ISSDA STAINLESS STEEL

Welding of Stainless Steels

PREFACE

Stainless steel are considered as an important group of materials for engineering industries and numerous other applications including consumer items due to their superior material characteristics and versatility. These steels can be easily fabricated by different fabrication processes. Bulk of the requirements of stainless steels for fabrication are in form of hot and cold rolled sheets, coils and plates. Indian plants have established to produce quality stainless steel conforming to international specifications.

There is a very high potential for use of stainless steel flat products in India, particularly in industrial sector. To tap this potential, it is necessary to step up developmental activities and assist customers in developing fabrication practices for promoting new applications

Welding is the most commonly used fabrication process for the manufacture of components from stainless steel flat products. Different welding processes are available with specific advantages and limitations.

This manual has been prepared with a view to render technical assistance to customers on basic information in welding of stainless steel including metallurgical fundamentals, selection of appropriate welding process, parameters and filler materials, common weld defects, their causes and precautions, inspection and testing of weld joints. Also, a glossary of common welding terms has been provided for easy reference.

It is hoped that the manual will serve the purpose for which is intended.

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A. INTRODUCTION

Stainless steels are extensively used in manufacture of industrial equipment and components, household appliances, building and construction, architectural and a variety of other applications due to their superior corrosion resistance, material characteristics, surface lustre and excellent performance in service condition. These steels can be fabricated easily to components by commonly available fabrication processes without sacrificing appreciably their basic material characteristics. Though apparently they are costly, their performance, durability and utility far outweigh initial investment on them. In addition, a judicious selection from a wide variety of stainless steels can further cut down the initial cost and enhance the performance in actual application.

Most of these steels can be easily welded by appropriate welding techniques to fabricate required components. It is, however, necessary to choose carefully specific welding process, equipment and take required precautions in welding of different grades of stainless steels, keeping in view their basic material characteristics, the changes they undergo on welding and their duty requirements in actual service.

B. METALLURGICAL FUNDAMENTALS OF STAINLESS STEELS

Stainless steels are iron based alloys containing a minimum of 10.5% Cr with or without other alloying elements such as nickel, manganese, molybdenum, silicon, niobium, titanium, aluminium, boron, cobalt, copper, nitrogen, etc. Addition of chromium improves the corrosion and oxidation resistance of steels. The presence of chromium leads to formation of a thin protective passive film of chromium oxide which reduces susceptibility to corrosion resistance, most of the grades of stainless steels contain much higher levels of chromium.

Classification of stainless steels
Stainless steels are conventionally classified into different types depending on their metallurgical structures in the condition of their actual application. Accordingly, these are broadly categorized as austenitic, ferritic, martensitic and duplex types of stainless steels. Normally, the austenitic stainless steels containnickel and chromium whereas the ferritic and martensitic stainless steels are nickel-free. The duplex stainless steels contain nickel and chromium in suitable proportions to give a mixed structure of ferrite and austenite.

Effect of alloying elements
Addition of chromium to iron tends to stabilise the ferrite phase. Consequently, iron chromium alloys with more than 13% Cr are ferritic at all temperatures upto their meeting range. Alloys with lower chromium content, however, form austinite in certain ranges of temperature which transforms to martensite on quenching.

Addition of nickel to iron chromium alloys extends the limits of austenitic phase. Nickel also decreases the temperature at which austenitic phase transforms to ferrite upon cooling. Alloys with high nickel content, therefore, exhibit austenitic structure at ambient temperature. Even alloys with lower nickel content such as 18-8 type of steels are austenitic on normal rate of cooling.

Since chromium and nickel promote the formation of ferrite and austenite respectively, for certaincomposition ranges, both ferrite and austenite phases can be present in the stainless steels at room temperature. Such steels fall in the category of duplex stainless steels.

A number of other elements are added in small amounts in stainless steels to modify certain properties and fabrication characteristics. For example molybdenum increases resistance to pitting corrosion and general resistance to corrosion in certain media, Sulphur or selenium increases free machining characteristics and silicon improves heat resistance. Titanium and niobium are added to prevent sensitization.

Austenitic stainless steels
These steels are characterized by face-centered cubic crystal structure. These steels are Cr-Ni, Cr-Mn, Cr-Ni-Mn stainless steels with or without addition of other alloying elements. Usually steels in this category have more than 17% Cr and 7% Ni. The primary role of chromium is to provide a self forming protective film for corrosion resistance and nickel stabilizes the austenitic structure. Low nickel or nickel-free austenitic stainless steel are, however, also available where austenitic phase is retained at room temperature with the help of nitrogen, manganese or copper.

Austenitic stainless steels are basically non-magnetic in nature. These steels are not hardenable by common heat treatment practices. However, these steels harden at a rapid rate by cold working which also makes them slightly magnetic. Austenitic grades exhibit excellent corrosion resistance. The presence of nickel in austenitic stainless steels enhances the corrosion resistance which can be further improved by an increase in chromium content or addition of other alloying elements. They also exhibit much higher ductility and toughness as compared to plain carbon steels and other categories of stainless steels. Austenitic stainless steels are available in many grades, depending on their composition.

On account of good corrosion resistance and formability, austenitic stainless steels find wide application in chemical, fertilizer, textile, pharmaceutical, paper, sugar and otherindustries. These are also used for medical appliances, surgical instruments, kitchenware, decorative items and numerous other applications requiring high strength and toughness at cryogenic, ambient and elevated temperatures.

Ferritic stainless steels

These steels are characterized by body-centered cubic structure and exhibit ferro-magnetic behavior below the Curie temperature. The ferritic grades of stainless steel contain chromium ranging from 12 to 30% and sometimes even higher with alloying additions like molybdenum, aluminium, titanium or niobium etc. Compared to austenitic stainless steels, the ductility and formability of these steels are inferior. These steels are susceptible to three types of embrittlement phenomena viz. embrittlement due to grain growth at very high temperature, formation of sigma phase at intermediate temperature and embrittlement in service at 475 ° C. The greatest advantage of ferritic stainless steels is their low cost as basically these are Fe-Cr alloys without any expensive alloying elements such as nickel. The corrosion resistance of ferritic stainless steels is moderate. By increasing chromium content, the corrosion resistance can be increased but forming becomes more difficult for such steels due to reduced ductility.

Thermal conductivity of ferriticstainless steels is nearly 20% higher than the most common austenitic stainless steels. In addition, co-efficients of thermal expansion are also significantly lower for such steels. These characteristics make them suitable for heat exchangers, furnace equipments and glass sealing. Also, ferritic stainless steels can be widely used for decoration of buildings, welded tubes for furniture, equipment for domestic appliances, dishes and flatwares, automobile components and other common applications.

Matensitic stainless steels

These steels are Fe-Cr-C alloys with or without addition of alloying elements in small quantities. High hardness and strength are specific characteristics of these steels in heat-treated condition. Hardness of these stainless steels is strongly dependent on carbon content and different grades of this type of steels are available in different carbon contents upto a maximum of 1.2%.

Low carbon martensitic stainless steels are used turbine blades, nuclear reactor components and fractional distillation towers. Addition of 1.5% to 2.5% nickel to martensitic grades improves their hardenability while their martensitic structure is still retained. Such alloys are used for springs, aircraft fittings and those machine parts where higher strength are advantageous. Martensitic grades with higher carbon content are used for surgical instruments, knives, cutlery and other wear-resisting parts. A modified version of high carbon grade with 12 to 14% Cr is extensively used for the manufacture of stainless steel razor blades.

Due to their limited corrosion resistance, these steels are not recommended for applications in severe corrosive media.

Duplex stainless steels

By adjusting the proportion of ferrite forming elements (Cr, Si and Mo) and austenite forming elements (C, N, Ni and Mn), duplex stainless steels can be produced with both ferrite and austenite phases in the structure. Such steels are characterized by high tensile strength and good stress corrosion resistance. These steels can be welded with much less risk of cracking than fully austenitic grades.

Application of modern duplexstainless steels is mostly in plate form and as tubes for heat exchangers. These are also used in pumps and valves for chemical industries and marine engineering applications.

Chemical composition, physical characteristics and mechanical properties of important grades of stainless steels are given in tables 1, 2 and 3 respectively.

Table 1: Important stainless steel grade and their chemical compositions

Type	Grade AISI	Chemical Composition Wt%							
		C Max	Si Max	Mn	P Max	S Max	Ni	Cr	Other
AUSTENTIC	201	0.15	1.00	5.50-7.50	0.060	0.030	3.50-5.50	16.00-18.00	N 0.25 max
	202	0.15	1.00	7.50-10.00	0.060	0.030	4.00-6.00	17.00-19.00	N 0.25 max
	301	0.15	1.0	2.00 max	0.045	0.030	8.00-10.00	16.00-18.00	-
	302	0.15	1.00	2.00 max	0.045	0.030	8.00-10.00	17.00-19.00	-
	303	0.15	1.00	2.00 max	0.200	*	8.00-10.00	17.00-19.00	Mo 0.60 max (opetional)
	303Se	0.15	1.00	2.00 max	0.200	0.060	8.00-10.00	17.00-19.00	Se 0.15 min
	304	0.08	1.00	2.00 max	0.045	0.030	8.00-10.50	18.00-20.00	-
	304L	0.03	1.00	2.00 max	0.045	0.030	8.00-12.00	18.00-20.00	-
	305	0.12	1.00	2.00 max	0.045	0.030	10.50-13.00	17.00-19.00	-
	308	0.08	1.00	2.00 max	0.045	0.030	10.00-12.00	19.00-21.00	-
	309	0.20	1.00	2.00 max	0.045	0.030	12.00-15.00	22.00-24.00	-
	309S	0.08	1.00	2.00 max	0.045	0.030	12.00-15.00	22.00-24.00	-
	310	0.25	1.50	2.00 max	0.045	0.030	19.00-22.00	24.00-26.00	-
	310S	0.08	1.50	2.00 max	0.045	0.030	19.00-22.00	24.00-26.00	-
	316	0.08	1.00	2.00 max	0.045		10.00-14.00	16.00-18.00	Mo 2.00-3.00
	316L	0.03	1.00	2.00 max	0.045		10.00-14.00	16.00-18.00	Mo 2.00-3.00
	317	0.08	1.00	2.00 max	0.045		11.00-15.00	18.00-20.00	Mo 3.00-4.00
	317L	0.03	1.00	2.00 max	0.045		11.00-15.00	18.00-20.00	Mo 3.00-4.00
	321	0.08	1.00	2.00 max	0.045		9.00-12.00	17.00-19.00	Ti 5XC min
	347	0.08	1.00	2.00 max	0.045		9.00-13.00	17.00-19.00	Nb+Ta 10XC min
DUPLEX FERRITIC	329	0.10	1.00	2.00 max	0.040	0.030	3.00-6.00	25.00-30.00	Mo 1.00-2.00
	405	0.08	1.00	1.00 max	0.040	0.030	-	11.50-14.50	Al 0.10-0.30
	409	0.08	1.00	1.00 max	0.045	0.045	-	10.50-11.75	Ti 6X6 min But 0.75 max
	410S	0.08	1.00	1.00 max	0.040	0.030	0.60 max	11.50-13.50	-
	430	0.12	1.00	1.00 max	0.040	0.030	-	16.00-18.00	-
	434	0.12	1.00	1.00 max	0.040	0.030	-	16.00-18.00	Mo 0.75-1.125
	446	0.20	1.00	1.50 max	0.040	0.030	-	23.00-27.00	N 0.25 max
MARTENSITIC	403	0.15	0.50	1.00 max	0.040	0.030	-	11.50-13.00	-
	410	0.15	1.00	1.00 max	0.040	0.030	-	11.50-13.50	-
	420	**	1.00	1.00 max	0.040	0.030	-	12.00-14.00	-
	431	0.020	1.00	1.00 max	0.040	0.030	1.25-2.50	15.00-17.00	-

**S : 0.150 min   **C : 0.15 min*

Table 2:Physical Properties (in annealed condition)

STAINLESS STEEL GRADE DESIGNATION AISI	Density Gm/cm3	Specific Electrical Resistance at 200C micro-Ohm cm	Specific Heat (0-1000C Joules/gm0C	Thermal conductivity at 1000C	Coeff. Of Thermal Expansion (per 0C x 10-6
201	7.9	72	0.50	16.33	15.7
202	7.9	72	0.50	16.33	18.4
301	8.0	72	0.50	16.33	17.0
302	8.0	72	0.50	16.33	17.2
304	8.0	72	0.50	16.33	17.3
304 L	8.0	72	0.50	16.33	17.3
309	8.0	78	0.50	14.24	15.0
310	8.0	78	0.50	14.24	15.9
310S	8.0	78	0.50	14.24	15.9
316	8.0	74	0.50	16.33	15.9
316L	8.0	74	0.50	16.33	15.9
321	8.0	72	0.50	16.33	16.6
347	8.0	73	0.50	16.33	16.6
409	7.7	60	0.46	25.12	11.7
430	7.8	60	0.46	25.95	10.4
434	7.8	60	0.46	25.95	11.9
410	7.8	57	0.46	25.12	9.9
420	7.8	55	0.6	25.12	10.3

Table 3: Mechanical Properties (in annealed condition)

Stainless steel Grade Designation AISI	U.T.S. N/m2 min	0.2% Proof Stress N/m2 min	% Elongation on 50 ml GL Min	Hardness RC Max
201	655	310	40	100
202	620	260	40	-
301	515	205	40	88
302	515	205	40	92
304	515	205	40	92
304L	485	170	40	88
305	515	205	40	88
309	515	205	40	95
309S	515	205	40	95
310	515	205	40	95
310S	515	205	40	95
316	515	205	40	95
316L	485	170	40	95
317	515	205	35	95
317L	515	205	40	95
321	515	205	40	95
347	515	205	40	95
405	415	170	20	88
409	380	205	20	80
430	450	205	22*	88
410	450	205	20	95
410S	415	205	22*	88

*20% min. for thickness <1.25 mm

C. WELDING CHARACTERISTICS OF STAINLESS STEELS

The welding characteristics of different types of stainless steels are given below:

Austenitic stainless steels

Austenitic stainless steels are the easiest to weld and produce weld joints which are characterized by a high degree of toughness even in as welded condition due to their face-centered cubic structure. Exceptions are the free machining grades (AISI 303 or 303Se) which contain sulphur or selenium. These elements make the stainless steels susceptible to hot-short cracking. The weldability and performance of these steels during service, however, depend to a great extent on their carbon contents. During welding, when the heat-affected zone passes through the temperature range of 425 to 900°C, carbon combines with chromium resulting in chromium carbide precipitation along the grain boundaries. This phenomenon is called 'Sensitization' which results in poor resistance to intergranular corrosion due to chromium depletion in the vicinity of precipitated carbides. Higher is the carbon content more is the susceptibility for sensitization.

The problem of carbide precipitation in heat-affected zone can be overcome by following three methods:

i. For grades like 302, 304, 316 and 317 sensitization can be removed by solution heat treatment. Carbides are put back into solution by this heat treatment and the normal corrosion resistance is restored. But the drawback of this treatment is that the temperature at which this is to be carried out is very high (1050 to 1100 ° C). At such high temperature, oxidation is likely to occur unless it is protected from atmosphere. Also, the components may sag or get severely distorted during rapid cooling.

   For such applications, it is preferable to use low carbon or stabilized grades of stainless steels.

ii. Grades like 304L, 316L and 317L which contain very low carbon are less susceptible to carbide precipitation in the sensitization range of temperatures. These steels are weldable without causing loss of corrosion resistance in the heat affected zone. However, if they are held at this temperature for prolonged periods, sensitization may occur. Therefore, they are normally used at temperatures below 425 ° C.

iii. Grades like 321 and 347 which are stabilized by adding titanium or columbium can be used at the sensitization range of temperatures. These stainless steels have higher strengths at elevated temperatures and they do not form intergranular chromium carbides when heated in the sensitization temperature range. Titanium or columbium form strong carbides in the matrix. These carbides do not go into solution during rapid heating caused by welding.

Another major problem that is encountered during welding of austenitic stainless steels is microfissure. Microfissure is the intergranular crack that occurs in the weld metal or in the heat-affected zone. Weld metal that is wholly austenitic is more susceptible to microfissuring than that which contains some delta ferrite. The composition of the

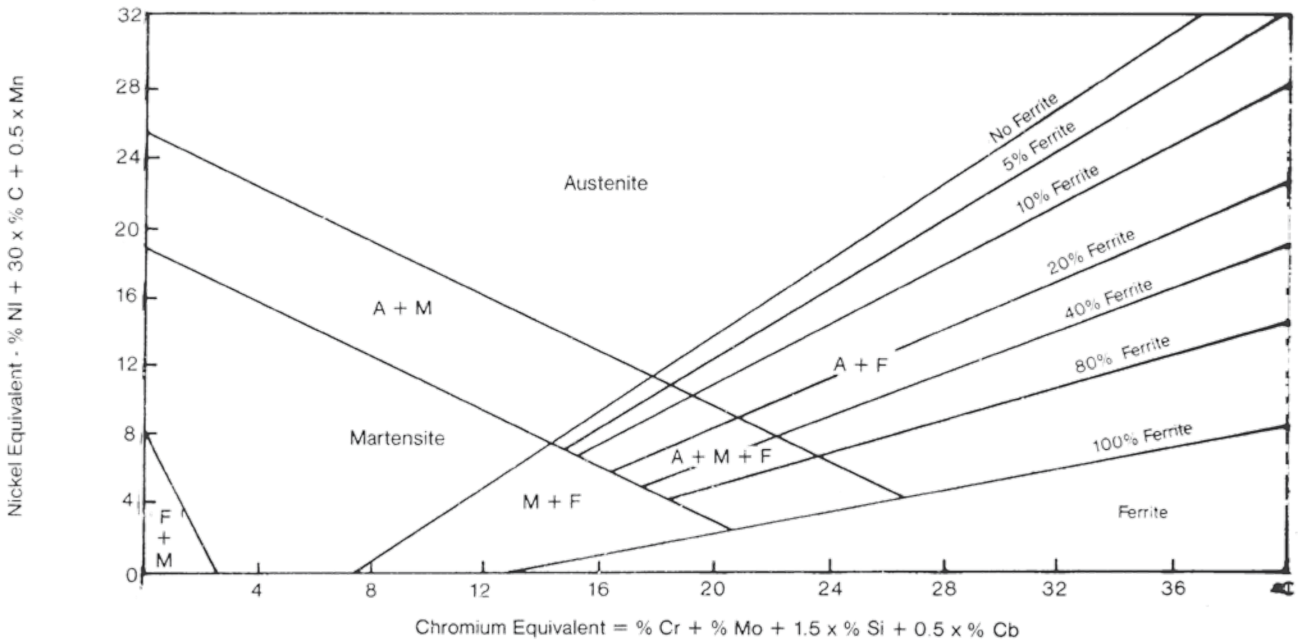


FIG.1 SCHAEFFLER CONSTITUTION DIAGRAM FOR STAINLESS STEEL WELD METAL

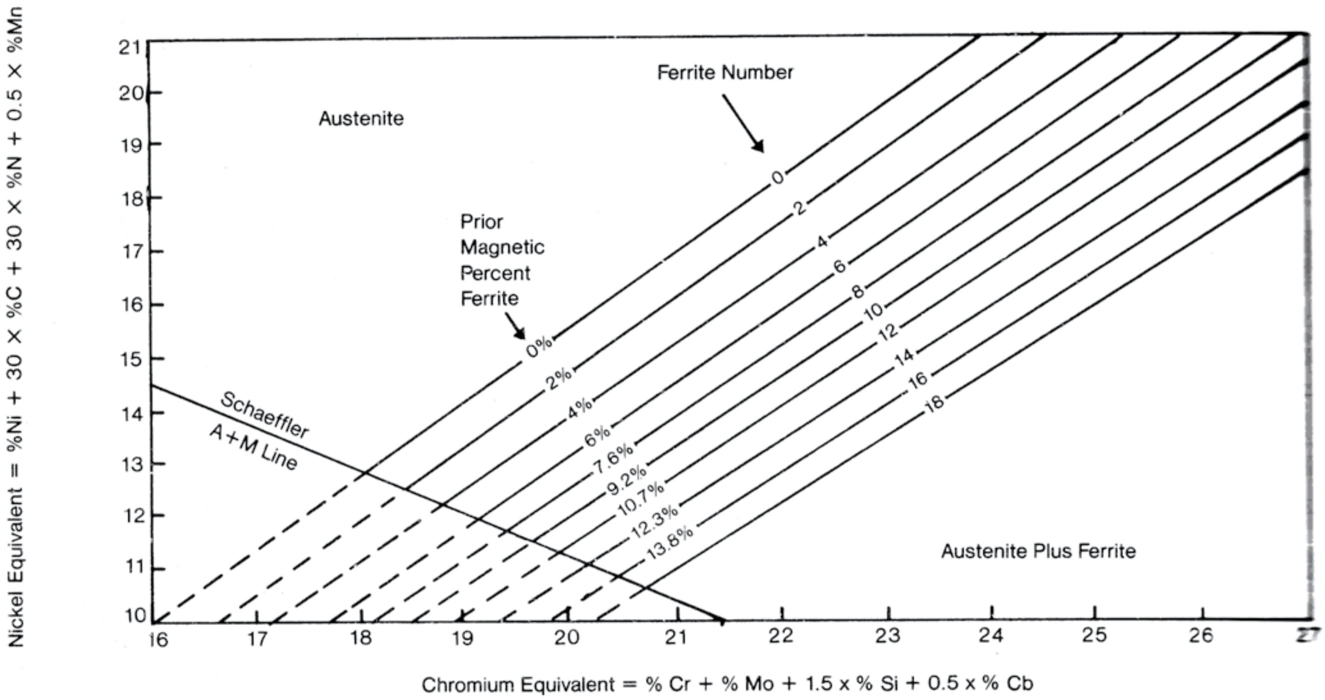


FIG.2 DELONG CONSTITUTION DIAGRAM FOR STAINLESS STEEL WELD METAL

weld metal is therefore very important, which determines the susceptibility of the material for microfissuring. Thus, the filler material must be of a suitable composition to produce a controlled amount of delta ferrite. 3 to 5% delta ferrite in the weld is the desired amount for most applications to prevent microfissuring.

Schaeffler diagram (Fig.1) and Delong diagram (Fig.2) can be used to determine the amount of ferrite present in a weld of given chemical composition.

Ferritic stainless steels

As compared to austenitic stainless steels, ferritic stainless steels are difficult to weld. Although, the composition of these steels lead to a ferritic structure at room temperature, a slight variation or segregation in the normal chemical composition may cause formation of small amount of martensite along the grain boundaries in the heat-affected zone. In addition, ferritic stainless steels are prone to rapid grain coarsening on heating above 950 ° C. These factors have deleterious effect on ductility, toughness and corrosion resistance.

The detrimental effect of martensite can be rectified by post welding annealing. Post welding annealing transforms material to ferrite and also relieves internal stresses. Thus, it results in a completely ferritic structure and restores the corrosion resistance and mechanical properties. In case, post weld heat treatment is not possible, a low carbon ferritic stainless steel (eg. AISI 405, 409) with strong ferrite formers (like Ti, Al, Nb) is preferable.

Martensitic stainless steels

Martensitic stainless steels are more difficult to weld than austenitic and even ferritic stainless steels due to the phase change from austenite to martensite that occurs during cooling after welding. This results in change in volume, increase in hardness and accompanying loss of ductility giving rise to cracks. To prevent this, preheating before welding and post weld heat treatment are required.

Preheating of these steels to 200-300°C before welding is essential to avoid cracking. Carbon content is the most important factor to decide whether preheating is necessary. Steels with 0.10% C or less may not require preheating but with steels with carbon content greater than 0.10% preheating is required to avoid cracking.

Post welding annealing is also required for martensitic stainless steels to regain uniform hardness in the welded area and to improve the ductility of the base metal in the heat affected zone.

Martensite structure makes the stainless steel hard and brittle. As a practice, these steels are always welded in annealed condition since thermal stresses imposed on martensitic structure due to welding result in cracking.

Post weld heat treatment is required to restore martensitic structure for actual application. This consists of heating the weld to a temperature high enough to form austenite and then rapidly quenching to room temperature. Enough care should be taken to prevent and distortion during quenching.

D. WELDING PROCESSES FOR STAINLESS STEELS

Fusion welding and resistance welding are most commonly used processes for joining stainless steels. In fusion welding, heat is produced with the help of an electric arc struck between an electrode and base metal. In resistance welding, joining is done by the combined effect of heat and pressure. Heat is generated by the resistance to the flow of electric current through the parts to be welded and pressure is applied by the electrodes.

The fusion welding processes include:
Shielded Metal Arc Welding (SMAW)
Gas Tungsten Arc Welding (GTAW)
Submerged Arc Welding (SAW)
Plasma Arc Welding (PAW)
Electron Beam Welding (EBW)
Laser Beam Welding (LBW)

The resistance welding may be either of spot or seam welding type.

Typical welding parameters and data for various welding processes are given in Section I

Shielded Metal Arc Welding (SMAW)
This manual process of welding is a common and versatile method used for joining shapes that cannot be easily setup for automatic welding methods. In this method, a solid electrode with an extruded baked-on coating material is used. A typical diagram for Shielded Metal Arc Welding is given in Figure 3.

The coating of the electrode has got several functions:

- Electrode material burns off faster than the coating flux that forms a "Crucible and this shields the arc from the atmosphere.

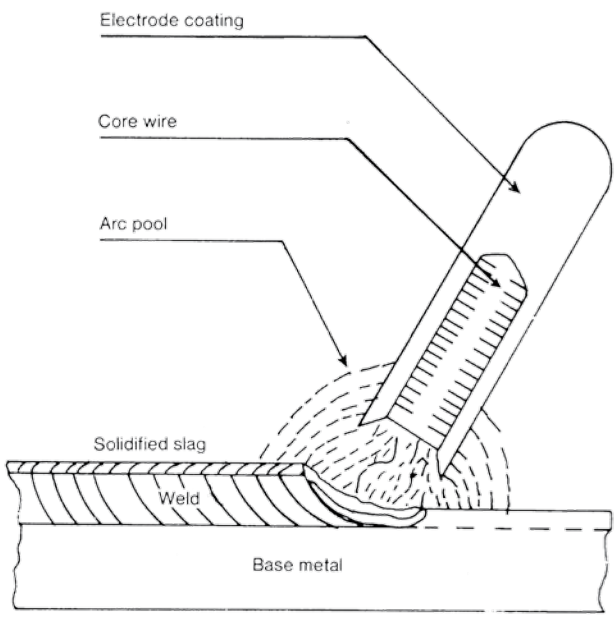


FIG.3 SHIELDED METAL ARC WELDING PROCESS

- Flux removes the impurities from the molten metal
- A gaseous envelope developed by the decomposition of the ingredients of the flux covers the molten weld pool, thereby protecting it from atmospheric contact.

- During cooling, the slag formed on the top of the weld metal acts as a protective cover against contamination by the atmosphere.
- It provides alloy additions to the weld metal.

While the equipment is less expensive and easy to operate in different locations, its operating cost is high due to excessive loss of electrode flux and unused stub-ends.

Gas Tungsten Arc Welding (GTAW)

This process is commonly known as Tungsten Inert Gas (TIG) welding. Gas tungsten arc welding uses the heat of an electric arc between a tungsten electrode and the base metal. Typical compositions for tungsten electrodes are given Table 4.

Table4: Non-consumable electrodes used in TIG welding

Non-consumable electrode (AWS)	Chemical composition
EWP	99.5% minimum tungsten
EWZr	99.2% tungsten + 0.15 to 0.40% zirconium
EWTh-3	98.95% tungsten + 0.35 to 0.55% thoria
EWTh-2	97.5% tungsten + 1.7 to 2.2% thoria
EWTh-1	98.5% tungsten + 0.8 to 1.2% thoria

The preferred types of electrodes for welding stainless steels are the thoriated electrodes containing 1.7% to 2.2% thoria.

A separate welding filler rod is fed into the molten base metal if needed. A shielding gas flows around the arc to keep away air and dirt.

Figure 4 illustrates a typical diagram for gas tungsten arc welding. An AC-DC welding machine may be used with a regulated flow of shielding gas, such as argon or helium. The shielding gas flows from a cylinder through a regulator, flow meter and a hose to the workpiece.

Heating characteristics of the arc may be controlled by changing current and arc length. Diameter of tungsten electrode, thickness and kind of base metal will determine welding amperage.

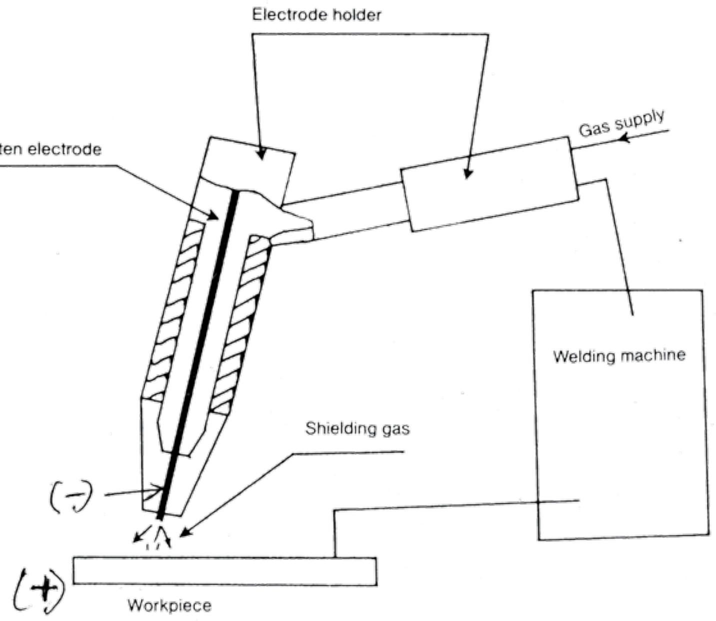


FIG.4 GAS-TUNGSTEN-ARC WELDING PROCESS

GTAW easily welds all types of stainless steels and is particularly suited for welding stainless steel pipes. It is also extensively used for joining tubes in heat exchanger. Generally, the filler metal is fed manually by the welder, but this method is slow, especially for thick components. To achieve higher deposition rates, the process can be automated and the filler wire is heated by resistance heating. The process is called hot wire GTAW and it can result even upto 100% increase in welding speed. Another variation of GTAW is pulsed arc. In this process, the pulsing arc provides control of the molten weld puddle to increase penetration and to minimize porosity.

Gas Metal Arc Welding (GMAW)

This process is commonly known as Metal Inert Gas (MIG) welding. In gas metal arc welding, an electric arc between a continuously fed metal electrode and the base metal produces heat. The arc is shielded by a gas like argon or helium. For stainless steel welding, an inert gas mixture of 98% argon and 2% oxygen is recommended. Power source is DC welding current. A shielding gas cylinder, a regulator and a hose provide a flow of shielding gas to the arc. Figure 5 illustrates typical diagram for GMAW.

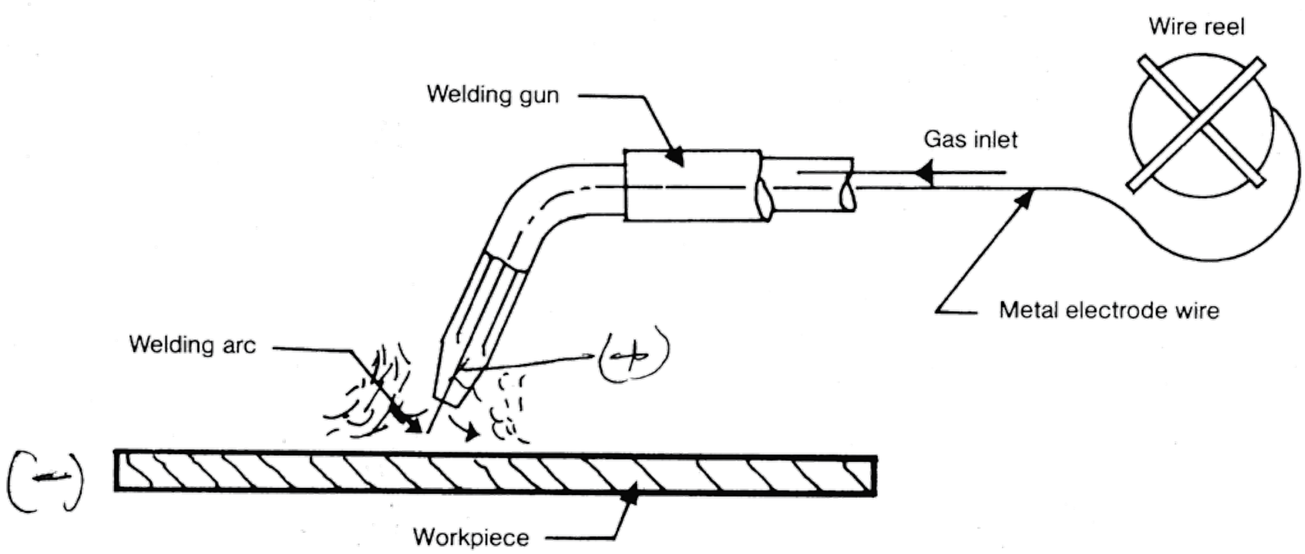


FIG.5 GAS-METAL-ARC WELDING PROCESS

There are three basic variations of GMAW process, depending on the method of transfer of metal. These are spray type transfer, short-circuiting transfer and pulsed type transfer. The spray type of transfer was the first to be developed and is characterized by a relatively hot arc and fluid puddle. Short-circuiting transfer utilizes small diameter wire and is particularly effective for welding thin material.

This increase the utility of basis GMAW, particularly in industries where thin gauge stainless steels are fabricated. The more recent variation of the gas metal arc process is pulsed-arc welding. This process is characterized by a controlled free-flight metal drop rate of 60 drops per second at a lower current density than conventional spray-arc welding.

The advantages of MIG process are high efficiency, high deposition rate and ease in continuous monitoring of the arc.

GMAW is about four time faster than GTAW.

Selection of inert gas for GMAW and GTAW

Argon, helium and carbon dioxide are generally used as shielding gases for GMAW and GTAW though carbon dioxide is not preferred for stainless steels Argon with 2 to 5% oxygen or 5 to 20% nitrogen is suitable for welding of stainless steel flat products in thinner gauges. Helium is preferred for welding of stainless steel in thicker gauges.

Submerged Arc Welding (SAW)

Submerged arc welding is a method in which the heat required to fuse the metal is generated by an electric current passing between the welding wire and the workpiece. The tip of the welding wire, the arc and the weld area are covered by a layer or granular flux. A hopper and feeding mechanism are used to provide a flow of flux over the joint being welded. Figure 6 illustrates a typical diagram for SAW.

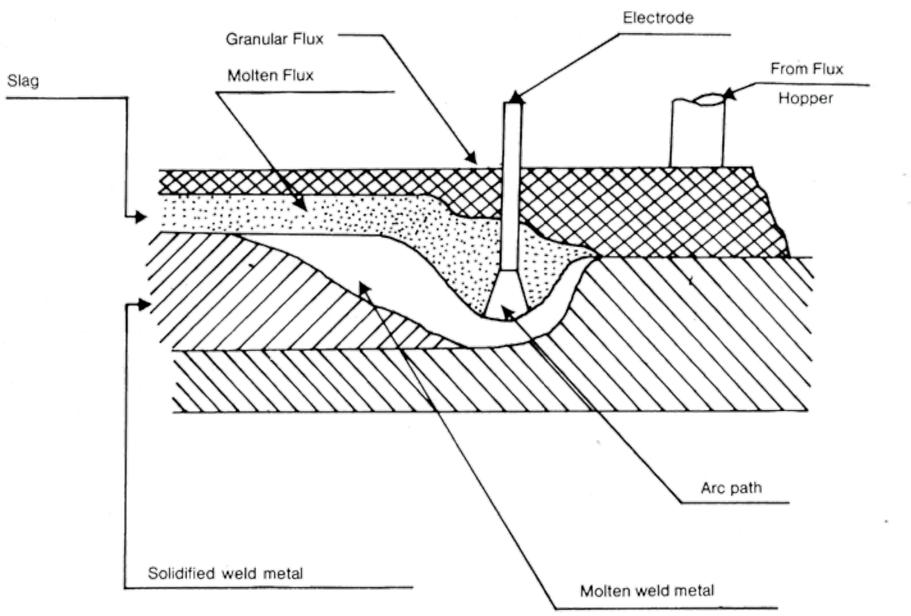


FIG.6 SUBMERGED ARC WELDING PROCESS

The intense heat evolved by the passage of electric current through the welding zone melts the end of the wire and the adjacent edges of the workpieces, creating a puddle of molten metal. The puddle is in a highly liquid state and is turbulent. For these reasons, any slag or gas bubbles are quickly swept to the surface. The flux completely shields the welding zone from contact with the atmosphere.

The difference between submerged arc welding and other processes used for welding stainless steel is that SAW can use much higher heat input than other processes and has slower solidification and cooling characteristic Also, the silicon contact will be much higher in submerged arc welding that with other methods. If care is not exercised in selecting proper flux material.

Submerged arc welding is not recommended where a weld deposit is needed to be fully austenitic or is controlled to alow delta ferrite content (below 4%). However, high quality welds may be produced for applications in which more that 4% delta ferrite in weld deposits is allowable SAW is used for welding of material in higher gauges.

Plasma Arc Welding (PAW)

Plasma arc welding is an inert gas, non-consumable electrode welding method utilizing a transferred, constricted arc. As the office gas passes through the torch to the work, it is heated by the arc, ionized and passes through the arc-constricting nozzle at ant accelerated rate. Since too powerful a jet would cause turbulence in the molten puddle, the jet would cause turbulence in the molten puddle, the het effect on the work is softened by limiting gas flow rates through the nozzle. Since this flow alone is not adequate to protect the molten puddle from atmospheric contamination, auxiliary shielding gas is provide through an outer gas cup on the torch. Figure 7 illustrates a typical diagram of plasma arc welding.

The main difference between PAW and GTAW processes is the “Keyhole” effect that is observed with plasma arc welding when performing square butt joints in the thickness range of 2 to 6 mm. A keyhole is formed at the leading edge of the weld metal where the forces of the plasma het displace the molten metal of permit the arc t pass completely through the work piece. The keyhole is an indication of complete penetration and sound weld.

In case of multipass plasma arc welding, a keyhole root pass is followed by one or more non-keyhole weld passes the filler metal.

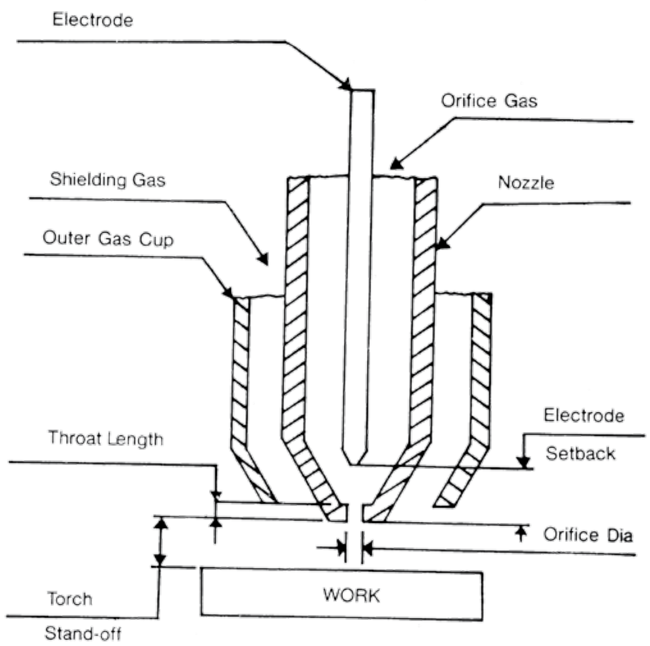


FIG.7 PLASMA ARC WELDING PROCESS

Continuously formed stainless steel tubes are preferably welded without filter metal by plasma arc welding process. This process has the advantage over gas tungsten arc welding process due to its higher speed of welding particularly for thicker tubes. The welding speed in the process is approximately twice as compared to gas tungsten arc welding process for same tube thickness.

Election Beam Welding (EBW)

Electron Beam Welding uses energy from a focused stream of electrons for heating and fusing metals. It is a very convenient process for welding heavy components when the distance between the two pieces to be weld is small. But, since the equipment is large and expensive, it is used only where conventional welding techniques cannot be used.

The machine uses an electronic tube which emits electrons. The streams of electrons are controlled by electro-magnets called magnetic lens and focussed to the weld area. Conventional welding techniques tend to melt only the surface of stainless steels so that penetration essentially comes by heat conduction. By contrast, EBW is capable of such intense local heating that is instantaneously vaporizes the metal so that a hole is formed through the entire thickness of the workpiece. This is similar to the keyhole in PAW.

EBW has hot significant advantages over other joining methods, It is a rapid and precise process which produces exceptionally high quality weld while minimizing distortion and other adverse effects on the workpiece.

Laser Beam Welding (LBW)

A LASE BEAM IS NA INTENSE, HIGHLY COHERENT BEAM OF MONOCHROMATIC LIGHT. Head of laser beam is very intense and is easily directed to sport where needed. Since laser beam can be reflected. It can be either continuous heat source or pulse beam.

In LBW, since the actual welding is done by light beam only, a clear line of sight is required and direct contact with the workpiece is not necessary. This method can be used for joining workpieces which are normally not accessible to conventional methods.

Only good physical contact between the pieces to be joined is desirable. Here the heat affected zone is either very small or for all practical purposes, non-existent. Carbide precipitation will be practically non-existent during laser welding because of high welding speed and low heat input.

Resistance Spot Welding

Stainless steels have 5 to 6 times more electrical, resistivity as compared to carbon steels. Hence, resistance welding is ideally suited for stainless steel. In resistance sport welding, electric current is passed through metal and the resistance to the flow of electric current heats the metal to welding temperature. The processis used to weld together two or more overlapping pieces. Figure B illustrates a typical diagram of Resistance Sport Welding. The process is commonly used to join auto body sections, cabinets and other sheet metal assembiles. The limitation of this process is high power requirement for thicker gauges. Resistance spot welding is practical and economical upto a thickness of 3.0 mm.

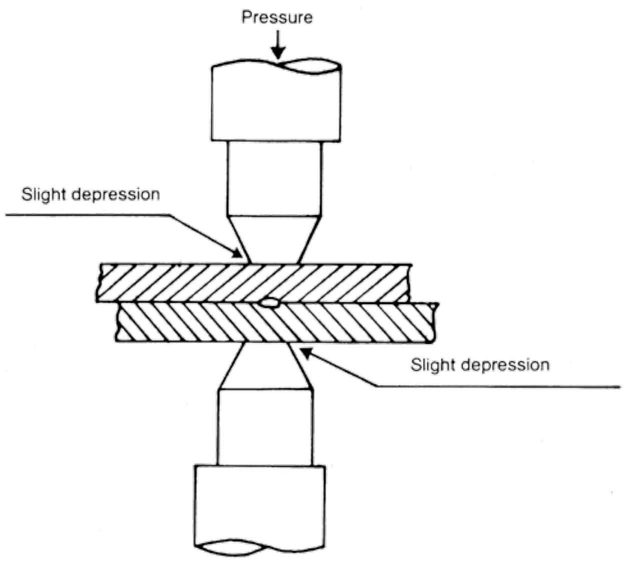


FIG.8 ELECTRICAL RESISTANCE SPOT
WELDING PROCESS

FIG.8 ELECTICAL RESISTANCE SPOT WELDING PROCESS

A Ste-down transformer converts fairly high voltage low amperage current to a low voltage high amperage current. The weld is made between two electrodes or wheels which press the overlapping pieces together. A heavy electrical current flows from one electrode through the metal pieces to be welded together, to the second electrode. These Electrode are special metal alloys (generally copper alloys) which can carry high current and still have physical strength to operate under high pressure.

Quality of resistance sport weld is controlled by the amperage, the electrode pressure and the length of time the current flows.

All the stainless steels which are not hardenable by heat treatment are readily sport welded. With special precautions and procedures all the stainless steels can be spot welded.

Resistance Seam Welding

In this method, the joint is produced by the heat developed from resistance to the flow of electric current through the workpieces which are held together under pressure by circular electrodes, The resultant weld is seam formed by a series of over-lapping sport welds made progressively along a joint by the rotating electrodes. Figure 9 illustrates a typical diagram of such welding.

In seam welding, the distortion will be greater that in sport welding because of higher heat input unless water cooling is utilized. Flooding the part of be welded with water will help minimize the distortion and increase the electrode life greatly.

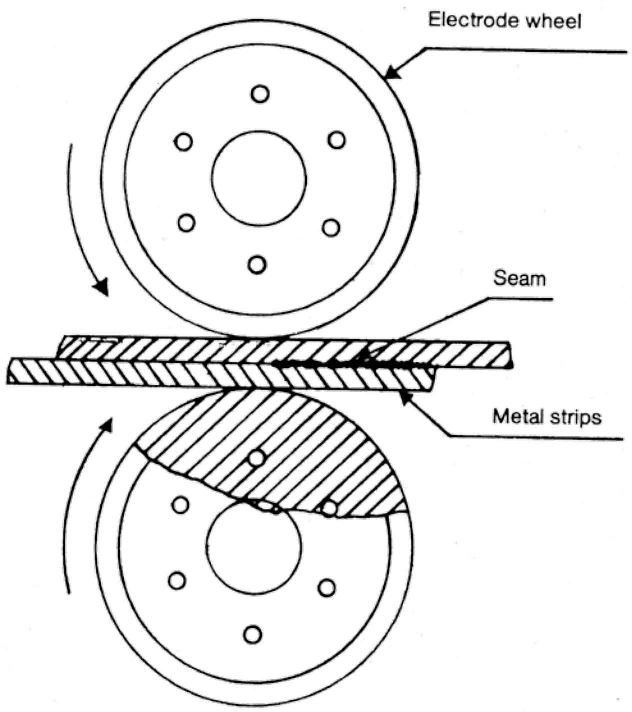


FIG.9 ELECTRICAL RESTANCE SEAM WLDING PROCESS

E SLECTION OF WLDING PROCESSES

General guideline for selection of appropriate method of welding for different types of stainless steels in different thickness, keeping in view the advantages and limitations of the welding processes, are give in Table 5.

Recommended wlding processes for typical applications are give in Table 6.

Table 5: Selection of welding processes for stainless steels

Welding Method	Recommended thickness mm	Weldability		
		Austenitic	Ferritic	Martensitic
Shield Metal Arc Welding (SMAW)	> 0.8	Easy to weld	Can be welded with care	Difficult to weld, can be Welded with care
Gas Tungsten Arc Welding (GTAW)	< 3.0	Easy to weld	Can be welded with care	Can be Welded with care
Gas Metal Arc Welding (GMAW)	> 3.0	Easy to weld	can be Welded with care	Can be Welded with care
Submerged Arc Welding (SAW)	> 6.0	Can be Welded with care	Can be Welded with care	Can be Welded with care`
Resistance Spot Welding	< 3.0	Easy to weld	Easy to weld	Can be Welded with care
Resistance Seam Welding	< 3.0	Easy to weld	Can be Welded with care	Difficult to weld, requires Special care

Table 6: Welding processes of typical applications

Applications	Material	Process recommended
Jobs for static loading	Austenitic Ferritic	Manual metal arc welding MIG welding
Job for dynamic loading	Austenitic or Ferritic	MIG or TIG
Tanks for storing normal chemicals and less corrosive liquids	Austenitic or Ferritic	Manual Metal arc welding
Tanks meant for highly corrosive liquids	Austenitic	TIG or MIG
Racks and decorative panels	Ferritic	Resistance Welding
Welding on thin sheets and foils	Austenitic or Ferritic	TIG without filler or plasma arc welding
Welding of silencer pipes	Ferritic	Spot Welding (resistance) or TIG welding
Welding of small jobs using thin sheets for laboratory or space craft	Austenitic or Ferritic	Plasma arc welding or electron beam welding

F. FILLER MATERIALS AND THEIR COMPOSITIONS

For ensuring good weld quality, it is essential to select proper filter material. The characteristics and soundness of the weld is primarily dependent on the chemical composition of the filter material compatible with composition of base metal and to some extent the protection of molten weld metal from atmospheric selected. Typical filler materials to be used for welding of different type of stainless steels are given in Table 7, 8 and 9.

Table 7: Filler materials for austenitic stainless steel

Base metal type AISI	Service condition	Filler material type
201, 202	As welded by fully Annealed	308
301, 302, 304, 305	As welded or fully	308
305	annealed	
304 L	As welded or stress relieved	347
303, 303Se	As welded or fully annealed	308 L
309, 309S	As welded	309
310, 310S	As welded	309, 310
316L	As welded or stress relieved	316
317	As welded or fully annealed	317
317L	As welded or stress relieved	317Cb
321	As welded or after stabilizing and 321 Stress relieving heat treatment	
347	As welded or after stabilizing and Stress relieving heat treatment	347
348	As welded or after stabilizing and Stress relieving heat treatment	347

Table 8: Filler materials for Ferritic stainless steels

Base metal type AISI	Service condition	Filler material type
405	Annealed As welded	405Cb, 430, 309, 310
430	Annealed As welded	405Cb, 430, 309, 310
446	Annealed As welded	446, 308, 309, 310

Table 9: Filler materials for martensitic stainless steels

Base metal type AISI	Service condition	Filler material type
403	Annealed or	410
	Hardened and stress relieved	
410	Annealed or	410 309, 310, 420
	Hardened and stress relieved As welded	
420	Annealed or	410 420
	Hardened and stress relieved	
431	Annealed or	410 308, 309, 310
	Hardened and stress relieved As welded	

Standard composition range for austenitic stainless steel welding wires are given in Tables 10 and 11. AWS-ASTM specifications designate bare filler wire by using prefix 'ER' and covered filer wire by prefixing "E" Covered filler wire or electrodes are available either with lime or titania coatings designated by the suffix "15" or "16" respectively.

Table 10: Composition of stainless steel bare welding wires

Filler materials (AWS-ASTM)	% C	% Cr	% Ni	% Mo	% Cb+Ta	% Mn	% Si	% P max	% S max
ER308	0.08 max	19.50-22.00	9.00-11.00	-	-	1.00-2.50	0.25-0.60	0.03	0.03
ER308L	0.03 max	19.50-22.00	9.00-11.00	-	-	1.00-2.50	0.25-0.60	0.03	0.03
ER309	0.12 max	23.00 -25.00	12.00-14.00	-	-	1.00-2.50	0.25-0.60	0.03	0.03
ER310	0.08 -0.15	25.00-28.00	20.00-22.00	-	-	1.00-2.50	0.25-0.60	0.03	0.03
ER312	0.08 -0.15	28.00-32.00	8.00-10.50	-	-	1.00-2.50	0.25-0.60	0.03	0.03
ER316	0.08 max	18.00-20.00	11.00-14.00	2.00-3.00	-	1.00-2.50	0.25-0.60	0.03	0.03
ER316L	0.03 max	18.00-20.00	11.00-14.00	2.00-3.00	-	1.00-2.50	00.25-0.60	0.03	0.03
ER317	0.08 max	18.50-20.50	13.00-15.00	3.00-4.00	-	1.00-2.50	0.25-0.60	0.03	0.03
ER318	0.08 max	18.00-20.00	11.00-14.00	2.00-3.00	8xC main 1.00 max	1.00-2.50	0.25-0.60	0.03	0.03
ER321	0.08 max	18.50-20.50	9.00-10.50	0.50 max	**	1.00-2.50	0.25-0.60	0.03	0.03
ER347	0.08 max	19.00-21.50	9.00-11.00	-	10XC min 1.00 max	1.00-2.50	0.25-0.60	0.03	0.03
ER348	0.08 max	19.00-21.50	9.000-11.00	-	10XC min 1.00 max	1.00-2.50	0.25-0.60	0.03	0.03

** Ti= 9xC min, 1.00 max * Ta = 0.10% max

Table 11: Composition of stainless steel coated welding wires

Filler materials (AWS-ASTM)	% C	% Cr	% Ni	% Mo	% Cb+Ta	% Mn	% Si	% P max	% S max
E308	0.08	18.00-21.00	9.00-11.00	-	-	2.50	0.90	0.04	0.03
E308L	0.04	18.00-21.00	9.00-11.00	-	-	2.50	0.90	0.04	0.03
E309	0.15	22.00-25.00	12.00-14.00	-	-	2.50	0.90	0.04	0.03
E309Cb	0.12	22.00-25.00	12.00-14.00	-	0.70-1.00	2.50	0.90	0.04	0.03
E310	0.20	25.00-28.00	20.00-22.50	-	-	2.50	0.75	0.03	0.03
E310Cb	0.12	25.00-28.00	20.00-22.00	-	0.70-1.00	2.50	0.75	0.03	0.03
E312	0.15	28.00-32.00	8.00-10.50	-	-	2.50	0.90	0.04	0.03
E316	0.08	17.00-20.00	11.00-14.00	2.00-3.00	-	2.50	0.90	0.04	0.03
E316L	0.04	17.00-20.00	11.00-14.00	2.00-3.00	-	2.50	0.90	0.04	0.03
E317	0.08	18.00-21.00	12.00-14.00	3.00-4.00	-	2.50	0.90	0.04	0.03
E318	0.08	17.00-20.00	11.00-14.00	2.00-2.50	6XC mix 1.00 max	2.50	0.90	0.04	0.03
E347	0.08	18.00-21.00	9.00-11.00	-	8xC min 1.00 max	2.50	0.90	0.04	0.03

G. COMMON WELDING DEFECTS AND PROCESS PROBLEMS

A sound weld is generally free from weld defects such as crack, incomplete fusion, undercut, poor penetration, porosity, stag inclusion, improper alignment, spatter etc and is characterized by similar material characteristics of base metal. Figure 10 shows typical weld defects.

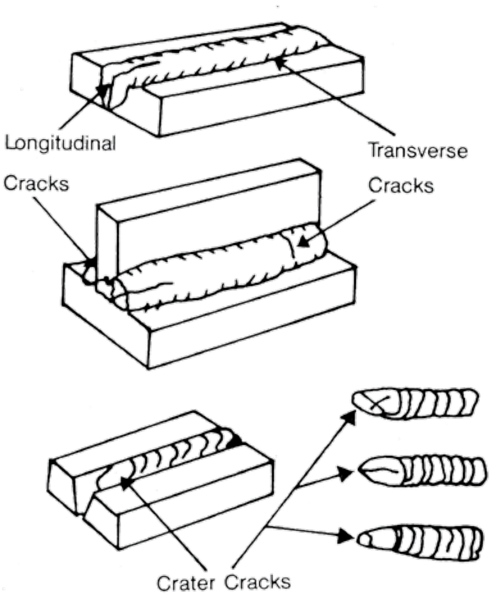
Some of the common defect and their probable causes for different welding processes are given below:

Shielded metal arc welding

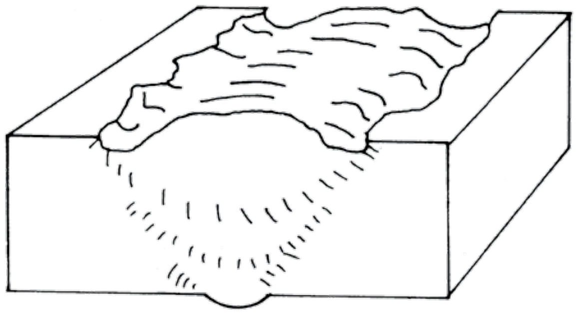
Defect		Cause
Erratic	–	Loose cable connection Poor ground connection Current set too low Arc blow
Excessive Spatter	–	Current set to high Damp electrodes Wrong polarity Arc length to long
Poor bead appearance	–	Incorrect current adjustment Faulty electrodes Electrode held at wrong angles Improper electrode manipulation
Poor fusion	–	Magnetic fields in the weld joint
Poor Penetration	–	Current se to low Welding speed to fast Improper joint preparation
Porosity	–	Joint not properly cleaned Insufficient pudding time Improper electrode selection
Cracking	–	Weld bead not proportional to the base metal thickness Improper electrode selection Crater not filled Joint not properly preheated Current se to high

Gas tungsten arc welding

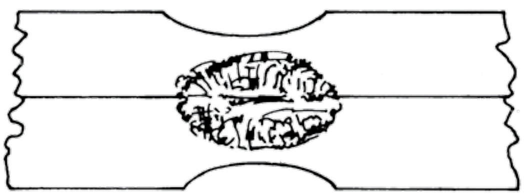
Defect		Cause
Poor arc ignition and maintenance	–	Poor ground connection Defect in high frequency circuit Tungsten diameter too large.
Arc Wander	–	Dirty tungsten Deformed tungsten tip contour Amperage to low for tungsten diameter
Tungsten contamination	–	Touching work with tungsten Filler rod pick up on the tungsten Inadequate post flow
Dirty welds	–	Incomplete oxide removal from work Oil or grease on work Dirty rod Inadequate shielding gas flow Loose gas cup or torch cap Contaminated shielding gas supply



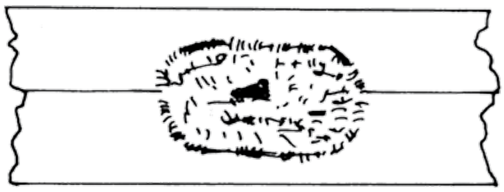
TYPES OF SURFACE CRACKS OF WELDS



UNDERCUT



EXCESSIVE INDENTATION IN SPOT WELDING



VOID IN NUGGET

POROSITY

FIG 10. TYPICAL WELD DEFECTS

Defect		Cause
Torch overheating	–	Excessive amperage beyond torch capacity Constricted cooling fluid flow High amperage welding in restricted joint areas.
Porosity	–	Dirty base metal Dirty road Inadequate shielding Excessive welding speed Excessive weld amperage
Lack of complete fusion	–	Amperage to low Welding to fast Improper choice of filler road diameter Improper torch angle to work.
Under cutting	–	Improper torch angle to work Improper size or application of filler road Welding too fast Excessive amperage
Cracking	–	Improper choice of filer rod type Excessive dilution of filler road with base metal Too rapid chilling of weld joint Highly restrained joints Unfilled craters

Gas tungsten arc welding

Defect		Cause
Wire burn back	–	Initial voltage too high Initial wire feed setting too low Nozzle to work distance too long Constriction in wire conduits
Erratic wire feed	–	Improper adjustment of wire drive rolls Improper operation of wire feed or drive and rake system Contact tip too short. Kinks in wire conduits
Poor weld starts or wire stubbing	–	Voltage too low Induction and/or slope too high Wire stick out too long

Defect		Cause
Dirty welds	–	Inadequate shielding gas flow rates Excessive torch angle to work Spatter build up in nozzle Excessive torch weaving
Porosity	–	Dirty base metal Improper wire chemistry Inadequate gas shielding Entrapment of "glass" from previous bead
Lack of fusion	–	Voltage and/or current too low Welding speed too slow Weld joint too narrow Failure to concentrate arc on leading edge of puddle
Poor base formation	–	Voltage too high Current too low Induction improperly adjusted Improper torch manipulation
Excessive spatter	–	Use of straight CO2 Voltage too low and/or current too high Raised induction and/or slope Excess nozzle to work distance
Under cutting	–	Travel speed too fast Voltage too high Welding with excess current Insufficient pause at edges of weld
Burn through	–	Current too high Travel to slow Excessive root opening Use of CO2 in welding
Cracking		Incorrect filler wire selection Beads too small Poor plate quality Rapid chilling of base metal

Spot welding in austenitic stainless steel

Defect		Cause
Excessive Expulsion at interface	–	Insufficient electrode force Excessive current and/or weld time Electrode dressing too sharp Foreign matter on interface
Surface expulsion	–	Electrode dress to sharp Excessive current in relation to pressure Foreign matter on surface Foreign matter on surface Insufficient electrical and/or thermal conductivity of electrodes
Excessive Indentation	–	Electrode dress to sharp Excessive electrode force Excessive current
Void in nugget	–	Insufficient electrode force Excessive current and/or weld time Electrode dressing too flat Insufficient hold time
Horizontal cracks at the centre of the nugget	–	Excessive current and/or weld time Insufficient electrode force Electrode dressing too flat Insufficient hold time

Defect		Cause
Excessive penetration	–	Excessive current Excessive weld time Electrode dressing too sharp Insufficient electrical or thermal conductivity of electrode Insufficient electrode force
Underside nugget	–	Insufficient current Insufficient weld time Excess electrode force
Unequal penetration	–	Unequal electrode dressing Unequal electrical and/ or thermal conductivity of electrodes
Unbalanced nugget	–	Misalignment of electrodes Off centre dressing of electrodes
Concave sides of nugget	–	Insufficient weld time Insufficient current Electrode diameter too small

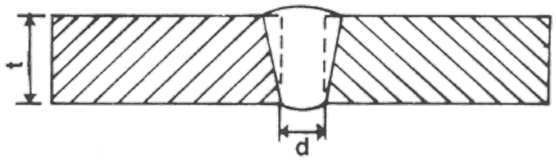
H. PRECAUTIONS

- Materials and electrodes which conform to standard specifications are only to be used to get good quality welds.
- Proper joint design is absolutely necessary to get sound weld. It also helps in easy slag removal.
- Proper bead formation is essential to avid poor penetration and slag pockets.
- Both the stainless steel base metal and the filler material to be used for joining should be free of moisture. Entrapped moisture in a fight joint can result in porosity. Moisture can come by absorption through electrode coatings or night time humidity that may condense at the joint.
- Stainless steel plate or sheet and the filler material to be used for joining are to be free of any contamination like oil, grease, varnish, adhesive, paint, etc. Some of these may act as a source of carbon during welding.
- During making a multiple pass weld, slag from the weld deposit should be cleaned thoroughly to prevent entrapment. Surface of the finished weld also has to be cleaned thoroughly.
- Too low an amperage results in unstable arc accompanied by electrode sticking, slag interference in the arc excessive spatter and poor bead shape,
- Too high amperage can cause poor bead control, cracks in weld, undercut, difficult slag removal and loss of corrosion resistance due to loss of chromium.
- In any welding process, the quality of weld improves by the use of chill bar or back up bar. Pure copper is the most satisfactory material for this purpose. Due to their high conductivity, chill bars do not stick tow weld metal and at the same time assure smooth weld metal surface owing to its chill-mould effect. In case of thin gauge material, chill bars control distortion and prevent excessive melting of base metal.

I. TYPICAL DATA FO RVARIOUS WELDING PROCESSES

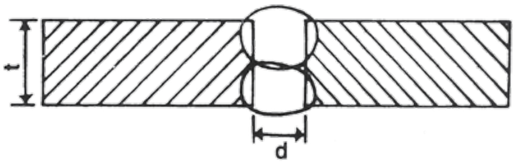
Typical parameters for welding stainless steel in different thicknesses by different commonly used welding process are given in Tables 12 to 23.

***Table 12 L But Welding from one side**



Material thickness t mm	Electrode diameter Mm	Gap width D Mm	Current A	Welding rate cm/min	Number of electrodes per metre of weld	Welding time per metre of weld min
1.5	2.0	05.-0.7	35-45	30	3.7	3.3
2.0	2.5	0.8-1.0	55-70	32	2.9	3.1
2.5	3.25	1.0-1.2	85-105	36	2.6	2.8
3.0	3.25	1.2-1.5	90-110	34	2.9	2.9

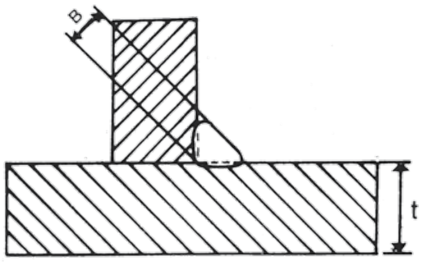
***Table 13 L But Welding from one side**



Material thickness t mm	Bead No.	Electrode diameter mm	Gap width d mm	Current A	Welding rate Cm/min	Number of electrodes per metre of weld	Welding time per metre of weld min
2.0	1	2.5	0.8-1.0	55-70	32	6.4	6.3
2.5	1	3.25	1.0-1.2	85-105	36	5.4	5.6
3.0	1	3.25	1.2-1.5	90-110	35	5.7	5.7
4.0	1 2	4.00 3.25	1.5-2.0	115-140 90-110	33	2.2 5.0 2.8	3.1 6.1 3.0
5.0	1 2	5.0 4.0	2.0-2.5	150-175 110-135	32	2.1 4.5 2.4	3.1 6.3 3.2

* (Courtesy : Peckner, D.and Bernstein, I.M., Hand Book of Stainless Steels, McGraw-Hill, 1977.)

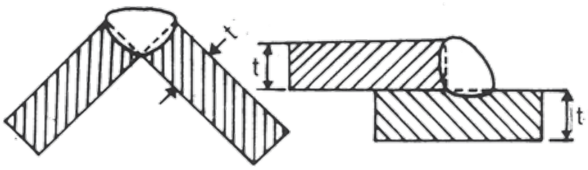
***Table 14: Fillet Weld**



Material thickness t mm	**Electrode diameter Mm**	**Bead thickness B mm**	**Current A**	**Welding rate Cm/min**	**Number of electrodes per metre of weld**	**Welding time per metre of weld min**
1.5	2.0	2.0	40-50	22	6.0	4.6
2.0	2.5	2.5	55-75	22	4.8	4.8
2.5	2.5	2.5	60-80	24	4.8	4.2
3.0	3.25	3.0	85-105	26	4.0	3.8
4.0	3.25	3.0	95-115	28	4.0	3.6
5.0	4.0	3.5	120-140	28	3.1	3.9
6.0	4.0	4.0	125-145	20	4.0	5.0
7.0	4.0	4.5	130-150	16	5.1	6.1
8.0	5.0	5.0	160-180	18	4.0	5.7
9.0	5.0	5.5	165-190	15	4.8	6.5
10.0	5.0	6.0	170-200	13	5.7	7.5

The data given here are value for a bead deposited on workpieces at right angles to each other.
* (Courtesy : Peckner, D and Bernstein, I.M. Hand Book of Stainless Steels McGraw-Hill, 1977.)

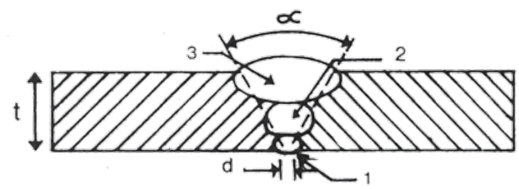
*Table 15: Corner and Lap Welds**



Material thickness t mm	Electrode diameter Mm	Current A	Welding rate Cm/min	Number of electrodes per metre of weld	Welding time per metre of weld min
1.5	2.0	45-55	50	2.9	2.0
2.0	2.5	65-75	45	2.4	2.2
2.5	2.5	70-80	42	2.6	2.4
3.0	3.25	95-105	40	2.2	2.5
4.0	3.25	100-115	33	3.2	3.0
5.0	4.0	125-140	29	2.7	3.4

The data given here are valid for one bead.
* (Courtesy : Peckner, D and Bernstein, I.M. Hand Book of Stainless Steels McGraw-Hill, 1977.)

***Table 16: Single _ V Groove Joint**



Material thickness t mm	**Bead No.**	**Electrode diameter Mm**	**Gap Width D mm**	**Current A**	**Welding rate Cm/min**	**Number of electrodes per metre of weld**	**Welding time per metre of weld min**
4.0	1 2	2.5 3.25	1.0	70-80 95-110	25	4.6 3.9 -8.5	8.0
5.0	1 2	2.5 4.0	1.0	65-75 110-135	24	4.6 3.1-7.7	8.2 6.0
6.0	1 2	3.25 4.0	1.5	80-100 120-140	20	4.0 4.3-8.3	10.0
7.0	1 2	3.25 5.0	1.5	90-110 150-180	18	4.5 4.1-8.6	11.0
8.0	1 2	4.0 5.0	2.0	110-130 155-190	18	3.5 4.4-7.9	11.2
9.0	1 2	4.0 5.0	2.0	110-130 160-195	15	4.0 5.8 -9.8	13.4
10.0	1 2	4.0 4.0 5.0	2.0	110-130 120-145 160-195	17	4.0 4.5 5.0 -13.5	17.9

* (Courtesy : Peckner, D and Bernstein, I.M. Hand Book of Stainless Steels, McGraw-Hill, 1977.)

Table 17: Typical data for TIG Welding

Type of joint	Thickness mm	Welding Current, A			Filler wire diameter Mm	Electrode diameter mm	Welding speed mm/m	No. of passes	Argon flow l/ min
		Horizontal	Vertical	Overhead					
	0.6	15-25	14-23	13-22		1.0	300-350	1	5
	0.8	15-30	14-28	13-27		1.0	300-350	1	3
	1.0	25-60	23-55	22-54	1.5	1.0	250-300	1	4
	1.5	25-60	23-55	22-54	1.5	1.0	250-300	1	4
	2.0	80-110	75-100	70-100	1.5-2.0	1.5-2.0	175-225	1	4
	3.0	120-200	110-185	110-180	2.0	2.0-3.0	125-175	1	5
	4.0	120-200	110-185	110-180	3.0	2.0	100-150	1	5
	5.0	150-250	140-230	135-225	3.0-4.0	2.0-3.0		1	5
	1.0	60	55	54	1.0	1.0	250-300	1	4
	1.5	95	90	85	1.5	1.0	250-300	1	4
	2.0	110	100	100	1.5	1.5-2.0	125-175	1	5
	3.0	130	120	150	2.0	2.0-3.0	125-175	1	5
	4.0	185	170	165	2.0	2.0	100-175	1	5
	6.0	310	290	280	4.0	3.0			
	1.0	40	37	36	1.0	1.0	250-300	1	4
	1.5	60	55	55	1.5	1.0	250-300	1	4
	2.0	80	75	70	1.5	1.5-2.0	175-225	1	4
	3.0	110	100	100	2.0	2.0-3.0	125-175	1	5
	1.0	55	51	50	1.5	1.0	250-300	1	4
	1.5	90	85	80	2.0	1.0	250-300	1	4
	2.0	105	98	95	2.0	1.5-2.0	175-225	1	4
	3.0	125	115	110	3.0	2.0-3.0	125-175	1	5
	4.0	180	165	160	2.0	2.0	100-150	1	5
	6.0	300	280	270	4.0	4.0	3.0		4
					4.0	4.0	3.0		4

* (Courtesy : Peckner, D and Bernstein, I.M. Hand Book of Stainless Steels, McGraw-Hill, 1977.)

Table 18: Nominal condition for GMAW of austenitic stainless steels with spray arc

Thickness of base Metal mm	Joint and Edge preparation	Electrode with diameter mm	Current (DCRP) A	Wire feed speed m/min	Welding speed m/min	Number passes
3.2	Square butt with backing	1.6	200-500	2.8-3.8	0.5	1
6.4	Single V-butt, 60O Incl. angle, no root face	1.6	250-300	3.8-5.0	0.4	2
9.5	Single V-butt, 60O Incl. angle1.6 mm root face	1.6	275-325	5.7-6.4	.5	2
12.7	Single V-butt, 60O Incl. angle, 1.6 mm root face	2.4	300-350	1.9-2.2	0.13	3-4

Table 19: Nominal condition for GMAW of austenitic stainless steels with short-circuiting arc

Thickness of base Metal mm	Joint and Edge preparation	Current (DCRP) A	Voltage V	Wire feed speed m/min	Welding speed m/min
1.6	Fillet or lap	85	21	4.7	0.46
1.6	Butt (Square edge)	85	22	4.7	0.50
2.0	Fillet or lap	90	22	4.9	0.36
2.2	Butt (Square edge)	90	22	4.9	0.30
2.4	Fillet or lap	105	23	5.9	3.38
3.2	Fillet or lap	125	23	7.1	0.40

Electrode wire diameter = 0.8 mm, one pass each, shielding gas containing 90% helium, 7.5% argon and 2.5% carbon dioxide

Table 20: Typical welding condition for single pass SAW of stainless steels

Thickness of base Metal mm	Type of Joint	Welding rod Diameter mm	Current A	Voltage V	Welding speed m/min
1.3	Square -butt joint	3.2	325	25	1.9
1.9	Square -butt joint	3.2	325	25	1.7
2.4	Square -butt joint	3.2	450	25	1.5
3.2	Square -butt joint	3.5	500	30	1.3
4.8	Square -butt joint	6.4	600	30	1.1
6.4	60 deg V-groove joint	6.4	750	35	0.9
9.5	60 deg V-groove joint	6.4	750	35	0.6
12.7	45 deg V-groove joint	9.5	800	35	0.5

Table 21: Typical welding condition PAW of stainless steels

Thickness of base Metal mm	Travel Speed cm/min	Current DCSP) A	Arc Voltage V	Gas	Gas flow m3/hr	
					Orific gas	Shielding gas
1.3	Square -butt joint	3.2	325	25	1.9	
1.9	Square -butt joint	3.2	325	25	1.7	
2.4	Square -butt joint	3.2	450	25	1.5	
3.2	Square -butt joint	3.5	500	30	1.3	
4.8	Square -butt joint	6.4	600	30	1.1	
6.4	60 deg V-groove joint	6.4	750	35	0.9	
9.5	60 deg V-groove joint	6.4	750	35	0.6	
12.7	45 deg V-groove joint	9.5	800	35	0.5	

Table 22: Recommended practices for sport welding austenitic stainless steels

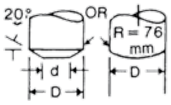
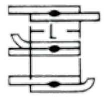
Thick-ness "T" of thinnest outside price	Electrode Diam-eter and shape 		Net elec-trode force	Weld time (single impluse cycle) (60 per sec.)	Minimum shear strength Kg Ultimate tensile strength of metal			Welding current (Approx) A		Diameter Of fused zone 	Mini-mum weld spacing	Minimum contacting overlap 
mm	**D Min mm**	**D Max mm**	**Kg**					**Tensile Strenght below 105 Kg/mm2**	**Tensil Strenght 105 and higher Kg/m m2**	**mm**	**mm**	**mm**
0.15	4.8	2.4	80	2	27	32	38	2000	2000	1.15	4.8	4.8
0.20	4.8	2.4	90	3	45	59	65	2000	2000	1.40	4.8	4.8
0.25	4.8	3.2	105	3	68	77	95	2000	2000	1.65	4.8	4.8
0.30	6.3	3.2	120	3	84	95	113	2100	2000	1.90	6.3	6.3
0.35	6.3	3.2	135	4	108	113	145	2500	2200	2.70	6.3	6.3
0.40	6.3	3.2	150	4	127	136	172	3000	2500	2.20	8.0	6.3
0.45	6.3	3.2	170	4	145	163	213	3500	2800	2.40	8.0	6.3
0.55	6.3	4.0	180	4	168	213	226	4000	3200	2.50	8.0	8.0
0.65	9.6	4.0	235	5	226	272	308	5000	4100	3.00	11.0	9.5
0.80	9.6	4.8	300	5	308	362	421	6000	4800	3.30	12.7	9.5
0.85	9.6	4.8	340	6	362	416	498	7000	5500	3.80	14.3	11.1
1.00	9.6	4.8	410	6	453	575	635	7800	6300	4.10	16.0	11.1
1.10	9.6	4.8	450	8	544	656	770	8700	7000	4.60	17.5	11.1
1.27	12.6	6.3	545	8	656	770	907	9500	7500	4.8	19.0	12.7
1.40	12.6	6.3	610	10	770	907	1110	10300	8300	5.30	22.2	14.3
1.60	12.6	6.3	680	10	883	1088	1314	11000	9000	5.60	25.4	16.0
1.80	16.0	6.3	770	12	1088	1270	1608	12300	10000	6.30	28.5	16.0
2.00	16.0	8.0	860	14	1224	1542	1814	14000	11000	7.50	31.7	17.5
2.40	16.0	8.0	1090	16	1608	1904	2300	15700	12700	7.20	34.9	19.0
2.80	19.0	9.6	1270	18	1904	2267	2900	17700	14000	7.40	38.0	20.6
3.20	19.0	9.6	1500	20	2267	2721	3442	18000	15500	7.60	50.0	22.2

Table 23: Recommended practices for seam welding austenitic stainless steels

Thickness "T" of thinnest outside price	Electrode Diameter and shape	Net electrode force	On Time cycle) (60 per sec.)	Off time for maximum speed (Pressure tight) Cycles		Maximum Weld Speed Per min mm		Welding Current (Approx)	Minimum contacting overtap
mm	W Min	Kg		2 "T"	4 "T"	2 "T"	4 "T"		
0.15	4.8	136	2	1	1	1500	1700	4000	6
0.20	4.8	159	2	1	2	1700	1400	4600	6
0.25	4.8	181	3	2	2	1100	1300	5000	6
0.30	6.3	204	3	2	2	1200	1400	5600	8
0.35	6.3	226	3	2	3	1300	1300	6200	8
0.40	6.3	272	3	2	3	1300	1300	6700	8
0.55	6.3	295	3	2	3	1400	1300	7300	8
0.65	9.6	385	3	3	4	1300	1200	9200	11
0.80	9.6	454	3	3	4	130	1200	40600	11
1.00	9.6	589	3	4	5	1200	1100	13000	13
1.25	12.6	725	4	4	5	1100	1100	14200	16
1.60	12.6	840	4	5	7	1000	1000	15100	16
1.80	16.0	975	4	5	7	1100	1000	15900	18
2.00	16.0	1043	4	6	7	1000	1000	16500	18
2.40	16.0	1156	5	6	7	900	1000	16600	19
2.80	19.0	1337	5	7	9	1000	900	16800	21
3.20	19.0	1495	6	6	8	1000	900	17000	22

J. INSPECTION AND TESTING OF WELDS

The general soundness of the welds can be assessed by visual inspection. In addition, it may be quite often necessary to assess the quality of welds by proven non-destructive and destructive tests.

Visual Inspection

Visual inspection is the most common, easy and inexpensive method of checking quality, used at all stages of different welding operations. For this purpose, only ordinary tools like magnifying glasses, weld viewers, weld gauges, measuring scales etc. may be required. This is the only inspection usually needed for general commercial welding.

This inspection gives a general indication about the weld soundness particularly in respect of cracks, inclusions, undercut, weld contour, excessive spatter, bead size, lack of fusion, incomplete penetration, warpage and dimensional accuracy.

Non-destructive tests

- Magnetic particles test
- Dye penetrant test
- Ultrasonic test
- Radiographic test

Magnetic particle test

This is an effective method for checking a weld for surface or near surface flows like cracks, porosity, slag, inclusions, lack of fusion and other discontinuities in ferro-magnetic materials. It is the most reliable method available, especially for very fine and shallow cracks. A liquid solution containing very tiny colored magnetic particles is painted or sprayed onto the surfaces being checked. The test piece is then subjected to a strong magnetic field. Any surface or sub-surface discontinuity present in the test piece creates a local north and south magnetic pole and attracts the metallic particles in the solution. When the magnetic field is removed, the presence of flaws in the material can be known due to concentration of magnetic particles in that area.

Dye penetrant test

The dye penetrant test is a sensitive method for detecting minute discontinuities like cracks and porosity which are open to the surface of the material being inspected. This method uses coloured liquid dyes and fluorescent liquid penetrants to check surface flaws. The liquid dye penetrant is sprayed onto the clean surface being inspected. After allowing a short duration for the liquid to penetrate, the excess amount of dye is removed with cleaner and the surface is washed with water and allowed to dry. After the surface is thoroughly dry, a developer is prayed on the surface to bring out the colour in the dye penetrant that has penetrated into any crack or pin hole.

The main advantages of this method are its suitability for both magnetic and non-magentic materials, its low cost, its portability and the ease with which the results can be interpreted. However, it cannot detect flaws which are not open to surface.

Ultrasonic Test

This method uses high frequency sound waves and can determine internal flaws as well as surface defects. Short pulses of ultrasonic waves are transmitted into a material being tested. These pulses are reflected by discontinuities or flaws in thir path or from any interface which they strike. The received reflection or echoes are then displayed on cathoderay tube (CRT) screen furnishes specific data as to the relative size of the discontinuity in terms of signal amplitiude and its location from the scanning surface by the proper calibration of CRT screen.

The advantages of ultrasonic test are:

- High sensitivity which permits detection of minute cracks.
- Great penetrating power which allows the examination of extremely thick section
- Accuracy in measurement of flow position and estimation of flaw size

Radiographic test

Radiography is one of the most versatile non-destructive tests used for locating sub-surface and internal defects in welds of all types of materials. The specific advantage of this method is that a permanent record of observation can be obtained for future reference which is not possible by other methods. X-rays or gamma rays are passed through the weld and the film kept behind the weld is exposed to the radiation for specific durations depending on nature and dimension of the weld. After developing the film, it can be seen that areas of film exposed to less energy remain lighter and consequently other portions where thickness has changed due to discontinuities, porosity or cracks will appear as dark outlines.

The salient features of commonly used non-destructive tests for weld are given in Table 24.

Destructive test

- Chemical analysis
- Tensile test
- Bend test
- Hardness test
- Impect test
- Macroscopic and microscopic examination
- Corrosion test
- Leak test
- Peel test

Chemical analysis

Chemical analysis is carried out for ascertaining the chemical composition of the weld vis-à-vis the base metal. Conventional methods of analysis and various instrumental methods of analysis are available for quick and accurate estimation of chemical composition.

Tensile test

In tensile test, a specimen of the weld is mounted in a tensile testing machine and stretched. This test determines tensile strength, yield strength and % elongation of the weld metal.

Table 24: Common non-destructive testing methods for welds

NDT	Equipment	Defects Detected	Advantages	Limitations	Remarks
Magnetic particle	Iron particles, wet of dry, fluorescent, ultra violet light for fluorescent type.	Surface or near surface discontinuities, cracks, porosity, slag etc.	Indicates discontinuities not visible to naked eye, relatively low cost, no size restriction.	Used on magnetic material only, requires skill to recognize and interpret flaws, difficult to use on rough surface.	Testing should be from two perpendicular directions to catch defects which may be parallel to one set of magnetic lines of force.
Dye penetrant	Fluorescent of visible penetrating liquids and developers, ultra violet for the fluorescent type.	Defect open to surface only. Good for leak detection.	Application to both magnetic and non magnetic materials Easy to use and interpret. Low cost.	Only surface defects are detectable time consuming process.	Often used on root pass of highly critical pipe weld. If material is not properly cleaned some indication may be misleading.
Ultrasonic	Ultrasonic units and probes with suitable couplant, standard reference block for interpretation.	Surface and subsurface flaws, including those too small for detection by other method especially for detecting sub surface, lamination like defects.	Very sensitive, permits inspection of joints inaccessible to radiography, can be used on all materials.	High degree of skill is required for interpretation. No permanent record is obtained.	Required by some code and specification.
Radiography	X-ray or gamma ray source, film and processing facilities, equipment.	Internal flaws viz. cracks porosity blow holes, non-metallic inclusions, incomplete root penetration, burn through, etc.	Provides permanent record of the defect, applicable on all materials.	Requires skill in choosing exposure angle, operating equipment and interpreting results. Not suitable for fillet weld inspection. Requires safety precaution.	Because of cost its use should be limited to those areas where other methods will nt provide the assurance, required by some codes and specifications.

Bend test

This test is useful or accessing the quality of identical components fabricated in large numbers commercially. This method is fast and shows most of the weld faults with fair degree of accuracy. A common method is to clamp the piece to be tested in a vice and bend the metal at the welded joint by means of a bending bar. This method of bending gives the approximates strength of the weld. Any cracking of the metal will indicate improper fusion or inadequate penetration.

Hardness test

The hardness of the weld is particularly important if the weld it to be machined. Hardness can be determined by Rockwell, Brinell, Vickers, Scelorscape hardness testing machines depending or specific requirement.

Impact test

This test is carried our for weld to assess their soundness by determining their impact resistance under a rapidly applied shock load. The impact test may be done by either lzod or Charpy method. These methods are similar, but the shape and position of the notch very. A test piece is notched in a specified manner and clamped in the jaws of an impact testing machine. A heavy pendulum is lifted to a given height and then released against the notched specimen to determine the impact force it can withstand.

Macroscopic and Microscopic examination

Macroscopic observation of weld sample is done at low magnifications and it covers a large area s compared to microscopic observation. Cracks, pits, pin hole, scales, inclusions are easily detected by this method.

Microscopic examination is commonly used in metallurgical laboratory for assessing quality of welds. Samples collected from the weld are polished and observed under microscope in unetched and etched condition at different magnifications. This is an effective method of examining microstructure of the weld and heat-affected zone. In addition defects like slag inclusion, poor fusion, incomplete penetration etc. can be observed Photomicrographs can also be taken to depict microstructure and defects in the weld.

Corrosion test

Samples of welded components may be subjected to suitable corrosion tests as per relevant specifications or service conditions for evaluation of their corrosion behavior vis-à-vis base metal.

Leak test

This is a common method of testing pressure vessel welds (eg. Tanks and pipe lines for liquids and gases) to determine whether any leak is present. A small pressure should be built up into the vessel or pipe and a soap and water solutionput on the outside of each weld. Leaks are indicated by the formation of bubbles. The vessel to be inspected may be pressurized and the pressure noted on a gauge. This can be observed over a period of time. Any drop in pressure indicates a leak.

Another test for pressure vessel is to coast the surface with lime solution. After the lime has dried, pressure is built up in the vessel. A flaw is indicated where the lime flakes from the metal.

Hydraulic pressure, using water a s the fluid is also used for detecting flaws in the weld. But water is not a reliable fluid for extremely small cracks.

Peel test

Lap joints may be tested to destruction by means of the peel test. This test is used to check the strength of a resistance sport weld, in this test, after welding, the test pieces are peeled apart. If the sport weld nugget is of correct diameter and is tom out of one piece, the spot weld is considered to be properly made. All machine settings are considered to be correct for the part to be welded when the peel test is made satisfactorily.

K. GLOSSARY OF COMMON WELDING TERMS

Arc blow : The deflection of an electric arc from its normal path because of magnetic forces.

Arc voltage : The voltage across the welding arc.

Arc Welding : Welding of metal using an electric arc as the heat source.

Arc welding gun : A device used in arc welding to transfer current, guide the electrode and direct shielding gas.

Axis of a weld: The line of direction along which the weld is being made.

Backhand welding : A welding technique in which the welding torch is directed opposite to the progress of welding.

Backing : A material placed at the root of a weld joint for the purpose of supporting molten weld metal.

Bare electrode : A filler metal electrode having no coating.

Base metal : The metal to be welded, brazed, soldered, or cut.

Burn-thru : A term erronesouly used to denote excessive melt-thru or a hole.

Butt jount : A jount between two members aligned approximately in the same plane.

Complete fusion : Fusion which has occurred over the entire base material surfaces intended for welding.

Complete joint penetration : Joint penetration in which the weld metal completely fills the groove and is fused to the base metal throughout its total thickness.

Constricted arc : A plasma arc column that is shaped by a constricting nozzle orifice.

Constricting nozzle : A water-cooled copper nozzle surrounding the electrode and containing the constricting office.

Constricting office : The hole in the constricting nozzle through which the arc passes.

Continuous weld : A weld which extends continuously from one end of a joint to the other.

Covered electrode : A flux covered arc welding electrode.

Crater : A depression at the termination of a weld bead or in the molten weld pool.

Crater crack : A crack in the crater of a weld bead.

Defective weld : A weld containing one or more defects.

Deposited metal: Filler metal deposit during welding.

Deposition rate: Material deposited in unit time.

Edge preparation : The surface prepared on the edge of a member for welding.

Electrode : A component of the welding circuit through which current is conducted to the arc, molten slag, or base metal.

Electron beam gun : A device for producting and accelerating electrons.

Electro beam welding : A welding process utilizing the head from a concentrated electron beam.

Ferrite number : A measure of ferrite content in an austenitic stainless steel weld metal.

Fillet weld : A weld of approximately triangular cross section joining two surfaces approximately at right angles to each other in a lap joint. T-joint, or corner joint.

Fish eye : A discontinuity found on the fracture surface of a weld consisting of a small pore or inclusion surrounded by roughly a round, bright area.

Fissure : A small crack-like discontinuity with only slight separation of the fracture surfaces. The prefixes macro or micro indicate relative size.

Fixture : A device designed to hold parts to be joined in proper relation to each other.

Fusion welding : any welding process or method which used fusion to complete the weld.

Gouging : forming of a bevel/groove by material removal.

Groove : An opening or channel in the surface of a part or between tow components to contain a weld.

Head affected zone (HAZ) : The portion of the base metal which has not been melted, but whose mechanical properties or microstructure have bee altered by the head of welding.

Hot wire welding : A variation of arc welding (GTAW, PAW, SAW) in which filler metal wire is preheated as it is fed into the molten weld pool.

Indentation : In a spot, seam, or projection weld, the depression on the exterior surface or surfaces or the base metal.

Inert gas : A gas which does not normally combine chemically with the base metal or filler metal.

Intermittent weld : A weld in which the continuity is broken by recurring unwelded spaces,

Joint : The junction of weldments.

Joint design : The joint geometry together with the require dimensions of the welded joint.

Keyhole : The technique of enlarging the root opening with the welding arc to ensure proper root punctuation and reinforcement.

Liquidus : The lowest temperature at which a metal or an alloy is completely liquid.

Melting range : The temperature range between solidus and liquidus.

Melt-thru : Complete joint penetration for a joint welded from one side.

Molten weld pool : The liquid state of a weld prior to solidification as weld metal.

Nozzle : A device which directs shielding media.

Nugget (resistance welding) : The weld metal joining the parts in sport, seam or projection welds,

Off time (resistance welding) : The time during which the electrodes are off the work. This term is generally used when the welding cycle is repetitive.

Open-circuit voltage : The voltage when no current is flowing in the circuit of welding machine.

Overhead position : The position in which welding is performed from the underside of the joint.

Peel test : A destructive method of inspection which mechanically separates a lap joint by peeling.

Porosity : Cavity type discontinuities formed by gas entrapment during solidification.

Preheating : Heating the base metal immediately before welding.

Protective atmosphere : A gas envelope surrounding the parts to be welded.

Residual stress : Stress remaining in a structure or member as a result of thermal or mechanical treatment or both.

Resistance welding : Welding by resistance to the flow of electric current that heats the work pieces held together under pressure.

Reverse polarity : DC welding current with electrode as positive and ground as negative.

Root crack : A crack at the root of weld or heat affected zone.

Seam weld : A continuous weld made between or upon overlapping members.

Shielding gas : Protective gas used to prevent atmospheric contamination.

Shrinkage void : A cavity type discontinuity normally formed by shrinkage during solidification.

Skull : The unmelted residue from a liquated filler metal.

Slag inclusion : Nom-metallic solid material entrapped in weld metal or between weld metal and base metal.

Solidus : The highest temperature at which a metal or alloy is completely solid.

Spatter : The metal particles expelled during welding and which do not from a part of the weld.

Straight polarity : DC welding current with electrode as negative and ground as positive.

Stress corrosion cracking : Failure of metals by cracking under combined action of corrosion and stress.

Stress relief heat treatment : Heat treatment to relieve residual stresses.

Tungsten electrode : A non-filler metal electrode used in arc welding made principally of tungsten.

Undercut : A groove melted into the base metal adjacent to the toe or rood of a weld and left unfilled by weld metal.

Weld bead : A weld deposit resulting from a pass.

Weldment : An assembly whose component part are joined by welding.

Weld metal : The portion of the base metal and filler rod which is melted and fused together during welding operation.

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