STAINLESS STEEL
INFORMATION SERIES

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development association

THE WELDING OF STAINLESS STEEL

AN OVERVIEW OF THE BASIC PRINCIPLES

Welding is the most used method of joining stainless steel. It is a special process whereby different pieces of solid metal are joined, at molten metal temperatures, to produce a joint that should have the same (or better) mechanical and corrosion resistant properties as the base material.

It is a key element in the fabrication of many stainless steel products. Moreover, the welding of stainless steel is different, but not necessarily difficult.

Therefore an understanding of the basic principles will assist in greater productivity in fabrication, operational integrity and efficiency and, if required, maintenance.

STAINLESS STEEL

Stainless steel is not a single material, but a family of different types and grades, based on alloying chromium (Cr) with iron (Fe). The details of the various classifications, grades and their properties and corrosion resistance have been covered in previous modules of this series.

THE THREE ZONES IN WELDING

In welding there are three zones of concern, as illustrated in Figure 1.

1. THE UNAFFECTED PARENT (OR BASE) METAL

The material being welded - at a relatively small distance from the weld it is only slightly warmed so that there is no change to its crystal structure, or to its properties.

2. THE HEAT AFFECTED ZONE (HAZ)

The area of the parent metal adjacent to the weld metal is heated through a range of higher temperatures up to the melting point, which occurs at the junction with the weld metal.

The actual temperature attained depends on the distance from the weld, the thermal conductivity of the steel and the amount of heat input.

The high temperatures reached induce changes to the crystal structure of the parent metal, which in turn may affect its mechanical, physical and corrosion resisting properties.

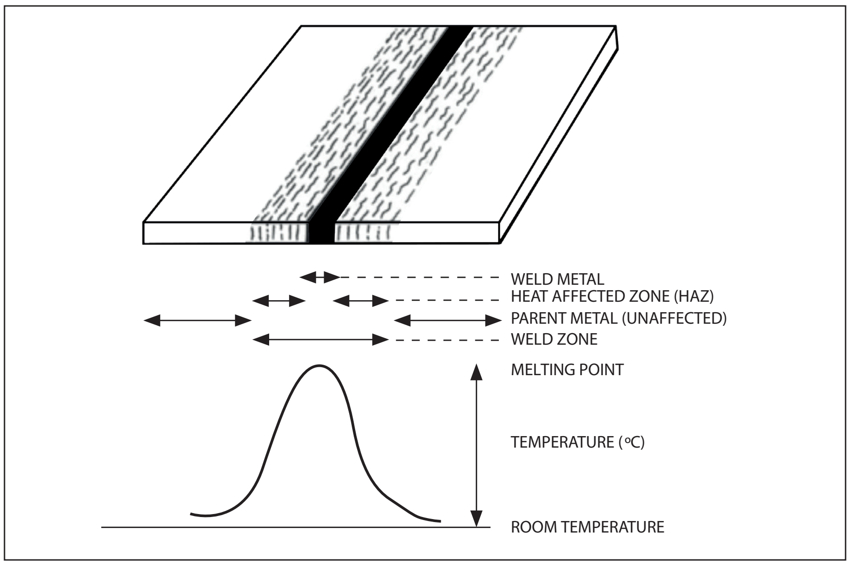

Figure 1 Schematic illustration of the three zones of welding and the related confined area of high temperature.

3. THE SOLIDIFIED WELD METAL

The composition of this can be either that of the parent metal if no filler metal is used (known as autogenous welding) or that resulting from a mixture of filler and parent metal (depending on the extent to which the parent metal has been melted, thereby diluting the filler metal).

Further, the solidified weld metal is a miniature "casting". Its cast grain structure will differ from the parent metal. This difference will be significant if the parent metal is plate or sheet, but also differs, to a lesser extent, if the parent metal is a casting.

WELDABILITY

The utilisation of welding in the fabrication of engineering components depends on the weldability of the steel. Weldability is not a precise or exactly quantifiable property, but rather implies the ability of the material to be joined by standard welding processes, so that the resultant mechanical, physical and chemical properties of the weld zone (i.e. both the weld metal and the HAZ) are at least equivalent to those of the parent metal.

Whereas all stainless steels may be welded, the weldability of the various classifications of stainless steel varies to a large degree, due both to the different chemical compositions and crystal structures as well as to the resultant reactions of these to the thermal cycles of welding.

To a lesser extent the weldability of the different grades within any one classification can also vary.

PHYSICAL PROPERTIES OF STAINLESS STEEL

As outlined in previous modules the physical properties of stainless steel may differ substantially from carbon and low-alloy steels (e.g. mild steels) and also between the various classifications of stainless steel.

The physical properties of major influence are:

- The coefficient of thermal expansion.
- The thermal conductivity.
- The electrical resistivity.
- The melting temperatures.

Typical values of these physical properties for various types of steel are given in Table 1.

COEFFICIENT OF THERMAL EXPANSION

Austenitic stainless steel, in particular, will expand to a greater rate, than mild steel.

Allowance must be made for this expansion and contraction to control distortion and prevent high levels of thermal stress, particularly during cooling, which can cause weld zone cracking or high levels of residual stress.

THERMAL CONDUCTIVITY

Austenitic stainless steels, in particular, will conduct heat more slowly than mild steel.

This promotes sharp temperature gradients, which, together with the high thermal expansion, will cause that distortion to be confined to a small area. The weld zone will remain at high temperatures for a longer time, which is of critical importance in controlling interpass temperatures.

ELECTRICAL RESISTANCE

The higher electrical resistance of stainless steel results in the generation of more heat for the same current.

This, together with the low heat conductivity, is an advantage when resistance welding processes are used.

But, in other welding processes it can, if not controlled, result in too great a heat input.

In manual metal arc (MMA) welding, the incorrect use of too high a welding current will cause overheating of the core wire of the electrode with associated damage to the flux coating.

MELTING TEMPERATURES

The lower melting temperatures of stainless steel compared with mild steel is an advantage, because less heat is required to produce fusion.

This in turn means faster welding for the same heat, or conversely less heat input for the same welding speed.

These factors demonstrate that a change from welding mild steel to stainless steel should not be made in an undisciplined manner.

With an appreciation of these differences, appropriate actions should be taken to avoid or minimise possible detrimental effects such as distortion and excessive heat input.

These can include using smaller and more frequent tack welds, the use of copper back-up bars and chill plates or step welding.

TABLE 1: TYPICAL PHYSICAL PROPERTIES FOR DIFFERENT TYPES OF STEEL

TYPE OF STEEL	Coefficient of Thermal Expansion (µm/m°C)	Thermal Conductivity (W/m°C)	Electrical Resistivity (µΩm)	Melting Point (°C)
PLAIN CHROMIUM FERRITIC & MARTENSITIC STAINLESS STEEL	11,3	24,0	0,060	1 430 to 1 510
AUSTENITIC STAINLESS STEEL	18,3	18,5	0,072	1 400 to 1 450
UTILITY FERRITIC STAINLESS STEEL	12,5	25,0	0,057	1 430 to 1 510
PLAIN CARBON AND LOW-ALLOY STEELS	13,8	65,0	0,016	1 500 to 1520

AUSTENITIC STAINLESS STEELS

These are also known as the 200 or 300 series, as outlined in the previous module.

Their weldability is generally excellent, except for the free machining grades such as 303 or 303Se.

They may be readily welded by any of the standard welding processes such as manual metal arc (MMA), tungsten inert gas (TIG), metal active gas (MAG), submerged arc welding (SAW), resistance welding, friction welding, plasma arc, laser welding and electron beam welding.

Advances in welding technology (particularly those associated with developments in the field of welding consumables) and in steel making technology, have virtually eradicated the two major problems associated with the welding of austenitic stainless steel.

These are:

- Hot cracking within the weld zone.
    - Weld metal cracking.
    - HAZ cracking.
- Loss of corrosion resistance through sensitization.

HOT CRACKING WITHIN THE WELD ZONE

Weld metal cracking

Resistance across the weld and the crystal structure development in the weld metal are the major influencing factors. Fully austenitic weld metals are more prone to cracking.

Two forms of closely related hot cracking occur:

1. **Solidification Cracking** takes place during and just after solidification. It is due to weld metal not being able to accommodate the thermal stresses during cooling. Mechanical failure takes place along the grain boundaries (intergranular cracking). This failure is more often than not the result of poor technique or poor consumable selection. Welding procedures suitable for mild steel are NOT directly applicable to stainless steel.

2. **Micro-fissuring** occurs at temperatures very close to that of final solidification. It is intergranular in nature and is due to low melting point compounds segregating out at the grain boundaries. It is more

difficult to avoid entirely and is not as dependent on welding conditions.

The presence of impurities, notably sulphur (S) and phosphorus (P) and to a slightly lesser extent silicon (Si) and niobium (Nb), has a marked influence on hot cracking. Modern steelmaking processes and impurity control have largely eliminated these problems

Resistance to hot cracking is improved if the weld metal solidifies as two-phase austenite plus a small amount of retained ferrite.

This is due to three factors:

1. **The ferrite dissolves** and retains in solution the impurities that would otherwise separate out.
2. **The ferrite present increases** the grain boundary area available and thereby "dilutes" any grain boundary segregates that may occur.
3. **The ferrite fraction has a lower high temperature strength** and therefore deforms without inducing cracking to accommodate the stresses.

The chemical composition of most filler metals is therefore adjusted to result in a weld metal that contains 6-10% ferrite. This is indicated by the ferrite number (FN) normally given by the suppliers of welding consumables. (At low levels the FN may be taken to be equal to the ferrite percentage).

HAZ cracking

This is also largely related to the impurity level. Ferrite, if present, has a beneficial effect. Fine grain sizes are less susceptible.

Wrought plate and sheet has a negligible ferrite content, but its fine grain size and low impurity levels are beneficial factors.

Cast materials usually have a higher ferrite content that counteracts the normally associated higher impurity levels and coarser grain sizes.

CRACKING IN PERSPECTIVE

An understanding of this has resulted in modifications to the composition of welding consumables and has virtually eliminated weld metal cracking (if a ferrite containing weld metal can be allowed).

Relatively few end-uses require ferrite-free, or very low ferrite content, weld deposits.

The chemical industry sometimes considers the presence of ferrite an adverse factor because it can be prone to localised corrosion (e.g. in urea manufacture).

Cryogenic and continuous high temperature applications are two further such end-uses.

Whereas generally there is a preference for the utilisation of ferrite containing weld metal, it must be stressed that significant amounts of fully austenitic (theoretically crack-prone) weld metal are successfully deposited (e.g. 310, ferrite-free 316).

However, the necessary precautions should be taken in these instances to:

- Minimise stress/restraint.
- Use narrow weld/smaller stringer beads.

The above factors demonstrate the importance of the correct composition of the weld deposit.

Electrodes often have the necessary alloys content contained in the flux, and filler wires are specifically produced to close chemical composition limits.

Therefore the following precautions should be noted:

- **DO NOT** use electrodes if the flux coating is damaged.
- **DO NOT** strip electrodes of the flux coating and use as filler wires.
- **DO NOT** use trimmings off sheet or random pieces of ordinary stainless steel wire as filler wire.

(N.B. These rules apply to the welding of ALL stainless steel and highly alloyed materials).

LOSS OF CORROSION RESISTANCE THROUGH SENSITISATION

Chromium has a high affinity for carbon at elevated temperatures. Heating the parent metal within the temperature of 450° - 850°C, can cause Cr and C to combine as a complex chromium carbide, Cr23C6. The HAZ is unavoidably subjected to this temperature range during welding.

These carbides form preferentially on the grain boundaries, causing these areas to be depleted in Cr.

The steel has therefor become **SENSITISED** and is prone to localised corrosion occurring close to the weld deposit and along an intergranular path, due to the lower corrosion resistance of these Cr depleted grain boundary areas. Note that this localised corrosion may only occur in specific conditions.

This corrosion is termed **WELD DECAY** and is typified by a rough granular appearance of the corroded surface (like grains of sugar, as illustrated in Figure 3).

Two methods are used to prevent weld decay:

1. **Stabilising alloying elements,** such as titanium (Ti) and niobium (Nb), are added to the steel. These have a higher affinity for C than Cr does. Provided they are present in sufficient quantities, they preferentially combine with and lock up the carbon to form stable Ti or Nb carbides. Therefore, Cr carbides cannot form and the steel retains its corrosion resistance.

The typical stabilised grades of austenitic stainless steel are 321, 316 Ti (containing Ti) and 347 (containing Nb). In the welding of these stabilised grades, it is generally recommended that a stabilised welding consumable be used. As Ti tends to be lost in the arc, Nb is used for stabilised consumables.

2. **The carbon content is reduced to very low levels.** The carbon content of the steels is held to the very low level of 0,03% max C.

In addition to temperature, sensitisation is also dependent on carbon content and the time within the sensitisation temperature range.

Referring to Figure 4, note that a 0,08% C steel can start to sensitise in under a minute, whereas a 0,03% C steel takes well over an hour.

The typical low carbon grades ("L" grades) are 304L, 316L and 317L.

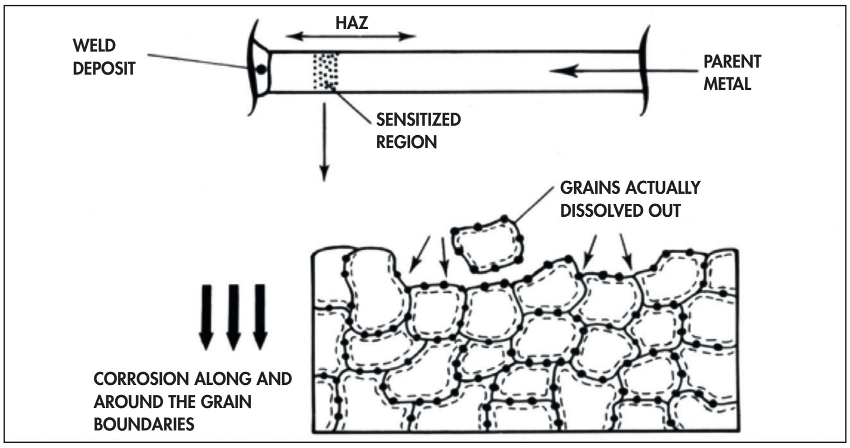

Figure 3 Schematic illustration of sensitisation within the HAZ; with associated chrome carbide and chromium depletion at the grain boundaries

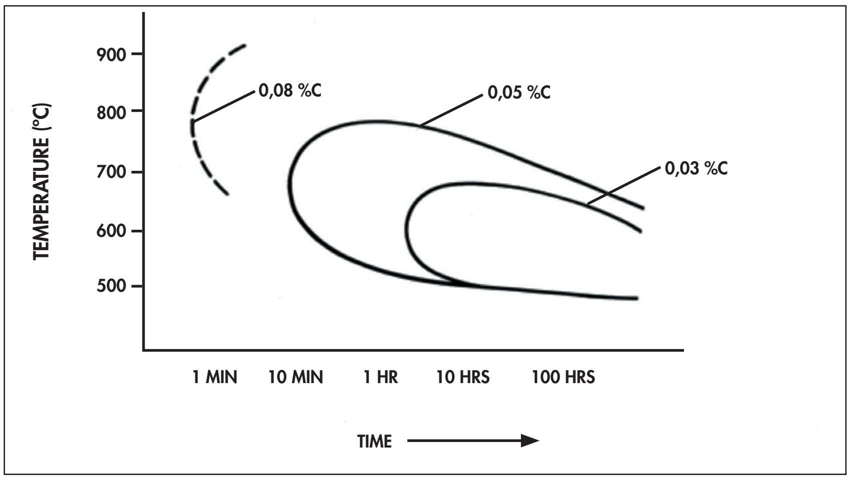

Figure 4 Schematic illustration of the major effect of carbon content on the time taken for sensitisation of a typical austenitic stainless steel

In the welding of these grades either "L" grade, or Nb stabilised welding consumables must be used.

Due to either of the above methods, coupled with modern welding equipment that allows faster, lower heat input procedures, the classical form of weld decay through sensitisation, as explained above, **SHOULD NOT OCCUR**. Note that even in normal carbon grades of austenitic stainless steels, the carbon content is now controlled to lower levels than in the past, thus minimising the incidence of this problem.

However, responsibility rests with the welder to ensure that contamination of the weld from sources of carbon such as dust off the workshop floor, paint, grease and oil do not occur.

The presence of such carbon contamination is often overlooked, as the source is not always readily apparent (e.g. a mist of oil contained in the exhaust of air motor machines, handling electrodes with oily or greasy gloves).

FERRITIC STAINLESS STEEL

There are three sub-classifications of ferritic stainless steel to be considered.

- Standard ferritic stainless steel.
- Super ferritic stainless steel.
- Utility ferritic grades.

STANDARD FERRITIC STAINLESS STEEL

Standard ferritic stainless steel contained within the AISI 400 series have been detailed previously.

In general the weldability of these steels is poor and they suffer from inferior properties in the "as-welded" condition.

This is due to

- Grain boundary breakdown at high temperatures (over 1 100°C) forming larger, coarser grains.
- Formation of Cr carbide and Cr nitride precipitates and relatively high carbon martensite.

Typically these steels are brittle after welding and prone to corrosion within the HAZ.

These deleterious properties generally render these steels unsuitable for engineering end-uses involving welded heavier gauge material.

Their normal applications as welded components are therefore limited to those utilising only thin gauge sheet material.

Such thin material is usually welded using an autogenous welding process (TIG or resistance welding), although MAG welding is also used in high production processes.

If a filler metal is used, or if thicker gauges are welded, the austenitic filler metals, grades 308L and 309L, must be used.

It is also necessary to minimise heat input and interpass temperatures.

SUPER FERRITIC STAINLESS STEEL

Several of the super-ferritic stainless steels available are proprietary grades but many are now included in international standards. Noticeable features of their chemical composition are:

- Increased Cr and additions of Mo to improve corrosion resistance.
- Very low C and N content.
- Stabilisation by additions of Ti, or Ti + Nb.

The weldability of these steels is better than that of standard ferritic steels.

Their corrosion resistance remains unimpaired and there is a far lower tendency for brittleness to develop.

These improvements are chiefly related to the very low levels of C and N, plus the usual addition of stabilising elements.

However, grain growth of the ferrite crystal structure can still detract from the properties in the "as-welded" condition.

Some manufacturers limit "good weldability" to a maximum thickness of 2,5mm but, in general, the weldability may be classed as "moderate" up to thicknesses of 5-6mm.

They are best welded by resistance welding or autogenous TIG welding processes.

For welding thicker gauges use TIG or MAG and high nickel-based consumables.

Matching filler metals tend to produce a coarse grained structure in the weld metal and are not recommended.

The inert gas welding processes are susceptible to CO_2, N, or H^2 impurities. Pure Argon is recommended for TIG and Argon +1 -2% O^2 for MIG. MMA welding is not recommended.

Cleanliness is essential, particularly with respect to possible contamination by C. Heat input and interpass temperatures should be restricted to minimise grain growth.

UTILITY FERRITIC STAINLESS STEEL

These steels were developed to overcome the problems limiting the weldability of plain Cr ferritic stainless steels for engineering applications, but with sufficient Cr content to impart useful corrosion resistance.

If welded in accordance with recommended procedures the weldability is good in thicknesses up to 25mm to 30mm.

In the HAZ, the adverse effects of the thermal cycle of welding are minimised due to:

- Very low C and N content (which may be additionally stabilised by the addition of Ti).
- The mixed crystal structure of the steel at high temperatures.

The formation of chromium carbides and nitrides are reduced to a minimum, thereby overcoming both their embrittling effect and their

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lowering of the corrosion resistance.

These steels develop a two-phase (i.e. mixed) crystal structure on heating to high temperatures.

The presence of this mixed crystal structure strongly inhibits grain growth; any martensite formed is very low in carbon and is therefore tough.

On cooling, the crystal structure retains the mixed and small grained structure of the parent material. Some increase of hardness and strength occurs.

The net result is that corrosion resistance is maintained and the properties are adequate for all applications, except severe engineering such as pressure vessels and highly stressed cyclic loading.

Thin gauge steels can be resistance welded.

However, as most applications involve the use of thicker sheet and plate, MMA and MIG processes are most often used, TIG to a lesser extent. SAW is not recommended as the heat input is too high.

In the welding procedures it is of paramount importance to:

- Ensure cleanliness, especially prevent any carbon contamination.
- Minimise N pick-up by ensuring good arc shielding, especially in MIG and TIG processes.
- Ensure close control of heat input and minimise interpass temperatures. In this respect positional welding should be avoided if possible.
- If unavoidable, use multipass narrow stringer bead welds (smaller gauge electrodes with lower current) to minimise heat input.

For MMA and MAG welding, austenitic consumables are recommended.

The austenitic welding consumable gives an austenite/ferrite weld deposit, depending on the FN of the consumable and the degree of dilution.

Fabricator experience indicates a preference for grade 309L. It is of sufficiently high alloy content to cater for dilution by the parent metal, but not so highly alloyed to result in a fully austenitic weld metal that could be prone to hot cracking.

If utility ferritic steel is being welded to austenitic stainless steel, or to plain carbon (mild) or low alloy steel, an austenitic grade consumable MUST be used. The shielding gases used for MAG welding are either 98/argon 2% CO_2 mixtures.

Pure CO_2 should NOT be used. If TIG welding is being carried out HIGH purity argon should be used.

MARTENSITIC STAINLESS STEEL

Martensitic stainless steels are typified by those contained within the AISI 400 series. Details of grades and chemical content have been covered in previous modules. These steels have been specifically formulated to render them amenable to heat treatment by quenching and tempering to produce high strength and harness levels.

The thermal cycle of heating and rapid cooling that occurs in the welding process HAZ is equivalent to a quenching cycle. A high carbon martensite crystal structure is produced, which is highly stressed and extremely brittle. Therefore there is a strong tendency for cracking in the HAZ.

Martensitic stainless steel therefore possesses very poor weldability.

In general the applications that utilise martensitic stainless steel seldom involve the necessity for welding. However, if they have to be welded, the following courses of action may be adopted to limit failure by cracking;

- Preheat to between 200ºC and 300ºC. This prevents rapid cooling of the HAZ by surrounding parent metal. Interpass temperature should be at the same level.
- Weld the steels in the annealed condition and subsequently give the necessary heat treatment to produce the required properties.
- Use an austenitic (e.g. 308, 309) consumable to improve ductility in the weld metal, but note that the mechanical properties in the weld metal will not match those of the parent metal. Matching consumables are available and if used, require extremely closely controlled conditions to prevent segregation and cracking of the weld metal.

DUPLEX STAINLESS STEEL

Many of the duplex stainless steels available are proprietary grades developed and produced by different steel makers, but several are now included in international standards.

Details of their constitution and properties have been covered in previous modules.

These steels consist of a two-phase crystal structure of ferrite and austenite, The ferrite:austenite ratio is now generally controlled to about 50:50.

A wide range of new duplex grades containing manganese as a partial replacement for nickel are now known as “lean duplex grades” and the addition of nitrogen to increase both the stability of the austenite and improvements in mechanical properties is now common across all the duplex grades.

Control of the nitrogen content in the weld metal is now considered crucial and a variety of nitrogen containing shielding gases are now available to assist.

As a result of continuous modification and development by the manufacturers the weldability of the duplex steels is now considered to be good, with engineering quality welds being achievable up to 50mm.

The weldability of these grades is determined by:

- The austenite changing to ferrite at high temperatures and subsequently reverting to austenite on cooling.
- The effect of the high temperatures on both the ferrite formed from the austenite and the ferrite fraction existing in the steel.

In welding the aim is to obtain conditions that maximise the reformation of austenite on cooling. The 50:50 ferrite:austenite crystal structure should be maintained after welding. Nitrogen (N) is an alloying element often used to attain this higher austenite content.

Duplex stainless steel has better heat conductivity than austenitic stainless steel. Faster cooling rates of the HAZ therefore occur. However, fast cooling retards the required re-formation of austenite. The mechanical properties (particularly toughness) are critically dependant on achieving a sufficiently high austenite content. Therefore, in comparison to the welding of other stainless steel, higher heat input and interpass temperatures are used when welding duplex stainless steels.

On the other hand, excessive heat inputs and slow cooling rates can promote an increase in the grain size of the ferrite and the formation of carbides that cause brittleness and loss of corrosion resistance.

A closely controlled balance between these two conditions has to be

attained in the welding procedure. It is therefore recommended that the welding conditions for each grade and thickness of material be determined and the optimum be formulated in a qualified welding procedure, which thereafter should be closely controlled and monitored.

Because of the relatively lower coefficient of thermal expansion of duplex stainless steel, the stresses imposed in the weld zone are less than those experienced with austenitic stainless steel.

The welding processes that may be used include MMA, MIG/MAG, TIG and SAW.

Welding consumables for duplex stainless steel are essentially matching alloys, albeit often slightly modified in terms of chemical composition to ensure an optimum crystal structure of the weld metal. Ordinary austenitic stainless steel consumables are NOT suitable.

Shielding gases used for MIG/MAG and TIG processes are 98% HP Argon 2% N2, heat input and interpass temperatures must be carefully controlled during the welding process.

PRECIPITATION HARDENING STAINLESS STEEL

There are three sub-classifications of precipitation hardening stainless steel:

- Martensitic.
- Semi-austenitic.
- Austenitic.

These are complex alloys and the welding and weldability of these is an extremely complicated subject.

These stainless steels can be successfully welded. However, the welding procedures are, in general, extremely complex and should not be entered into lightly without obtaining full details from the manufacturer of the specific alloy, training of the welders to be employed and using fully qualified welding procedures.

PICKLING AND PASSIVATION

After welding of any of the types of stainless steel covered above, the heat affected zone will show some degree of oxide discolouration due to exposure to elevated temperatures. This oxide is not the same as the passive layer and will actually impair the corrosion resistance of the underlying stainless steel. It MUST therefore be removed before the fabrication enters service.

This can be done either by mechanical means (grinding, bead/grit blasting or polishing the affected area) or by pickling with suitable acid solutions or pastes, or a combination of both. The acid mixture generally used for pickling of stainless steel is a combination of nitric and hydrofluoric acids, normally applied hot. Details of the concentration, time and temperature will vary depending on the grade of stainless steel used and the degree of oxide present and assistance from a welding supplier, stainless steel cleaning company or **sassda** technical staff should be sought.

It is generally good practice to wash down the completed fabrication with a dilute solution of nitric acid in a mild detergent, followed by thorough rinsing in clean water. This will remove any dirt and grease, any mild steel contamination and will restore the passivity of the stainless steel to it's optimum level.

CONCLUSION

As stated earlier, the welding of stainless steel is not difficult, only different. All people involved in its welding should have an appreciation and understanding of the basic principles, which are different from those applicable to the welding of plain carbon and low alloy steels. There are some newer hybrid welding processes such as pulsed MIG/MAG, synergic MIG/MAG CMT (cold metal transfer) and STT, which produce very high quality welds with complete control of the heat affected zone and distortion on thinner materials.

Stainless steel, by its very nature, is often employed in aggressive situations as critical components, where the consequence of failure can be significant.

Therefore, those who utilise welding in the fabrication and maintenance of stainless steel equipment should note:

- The people involved must have the required knowledge, experience and ability.
- Simple basic precautions must be observed.