze AWS A5.7 ERCuSn-A"	0.01			Bal							0.10-0.35	0.020			4.00-6.00				Cu+sum of named elements 99.5 min
C61400	Aluminium Bronze D	6.0-8.0			Bal (2)	1.50-3.50	1.00					0.015	0.010						0.20	Cu+sum of named elements 99.5 min
C61800	Aluminium Bronze AWS A5.7 ERCuAl-A2	8.5-11.5			Bal (2)	050-1.50						0.020	0.020		0.10				0.02	Cu+sum of named elements 99.5 min
C65600	Silicon Bronze ERCuSi-A"	0.01			Bal (2)	0.50	1.50						0.020		2.80-4.00	1.50			1.50	Cu+sum of named elements 99.5 mi
C70600 (Welding grade)	10% Cupronickel (Welding grade)		0.05		Bal (2)	1.00-1.80	1.00			9.00-11.00 (3)		0.020	0.020	0.020					0.50	Cu+sum of named elements 99.5 min
C71000	80-20 Cupronickel				Bal (2)	1.00	1.00			19.00-23.00			0.050						1.00	Cu+sum of named elements 99.5 min
C71581	Cupronickel AWS A5.7 ERCuNi				Bal (2)	0.40 - 0.70	1.00			29.0-32.0		0.020	0.020	0.010	0.25		0.20-0.50			Cu+sum of named elements 99.5 min

MATERIAL	ALSO KNOWN AS	Al	C	Cr	Cu	Fe	Mn	Mo	N	Ni	Nb	P	Pb	S	Si	Sn	Ti	W	Zn	Other
N02061	AWS A5.14 ERNi-1	1.50	0.15		0.25	1.00	1.00			93.0 min		0.030		0.015	0.75		2.00-3.50			
N02200	Commercially pure nickel		0.15		0.25	0.40	0.35			99.0 min				0.010	0.035					
N04060	AWS 5.14 ERCuNi-7	1.25	0.15		Bal	2.50	4.00			62.00-69.00		0.020		0.015	1.25		1.50-3.00			
N04400	MONEL®400		0.30		Bal	2.50	2.00			63.00-70.00				0.024	0.50					
N06082	AWS 5.14 ERNiCr-3		0.10	18.00-22.00	0.50	3.00	2.50-3.50			67.0 min	2.00 - 3.00 (1)	0.030		0.015	0.50		0.75			
N06455	Hastelloy®C4 AWS 5.14 ERNiMo-7		0.015	14.00-18.00		3.00	1.00	14.00-17.00		Bal		0.040		0.030	0.08		0.70			Co: 2.0
N06600	INCOLOY®600		0.15	14.00-17.00	0.50	6.00-10.00	1.00			72.0 min				0.015	0.50					
N06625	INCONEL®625 - AWS A5.14 ERNiCrMo-3	0.40	0.10	20.00-23.00		5.00	0.50	8.00-10.00		Bal	3.15-4.15	0.015		0.015	0.50		0.40			
N07092	AWS A5.14 ERNiCrFe-6		0.08	14.00-17.00	0.50	8.00	2.00-2.75			67.0 min		0.030		0.015	0.35		2.50-3.50			
N08330	RA330®		0.08	17.00-20.00	1.00	Bal	2.00			34.70-37.00		0.030	0.005	0.030	0.75 -1.50	0.025				
N08800	INCONEL®800	0.15-0.60	0.10	19.00-23.00	0.75	Bal	1.50			30.00-35.0				0.015	1.00		0.15-0.60			
N08825	INCOLOY®825	0.20	0.05	19.50-23.50	1.5-3.5	Bal	1.00	2.50-3.50		38.00-46.00		0.030		0.030	0.50		0.60-1.20			
N10276	C276 AWS A5.14 ERNiCrMo-4		0.02	14.50-16.50		4.00-7.00	1.00	15.00-17.00		Bal		0.030		0.030	0.08			3.00-4.50		Co: 2.5; V: 0.35
N10665	Hastelloy®B2 AWS A5.14 ERNiMo-7		0.02	1.00		2.00	1.00	26.00-30.00		Bal		0.040		0.030	0.10					Co: 1.0

MATERIAL	ALSO KNOWN AS	Al	C	Cr	Cu	Fe	Mn	Mo	N	Ni	Nb	P	Pb	S	Si	Sn	Ti	W	Zn	Other
N99600	AWS 5.8 BNi1	0.05	0.60-0.90	13.00-15.00		4.00-5.00				Bal		0.020		0.020	4.00-5.00		0.05			B: 2.75-3.5; Co: 0.10; Se: 0.005; Zr: 0.05; Others 0.50 max
P07400	AWS 5.8 BAg5				29.00-31.00					1.50-2.50									26.00-30.00	Ag: 39.0-41.0
S30400	304		0.08	18.00-20.00			2.00			8.00-10.50		0.045		0.030	1.00					
S30403	304L		0.03	18.00-20.00			2.00			8.00-12.00		0.045		0.030	1.00					
S30800			0.08	19.00-21.00			2.00			10.00-12.00		0.045		0.030	1.00					
S30900	309		0.20	22.00-24.00			2.00			12.00-15.00		0.045		0.030	1.00					
S30982	AWS 5.9 ER309Mo		0.12	23.00-25.00	0.75		1.0-2.5	2.00-3.00		12.00-14.00				0.030	0.30-0.65					
S30983	309L AWS 5.9 ER309L		0.03	23.00-25.00	0.75		1.00-2.50	0.75		12.00-14.00		0.030		0.030	0.30-0.65					
S31000	310		0.25	24.00-26.0			2.00			19.00-22.00		0.045		0.030	1.50					
S31600	316		0.08	16.00-18.00			2.00	2.0-3.0		10.00-14.00		0.045		0.030	1.00					
S31603	316L		0.08	16.00-18.00			2.00	2.0-3.0		10.00-14.00		0.045		0.030	1.00					
S31803	SAF 2205		0.03	21.00-23.00			2.00	2.50-3.50	0.08-0.20	4.50-6.50		0.020		0.030	1.00					
S32100	321		0.08	17.00-19.00			2.00			9.00-12.00		0.045		0.030	1.00		5x%C min			
S32750	SAF 2507		0.03	24.00-26.00			1.20	3.0-5.0	0.24-0.32	6.00-8.00		0.035		0.020	0.80					
S34700	347		0.08	17.00-19.00			2.00			9.00-13.00	10x%C min	0.045		0.030	1.00					
S41000	410		0.15	11.50-13.50			1.00					0.040		0.030	1.00					
S43000	430		0.12	16.00-18.00			1.00					0.040		0.030	1.00					

MATERIAL	ALSO KNOWN AS	Al	C	Cr	Cu	Fe	Mn	Mo	N	Ni	Nb	P	Pb	S	Si	Sn	Ti	W	Zn	Other
S44400	440		0.03	17.50-19.50			1.00	1.75-2.50	0.025	1.00		0.040	0.030	1.000						Nb+Ti: (0.20+ 4 x (C+N)-0.80
W39209	AWS 5.14 E2209		0.04	21.50-23.50	0.75		0.5-0.20	2.5-3.5	0.08-0.20	8.50-10.50		0.040		0.030	0.90					
W86182	AWS 5.11 ENiCrFe-3		0.10	13.00-17.00	0.50	10.00	5.0-9.5			59.0 min	1.0-2.5 (1)	0.030		0.015	1.0			1.0		
- - - - -	AWS 5.8 RBCu-ZnA				59.25 (nom)											0.25 (nom)			40 (nom)	
	Notes	1	Includes Ta			INCOLOY, INCONEL and MONEL are registered trademarks of the INCO family of companies														
		2	Inccludes Ag			HASTELLOY is a registered trademark of Haynes In														
		3	Includes Co			RA330 is a registered trademark of Rolled Alloys Inc														

INDEX