CIGWELD

WELDING OF STAINLESS STEEL

Introduction.

This section is designed to provide the reader with a technical overview for welding the major types of stainless steels available today.

Types of Stainless Steels:

Stainless steels are an important grade of structural material used worldwide for a multitude of applications based on their corrosion resistance, heat resistance, aesthetic appeal, low temperature properties, high strength and/or ease of cleaning and sterilising.

The main types of weldable stainless steels available include:

- Austenitic stainless steels (AISI 200 and 300 series / UNS S20000 and S30000 series) which are easy to weld and by far the most popular type - accounting for over 70% of the stainless steel sold around the world.
- Ferritic stainless steels (AISI 400 series / UNS S40000 series) which are weldable particularly in thin sections and commonly used for elevated temperature applications.
- Martensitic stainless steels (AISI 400 series / UNS S40000 series) which are difficult to weld and commonly used for wear resistant applications.
- Duplex stainless steels (UNS S30000 series) which are weldable with precautions and used for corrosion resistant applications as an alternative to 300 series austenitic stainless steels.

WELDING TECHNIQUE

The technique of welding stainless steels does not differ greatly from that of the welding of mild steel, but as the material being handled is very expensive, and exacting conditions of service are usually involved, extra precautions and attention to detail at all stages of fabrication is desirable. In principle, all stainless steel for high-class work should be welded with a short arc.
Any techniques which aim at increasing the penetration, speed of travel or the use of wide weaving techniques are to be discouraged. Usually the lowest convenient current should be used. Weaving should be not wider than twice the diameter of the electrode for base material and electrodes of like composition, and even less for plate of dissimilar composition.

The edges of the preparation should be free from scale. Clamps and jigs are advisable when welding sheets thinner than 3 mm (1/8 in) while cooling blocks are helpful with sheets 1.6mm to 2.5 mm (1/16 in to 3/32 in) thick. Tack welds, particularly on thin sheets, should be placed much closer together than is the usual practice for mild steel. This procedure is necessary as the thermal conductivity of these alloy steels is less and the coefficient of expansion is considerably greater than that of mild steel.

NOTES ON TECHNIQUE:

1. Ensure that the surface of the material in the weld area is clean and free from foreign matter.
2. Use the edge preparation shown in Table 1 over the page.
3. Tack at regular intervals, at about half the pitch used for mild steel.
4. Maintain a short arc during welding, to avoid loss of alloying materials during transfer across the arc.

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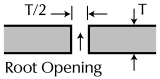
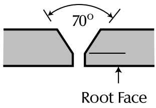
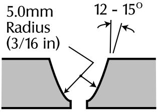
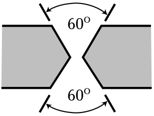
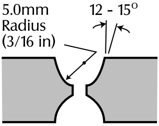
NOTES ON TECHNIQUE cont.:

5. Use stringer passes rather than wide weaves.
6. To minimise distortion, employ back step or block sequences when welding.
7. Thoroughly remove slag from welds between passes.
8. When welding double V or U joints, balance the welding on each side, to minimise distortion.
9. Never use emery wheels or buffs for grinding or polishing stainless if they have previously been used for mild steel.
10. Do not use excessive welding current. Because of the high electrical resistance and low thermal conductivity, the currents used with stainless steel electrodes are somewhat lower than those used for mild steel.

TABLE 1. EDGE PREPARATION FOR MANUAL METAL ARC WELDING:

Thickness (mm)	Edge Preparation	Notes
Up to 1.5 (1/16″)		Square butt joint - not gap.
1.5 - 5.0 (1/16″ - 3/16″)		Square butt joint - gap equal to half thickness.
5.0 - 13.0 (3/16″ - 1/2″)		Single V preparation - 1.5 mm (1/16 ″) landing, 1.5 mm (1/16 ″) gap.
13.0 - 20.0 (1/2″ - 3/4″)		Single U preparation - 3 mm (1/8″) landing, 3 mm (1/8″) gap.
Over 20 (3/4″)		Double V preparation - 1.5mm (1/16″) max. landing, 1.5 mm (1/16″) gap.
		Double U preparation - 3 mm (1/8″) landing, 1.5 mm (1/16″) to 3mm (1/8″) gap.

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Austenitic Stainless Steels

Austenitic stainless steels are easily welded with all standard arc welding processes, without preheat and using matching or near matching welding consumables. Because of their high thermal expansion and low thermal conductivity compared to carbon steel they will distort more during and after welding. This can be minimised by more frequent tacking prior to welding, balanced and back step welding methods and the use of lower welding current and heat input parameters. Low carbon austenitic stainless steels are commonly used because they are less susceptible to sensitisation (or carbide precipitation) during welding or high temperature service which can result in intergranular corrosion in a caustic environment. Matching low carbon welding consumables (designated with an "L") are also commonly used to de-sensitise the weld deposit, in the same way as the parent metal, and eliminate the risk of intergranular corrosion of the welded joint.

The common welding consumable types used for welding the many austenitic stainless steel grades are shown in the following table.

Austenitic Stainless Steel Grades - Welding Consumable Selection Guide.

Stainless Steel Grade			Welding consumable type		
AISI No:	UNS No:	Werkstoffe No:	1st Choice	2nd Choice	3rd Choice
201	S20100	---	308 / 308L	316L	347
202	S20200	1.4371	308 / 308L	316L	347
205	S20500	---	308 / 308L	316L	347
209	S20910	1.4565	308 / 308L	316L	347
301	S30100	1.4310	308 / 308L	316L	347
302	S30200	---	308 / 308L	316L	347
303	S30300	1.4305	312 (Weldall)	309L / 309Mo	308 / 308L
303Se	S30323		312 (Weldall)	309L / 309Mo	308 / 308L
304	S30400	1.4301	308 / 308L	316L	347
304L	S30403	1.4306	308 / 308L	316L	347
304H	S30409	1.4948	308H	308L	316L
304N	S30451	---	308L / 308	316L	347
304LN	S30453	1.4311	308L / 308	316L	347
305	S30500	1.4303	308 / 308L	316L	347
308	S30800	---	308 / 308L	316L	347
309	S30900	1.4828	309 / 309L / 309Mo	312 (Weldall)	---
309S	S30908	1.4833	309L / 309Mo	312 (Weldall)	---
310	S31000	1.4841	310	312 (Weldall)	---
310S	S31008	1.4845	310	312 (Weldall)	---
314	S31400	---	316 / 316L	318	309L / 309Mo
316	S31600	1.4401	316 / 316L	318	309L / 309Mo
316L	S31603	1.4404	316L / 316	318L	309L / 309Mo
316H	S31609	1.4919	316H	316L / 318	309L / 309Mo
316N	S31651	---	316L / 316	318	309L / 309Mo
316LN	S31653	1.4406	316L / 316	318	309L / 309Mo
317	S31700	1.4429	317 / 317L	318	316L
317L	S31703	1.4438	317L	318	316L
321	S32100	1.4541	347	318	308 / 308L
321H	S32109	1.4941	347	318	308 / 308L
347	S34700	1.4550	347	318	308 / 308L
347H	S34709	---	347	318	308 / 308L
348	S34800	---	347	318	308 / 308L
384	S38400	---	309L / 309Mo	312 (Weldall)	---

Ferritic Stainless Steels:

Ferritic stainless steels can be welded under strict precautions using all standard arc welding processes. They can be joined with welding consumables which match or near match the base metal or with austenitic welding consumables, for example Satincrome 308L-17 & 316L-17 electrodes or Autocraft 308LSi & 316LSi GMAW wires. During welding, ferritic stainless steel grades can suffer a loss of ductility due to grain growth, martensite formation and carbide precipitation. To achieve good welds, in thicker sections, it is often necessary to preheat the work to ≈100-120°C and minimise the heat input during welding. To dissolve or modify carbides in the Heat Affected Zone (HAZ) and reduce welding stresses, post-weld heat treatment to 750-850°C for 30-60 minutes is necessary. This heat treatment will improve the ductility, toughness and corrosion resistance of the Heat Affected Zone.

Ferritic Stainless Steel Grades - Welding Consumable Selection Guide.

Stainless Steel Grade			Welding consumable type		
AISI No:	UNS No:	Werkstoffe No:	1st Choice	2nd Choice	3rd Choice
405	S40500	1.4002	430	309L / 309Mo	308
409	S40900	1.4512	309L / 309Mo	312 (Weldall)	---
429	S42900	1.4001	430	308 / 308L	309L / 309Mo
430	S43000	1.4016	430	308 / 308L	309L / 309Mo
430F	S43020	1.4104	430	308 / 308L	309L / 309Mo
430FSe	S43023	---	430	308 / 308L	309L / 309Mo
434	S43400	1.4113	430	308 / 308L	309L / 309Mo
436	S43500	---	430	308 / 308L	309L / 309Mo
442	S44200	---	316L	318	309L / 309Mo
444	S44400	1.4521	316L	318	309L / 309Mo
446	S44600	1.4762	308 / 308L	309L / 309Mo	310
3Cr12#	---	---	309L / 309Mo	316L	308L

- 3Cr12 is a trademark of B.H.P. Ltd.

Martensitic Stainless Steels:

Martensitic stainless steels are difficult to weld successfully due to the formation of hard and brittle martensite in the Heat Affected Zone (HAZ) of the joint. To reduce the affects of martensite formation, adequate control over pre-heat, interpass temperatures and heat input are essential. Depending on the carbon content of the particular martensitic steel, preheat temperatures of between 100 - 300°C are commonly recommended to avoid cracking. Interpass temperature also plays an important role in reducing the risk of cracking. In multipass welding, an interpass temperature between the martensite start and finish temperatures (Ms and Mf) will minimise crack sensitivity by allowing each subsequent weld pass to be tempered. Post Weld-Heat Treatment (PWHT) is also carried out to improve mechanical properties and reduce welding stresses. For complicated joint configurations PWHT is commenced once the fully welded joint has cooled to just under the martensite start temperature (≈130 -150°C). This is done to ensure the complete transformation of austenite to martensite before PWHT.

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Martensitic Stainless Steel Grades - Welding Consumable Selection Guide.

Stainless Steel Grade			Welding consumable type		
AISI No:	UNS No:	Werkstoffe No:	1st Choice	2nd Choice	3rd Choice
403	S40300	1.4000	410	309L / 309Mo	310
410	S41000	1.4006	410	309L / 309Mo	310
414	S41400	---	410	309L / 309Mo	310
415	S41500	1.4313	410	309L / 309Mo	310
416	S41600	---	410	309L / 309Mo	310
416Se	S41623	---	410	309L / 309Mo	310
420	S42000	---	410	309L / 309Mo	310
431	S43100	1.4057	430	308L / 308	309
440A	S44002	---	312 (Weldall)	309L / 309Mo	---
440B	S44003	---	312 (Weldall)	309L / 309Mo	---
440C	S44004	---	312 (Weldall)	309L / 309Mo	---

Duplex Stainless Steels:

Duplex stainless steels consist of two microstructure phases, ferrite and austenite and are also referred to as Ferritic-Austenitic stainless steels. A typical duplex microstructure consists of approximately 50% ferrite and 50% austenite.

Duplex stainless steels are readily welded with precautions using all common arc welding processes. Careful attention must be given to heat input and consumable selection to prevent the formation of excessive ferrite levels in both the base metal and weld metal , which can reduce joint toughness and corrosion resistance.

The main grades of duplex stainless steels used in industry today are listed below. These alloys can be classified into two (2) main groups:

Duplex Stainless Steels = S32900 (329), S39205 (2205) and S39230 (2304)

Super Duplex Stainless Steels = S39553, S39275 (2507) and S39276 (Zeron 100).

Welding Consumables for duplex stainless steels contain Nitrogen (a strong austenite stabiliser) as an alloying element, which helps to achieve the correct balance of austenite and ferrite in the weld deposit microstructure. In addition to welding consumable selection, careful attention must also be given to heat input and interpass temperature to promote the desired balance of ferrite and austenite in the weld and surrounding heat affected zone (HAZ) of the base material.

If the base metal and weld metal ferrite levels are controlled to 25-50% (FN 30-70) then a good combination of strength, toughness and corrosion resistance will be achieved in the welded joint.

Heat Input:

When the weld pool solidifies, the weld metal consists of 100% ferrite which begins to transform to austenite upon cooling. If the correct heat input is used the resultant cooling rate will promote the formation of an even distribution of the ferrite and austenite (≈50:50) in the weld deposit and Heat Affected Zone (HAZ).

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Duplex Stainless Steels cont.:

Generally heat input should be limited to between 0.6 - 2.6 kJ/mm. When a welding process with less than 0.6kJ/mm heat input is used (as in automatic GMAW), preheating up to 150°C maximum may be required to reduce the cooling rate and increase austenite in the weld and the HAZ.

$$\text{Heat Input (kJ/mm)} = \frac{\text{Volts x Amps x 60}}{\text{Travel Speed (mm/min) x 1000}}$$

Interpass Temperature Control:

Interpass temperature should be limited to between 75-150°C.

Preheat:

On thicknesses below 6mm no preheat is required. For heavier sections or for welds under high restraint preheat may be used to minimise the risk of weld cracking. When a welding process with less than 0.6kJ/mm heat input is used, preheating to between 50-200°C is helpful in reducing the cooling rate and increasing austenite in the weld and the HAZ. If the air temperature is below 15°C preheat of ≈ 50°C should be used.

Correct Welding Consumables and Shielding Gas:

Always use the correct welding electrode, wire or rod (refer to the welding consumable selection guide shown below). For GTAW (TIG) welding do not weld without a filler rod unless using the correct nitrogen content shielding gas. Always use an inert (nitrogen containing) backing gas when completing root runs. Consult your local gas supplier for detailed information.

Duplex Stainless Steel Grades - Welding Consumable Selection Guide.

Duplex stainless steel grade				Welding Consumable Type
Name or No:	UNS No:	Werkstoffe No:	ASTM Specification No:	
329	S32900	1.4460	A240, A789, A790	329
2RE60	S31500	1.4841	A789, A790, A815	2209
2205 Bohler A903	S31803* **S39205**	1.4462	A182, A240, A276, A789, A790, A815	2209
2304	S32304* **S39230**	1.4362	A789, A790	2209
Ferralium# 255	S32550* **S39553**	1.4507	A240, A789, A790	2507
2507	S32750* **S39275**	1.4410	A789, A790	2507
Zeron# 100	S32760* **S39276**	1.4501	A182, A276, A790, A815	2507

** - old UNS number, replaced by the number beneath in bold.*
 # - Ferralium is a trademark of Langley Alloys Ltd. Zeron is a trademark of Weir Material Services Ltd.

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Duplex Stainless Steels cont.:

ASTM Specification No:	Description of Product Types:
A182	Fittings, Valves, Flanges and other items for high temperature service
A240	Plate, strip and sheet for pressure vessels and pressure equipment
A276	Bars and extruded shapes
A789	Tubing, welded and seamless for general work
A790	Pipe, welded and seamless
A815	Pipe fittings, welded and seamless

Schaeffler and De Long Diagrams:

The alloying elements used in stainless steel base metals and welding consumables have a significant influence on the resultant microstructure. Anton Schaeffler was the first person to carry out a detailed study of the relationship between the composition and microstructure of stainless steel weld metals. The results of this research are summarised in the Schaeffler diagram shown in Diagram 1 which predicts the microstructure of freely cooled All Weld Metal (AWM) stainless steel deposit s as a function of Chromium and Nickel Equivalents.

Chromium and Nickel Equivalents for the Schaeffler diagram are calculated as follows:

- Chromium Equivalent = %Cr + %Mo + 1.5 x %Si + 0.5 x %Nb

- Nickel Equivalent = %Ni + 30 x %C + 0.5 x %Mn

Once the Chromium and Nickel equivalent have been calculated the Schaeffler diagram can be used to estimate the microstructural phases present. It should be noted that the Schaeffler diagram is not applicable to the Heat affected Zone (HAZ) of the welded joint nor is it usable for weld deposits which have been heat treated after welding.

The De Long Diagram shown in Diagram 2 is a later development of the central part of the Schaeffler diagram. The De Long diagram works in a similar way to the Schaeffler diagram, however it incorporates nitrogen in the calculation of the Nickel Equivalent which is particularly important for the gas shielded welding processes such as Gas Metal Arc and Gas Tungsten Arc Welding where gas shielding can significantly influence nitrogen pickup in the weld deposit. The De Long diagram also classifies ferrite content as a Ferrite Number (FN) rather than as a percentage.

Once the Chromium and Nickel Equivalents are calculated they can be plotted on the Schaeffler or De Long diagrams to determine the microstructural phases present in the weld deposit. The crack free, austenite - ferrite microstructure of CIGWELD Satincrome 309Mo-17 manual arc electrode is shown as Point D in Diagram 1, calculated from typical AWM chemical analysis. In predicting the microstructural phases present in the weld deposit the Schaeffler diagram is also a guide to potential joint problems such as hot cracking, sigma phase embrittlement, martensitic cracking and brittle grain coarsening. See the shaded regions on the Schaeffler diagram for details.

The Schaeffler diagram is commonly used to predict weld deposit microstructures for the joining of dissimilar metals, given the chemical analyses of both base metals and the welding consumable AWM deposit. For example, the resultant weld deposit microstructure from joining mild steel to 316 austenitic stainless steel using Satincrome 309Mo-17 is shown in Diagram 1.

By explanation:

Point A on the Schaeffler diagram = microstructure of mild steel base metal.

Point B on the Schaeffler diagram = microstructure of 316 stainless steel base metal.

Point C on the Schaeffler diagram = weld deposit microstructure for joining mild steel to 316 stainless steel <u>without</u> a filler metal.

Point D on Schaeffler diagram = microstructure of AWM deposit with Satincrome 309Mo-17.

Point E on Schaeffler diagram = microstructure of weld deposit assuming 30% dilution using the manual metal arc welding process.

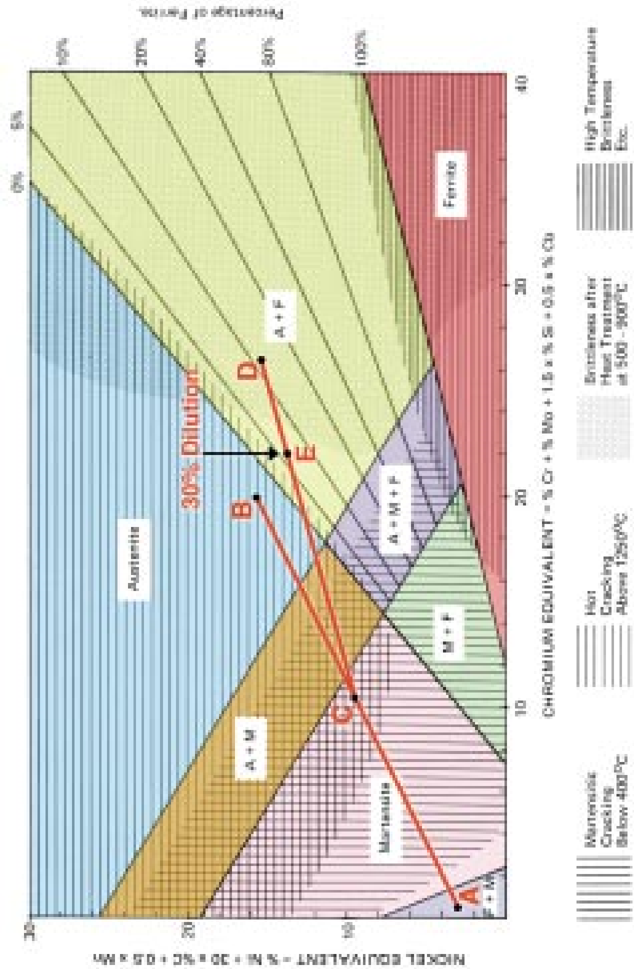

Diagram 1. Schaeffler Diagram. Showing approximate regions of potential weld problems depending on composition and phase balance.

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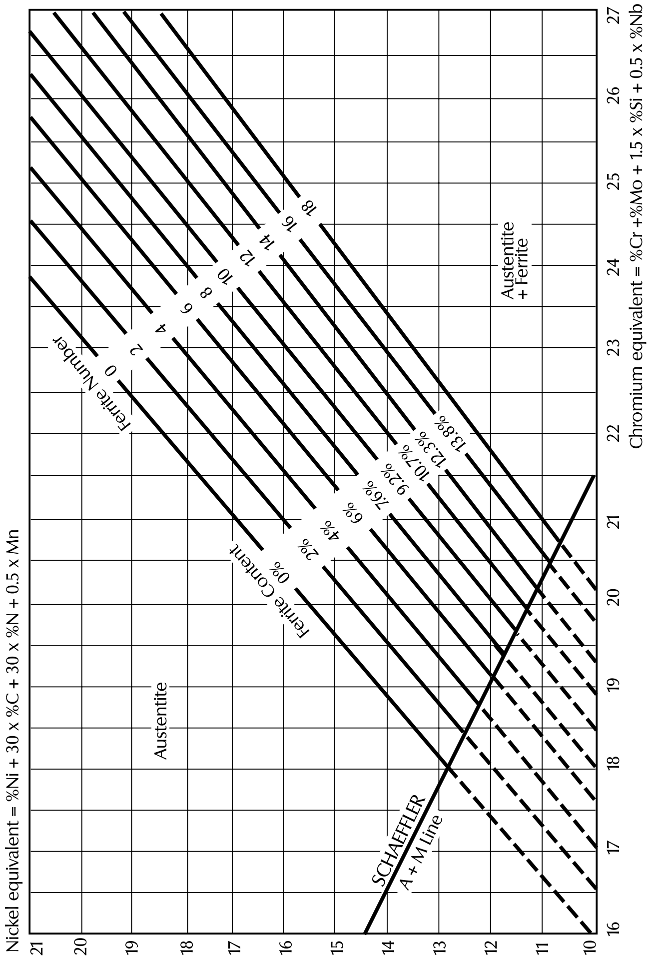

Diagram 2. **De Long Diagram.**

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Definition of Dilution:

Dilution is the degree to which the base metal(s) contributes to the resultant weld deposit. It is normally expressed as the percentage of melted parent metal in the total weld metal.

i.e. 30% dilution = 30 parts of base material per 100 parts of weld deposit.

The dilution for any given process will always be the same irrespective of the parent metals involved but may be influenced by preheating. It is often assumed that the parent metals each contribute equal parts in the resultant weld.

i.e. 30% dilution = 15% contribution from **parent metal 1**, + 15% contribution from **parent metal 2**, see Figure 1 below.

Dilution can be approximately calculated using a geometric approach involving the cross-section of the weld.

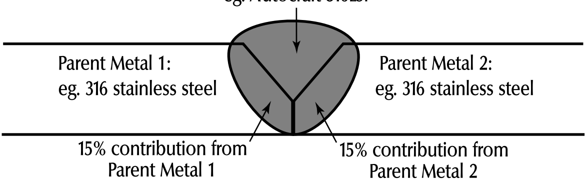

Figure 1. Example of 30% dilution in a stainless steel butt weld using the GMAW process with Autocraft 316LSi welding wire.

Calculating Dilution:

Dilution can be calculated using the following formula. For the purpose of this example Nickel content will be used since the transfer of nickel from the filler metal to the weld metal is virtually 100%.

$$x = \frac{F - W}{F - P} \times 100$$

x = Percentage Dilution (%)
F = Percentage nickel in the filler metal
W = Percentage nickel in the weld metal
P = Percentage nickel in the parent metal

Therefore, if for example F = 13%, W = 12.7% and P = 12%

$$x = \frac{13 - 12.7}{13 - 12} \times 100 = 0.3 \times 100 = \textbf{30\% dilution}$$

The following values are a guide to typical dilution levels expected in a butt weld:

Welding Process Used	Dilution %
Manual metal arc welding	20-30
Gas Metal Arc Welding & Gas Tungsten Arc Welding	20-40
Submerged-arc welding	30-40