WELDING OF STAINLESS STEELS

(30 JUNE 2014)

PROPERTIES AND CHARACTERISTICS

- Major element : Cr (at least 12%) and Ni
- Do not get oxidized easily
- High corrosion resistance
- High thermal expansion
  - Greater shrinkage stresses
  - Greater distortion

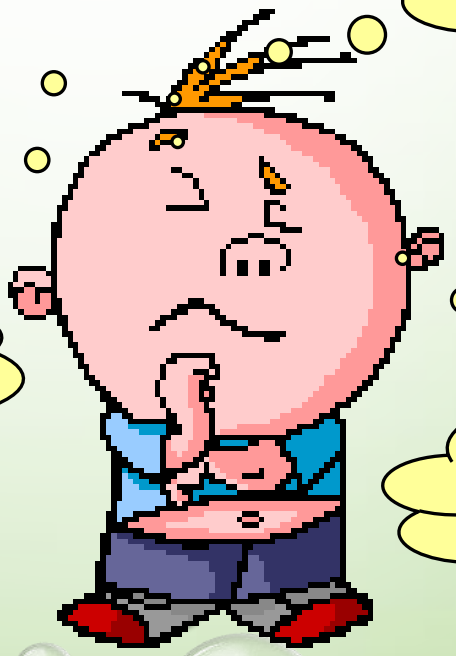
PROPERTIES AND CHARACTERISTICS

- Low thermal conductivity
  - Heat remains for a long period giving rise a number of difficulties - hot cracking/ sensitization
- Excellent resistance to corrosion at both normal and elevated temperature
- Addition of other alloying elements promote various types of properties

CLASSIFICATION

AUSTENITIC

FERRITIC



MARTENITIC

DUPLEX

AUSTENITIC STAINLESS STEEL

GENERAL CHARACTERISTICS

- Is a Cr-Ni alloy
- Contain 16-23% Cr, 4.5–14% Ni and $<$0.06 % C
- Other alloys (Mn, Si, Mo, Nb/Ti and N2)
- Addition of either Ti (321) or Nb (347) inhibit the formation of Cr carbides, thus improve corrosion resistance

GENERAL CHARACTERISTICS

- Excellent ductility and toughness
- Relative high UTS, good oxidation and corrosion resistance
- Hardened by cold work or by solid solution
- Non-magnetic and FCC crystal structure

TYPICAL EXAMPLES

Type	Alloying elements	Characteristics	Applications
304 (1.4301)	18/8	Non-magnetic	Corrosion resistance vessel, table ware, furniture, handrail, medical apparatus
304L (1.4307)	Same as 304 but lower carbon content	increase corrosion resistance, Less mechanical properties Good weldability	Knife, Spring, Valve

TYPICAL EXAMPLES

Type	Alloying elements	Characteristics	Applications
316 (1.4401)	Mo	Higher corrosion resistance Higher resistance on chloride corrosion	Food industry, Surgical apparatus, Chemical industry facilities and accessories when environment are corrosion-sea front
316L (1.4404)	Same as 316 but lower carbon content	Increase corrosion resistance,	Nuclear energy industry Refrigerating apparatus

WELDABILITY

- Very weldable (All common welding processes)
- Heat input should keep low to reduce
  - Risk of distortion
  - Hot cracking and sensitization / inter-metallic precipitation (Sigma phase)
- Preheat should be avoided for increasing heat input

WELDABILITY

- Chemical composition of filler metal is usually slightly over-alloyed with respect to the parent metal
  - To optimize corrosion resistance by compensating for alloy losses
- Low heat input and avoid wide weld pools

WELDABILITY

- Reduce inter-pass temperature (150C max)
- Reduce travel speed
- The W/D ratio of the weld should be 1 to 1.5 approx
- PWHT is not usually required (excellent ductility)

CONSEQUENCES OF WELDING

- Unlikely suffer from cold cracking (high ductility and toughness)
- Susceptible to hot cracking (because of impurity elements such as S and P)

CONSEQUENCES OF WELDING

- Recommendations for avoiding hot cracking
  - Select consumables that can give ferrite content between 3FN and 15FN in weld metal
  - Ensure optimum cleanliness
  - Reduce restraint on the joint

FERRITE NUMBER (FN)

- The amount of ferrite present in steel is generally expressed in terms of its Ferrite Number (FN)

CONSEQUENCES OF WELDING

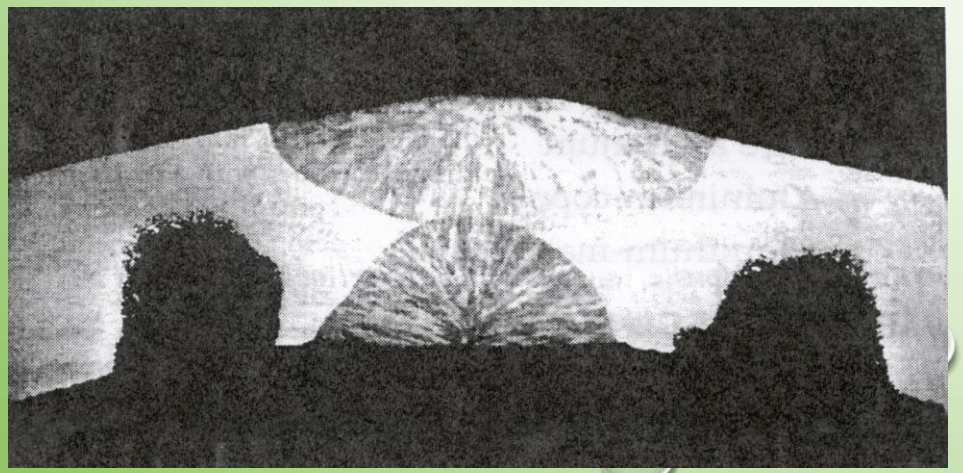
- Susceptible to hard and brittle **Inter-Metallic Precipitation (Sigma Phase)**
  - Cr + Mo > 22% in temperature (550 - 850 C) decrease corrosion resistance and impact strength
  - Reduce impact strength and resistance to corrosion

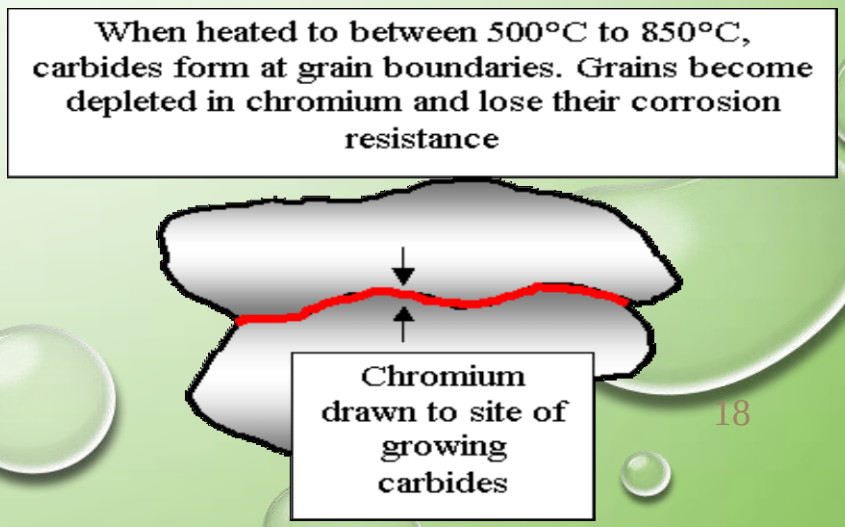
CONSEQUENCES OF WELDING

- Susceptible to **"Hot Short Crack"**
  - Can be controlled by the composition of the base and filler metal to promote the formation of a "delta ferrite" phase (by selection of filler metals with delta ferrite of 4-10%)

CONSEQUENCES OF WELDING

- Susceptible to **"Inter-granular Corrosion / Carbide Precipitation / Sensitization"**
  - prolong period at temperature 400-800C
  - Cr carbide decrease corrosion resistance





CONSEQUENCES OF WELDING

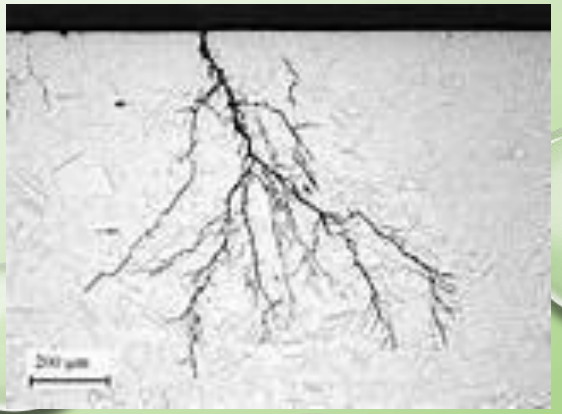
- Methods to mininize
  - Use low C content base metal and/or consumables (XLC)
  - Eliminated by using stabilized steels and consumable such as 321 (Ti) or 347 (Nb)
  - Or by reheat the structure to 1100C and quenching but promote severe distortion

CONSEQUENCES OF WELDING

- Susceptible to **"Stress Corrosion Cracking (SCC)"**
  - Occurs at the presence of certain corrosives environment (Cl, Fl) coupled with tensile stress (applied loads, residual stresses)

CONSEQUENCES OF WELDING

- Susceptible to **"Stress Corrosion Cracking (SCC)"**
  - Minimize the residual stresses in fabrication may decrease the susceptible to the cracking



WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No (BS EN 10088-2)	1st Choice	2nd Choice	3rd Choice
201		308/308L	316L	347
202	1.4371	308/308L	316L	347
205		308/308L	316L	347
209	1.4565	308/308L	316L	347
301		308/308L	316L	347
302		308/308L	316L	347

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No. (BS EN 10088-2)	1st Choice	2nd Choice	3rd Choice
303	1.4305	312	309L/309Mo	308/308L
303Se		312	309L/309Mo	308/308L
304	1.4301	308/308L	316L	347
304L	1.4306	308/308L	316L	347
304H	1.4948	308H	308L	316L
304N		308/308L	316L	347

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No. (BS EN 1088-2)	1st Choice	2nd Choice	3rd Choice
304LN	1.4311	308/308L	316L	347
305	1.4303	308/308L	316L	347
308		308/308L	316L	347
309	1.4828	309/309L/ 309Mo	312	
309S	1.4833	309L/309Mo	312	

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No. (BS EN 1088-2)	1st Choice	2nd Choice	3rd Choice
310	1.4841	310		
310S	1.4845	310		
314		310	318	309L/309Mo
316	1.4401	316/316L	318	309L/309Mo
316L	1.4404	316/316L	318L	309L/309Mo
316H	1.4919	316H	316L/318	309L/309Mo

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No. (BS EN 1088-2)	1st Choice	2nd Choice	3rd Choice
316N		316/316L	318	309L/309Mo
316LN	1.4406	316/316L	318	309L/309Mo
317	1.4429	317/317L	318	316L
317L	1.4438	317L	318	316L
321	1.4541	347	318	308/308L
321H	1.4941	347	318	308/308L

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No. (BS EN 10088-2)	1st Choice	2nd Choice	3rd Choice
347	1.4550	347	318	308/308L
347H		347	318	308/308L
348		347	318	308/308L
384		309L/309Mo	312	

FERRITIC

STAINLESS STEEL

GENERAL CHARACTERISTICS

- Sufficient Cr (10.5 to 30%) and low C (0.08%)
- With addition of Mo, Al, Ti/Nb inhibit the formation of austenite on heating
- Low distortion (high thermal conductivity and low thermal expansion)
- BCC crystal structure at all temperature and regarded as ferromagnetic

GENERAL CHARACTERISTICS

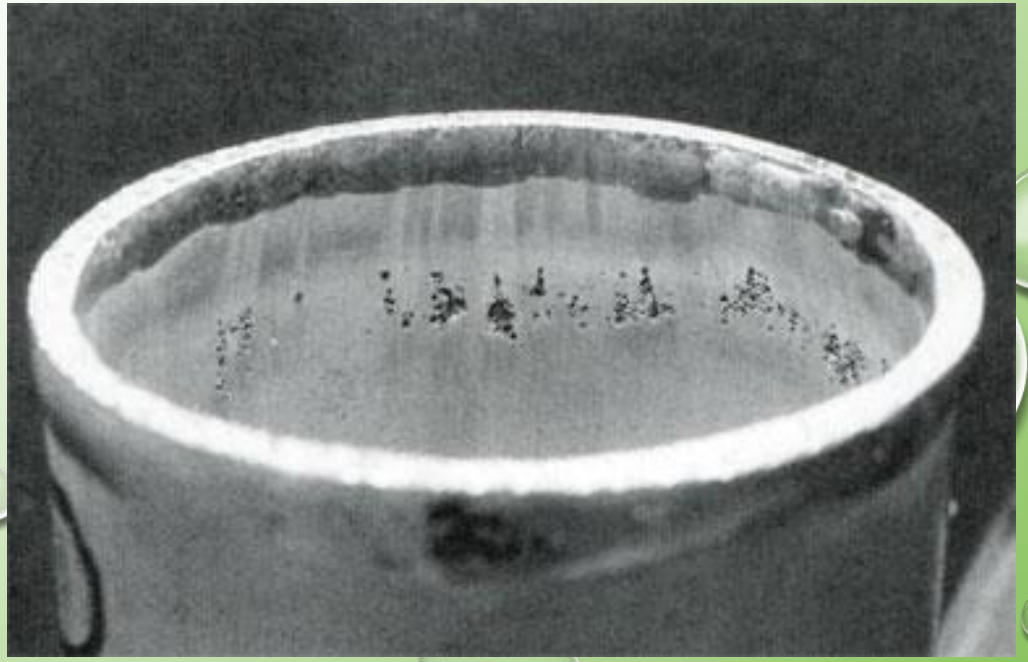
- Decrease corrosion resistance and impact strength due to Sigma phase
- With Cr in the low range and without nickel demonstrates a weaker passive film in many chemical agents
- For less aggressive conditions their corrosion resistance may be sufficient

GENERAL CHARACTERISTICS

- Hardness achieved by cold work only, not by heat treatment
- Good resistance to stress-corrosion cracking (SCC) at high temperature
- Good resistance to Pitting and Crevice Corrosion in chloride environment

CREVICE CORROSION

- Under certain specific conditions, particularly chlorides (NaCl in sea water) and exacerbated by elevated temperature small pits can form in the surface of the steel



CREVICE CORROSION

- Examples : corners, overlapping metal surfaces, non-metallic gaskets or incomplete weld penetration

TYPICAL EXAMPLES

Type	Alloying elements	Characteristics	Applications
409 (1.4514)	Ti	Good weldability	Automobile exhaust pipe
430 (1.4016)	16-18% Cr, low C	Easy forming and Poor corrosion resistance	General decoration, table ware, furniture accessories
434 (1.4512)	Mo	High corrosion resistance than 430	Table ware, windscreen-wiper

WELDABILITY

- Can be welded by MMA, MIG/MAG, TIG and PAW
- Heat input should be kept low (small weld pool and great travel speed)
  - lower the susceptible of excessive grain growth
  - Minimize the width of coarse grain zone

WELDABILITY

- C and N2 pick up during welding should be kept low (by using short arc length and clean weld area)
- Use of austenitic filler metal to produce a tougher weld metal, but ferrite type may be used in case of
  - Similar thermal expansion
  - Similar surface colour of welds, or
  - Nickel-free weld

CONSEQUENCES OF WELDING

- Susceptible to inter-granular corrosion (Cr carbide) reduce the ductility and resistance to corrosion
- Poor toughness in HAZ
  - Severe grain growth (coarse grain HAZ) when heated above 927C
  - Induce cracking (highly restrained joints and thick section)

CONSEQUENCES OF WELDING

- Low heat input (minimize the width of the coarsened grain zone)
- Use austenitic filler metal to produce a tougher weld metal
- Preheat (50 to 250C) used to reduce the cooling rate and the residue stress

CONSEQUENCES OF WELDING

- Susceptible to cold cracking due to low toughness
- Susceptible to hydrogen induced cracking
  - Hydrogen content should be kept as low as possible by cleaning, preheat, etc.
- Susceptible to **"Inter-granular Corrosion / Carbide Precipitation / Sensitization"**

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No (BSEN 10088-2)	1st Choice	2nd Choice	3rd Choice
405	1.4002	430	309L/309mo	308
409	1.4512	309L/309Mo	312	
429	1.4001	430	308/308L	309L/309Mo
430	1.4016	430	308/308L	309L/309Mo
430F	1.4104	430	308/308L	309L/309Mo

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No (BSEN 10088-2)	1st Choice	2nd Choice	3rd Choice
430F Se		430	308/308L	309L/309Mo
434	1.4113	430	308/308L	309L/309Mo
436		430	308/308L	309L/309Mo
442		316L	318	309L/309Mo
444	1.4521	316L	318	309L/309Mo
446		309L/309Mo	316L	308L

MARTENSITIC STAINLESS STEEL

GENERAL CHARACTERISTICS

- Contain 13-17% Cr, with up to 4% Ni and 1 % C
- Adding of Mo, V, Nb and W improve elevated temperature properties
- Transformation from austenite to martensite during cooling produce a very hard and brittle structure at room temperature

GENERAL CHARACTERISTICS

- Less resistance to corrosion than some other grade of SS (due to low Cr)
- Satisfactory for both cold and hot working
- Ferromagnetic in all condition

TYPICAL EXAMPLES

Type	Alloying elements	Characteristics	Applications
410 (1.4006)		Magnetic, good resistance to abrasion less resistance to corrosion	Bearing, Medical apparatus, Cutting tools
420 (1.4021)			Knife, Spring, Valve
440 (1.4118)		Highest hardness	Razor / Shaver

WELDABILITY

- Difficult to weld successfully (formation martensite in HAZ induces cracking)
- Can be welded providing precautions are taken to prevent cracking in thick section and highly restrained joint
- Adequate control over pre-heat, inter-pass temperature and heat input are essential
- Excessively low heat input should be avoided

CONSEQUENCES OF WELDING

- Susceptibility of Cold cracking
  - Hydrogen level
  - Stress
  - Cooling rate
  - Chemical composition (Cracking sensitivity increases with C content increase)

CONSEQUENCES OF WELDING

- Preheat avoid cold cracking
- Use austenitic filler metals significantly reduces the hydrogen cracking (higher hydrogen solubility of the austenite)
- Corrosion resistance is generally lower than that of austenitic grade
- Suffer from crevice and pitting corrosion
- Not usually used in highly corrosive environment, but are selected for wear resistance

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No (BS EN 10088-2)	1st Choice	2nd Choice	3rd Choice
403	1.4000	410	309L/309Mo	310
410	1.4006	410	309L/309Mo	310
414		410	309L/309Mo	310
415	1.4313	410	309L/309Mo	310
416	1.4521	410	309L/309Mo	310
416Se		410	309L/309Mo	310

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No (BS EN 10088-2)	1st Choice	2nd Choice	3rd Choice
420		410	309L/309Mo	310
431	1.4057	430	308/308 L	309
440A		312	309L/309Mo	
440B		312	309L/309Mo	
440C		312	309L/309Mo	

DUPLEX

STAINLESS STEEL

GENERAL CHARACTERISTICS

- Two phase structure (austenite and ferrite)
- 50/50 proportion provide optimum corrosion resistance, particularly resistance to SCC in a chloride environment
- Contain 21-28% Cr, 3.5-8% Ni, 0.1-4.5% Mo and 0.05-0.35% N2

GENERAL CHARACTERISTICS

- N2 is a strong austenite former, balancing, improve superior corrosion resistance and weldability
- Loss of nitrogen leads to high ferrite and reduce corrosion resistance
- Nitrogen can be added through shielding gas but not by filler metal

TYPICAL EXAMPLES

Type	Alloying elements	Characteristics	Applications
2304 (1.4362), 2205 (1.4462)		Low or medium Mo minimize suffer from stress corrosion cracking	Chemical, petrochemical and off-shore applications
Super duplex grade : 2507 (1.4410)	Higher Cr, Mo and N2		Severe corrosive environments

WELDABILITY

- All common arc welding processes
- Too fast cooling and low heat input should be avoided
- Heat input should be range from 0.2 to 2.5 kJ/mm (depend on the type)

WELDABILITY

- During welding, fast cooling is most likely, filler metals usually contain up to 2-4 % extra nickel to be used for promoting austenite in the weld metal
- Never be welded without filler metal as this will promote excessive ferrite unless solution annealing is carried out after welding
- Preheat is not required but can be used to a max. of 100C for removing moisture

WELDABILITY

- A wider angle and root opening than austenitic grades for V-joints for getting good penetration
- Recommended shielding gases
  - For TIG and PAW - Ar, Ar-He, or Ar up to 3% N2
  - For MAG - Ar up to 2.5 % CO2, Ar-He-O2 mixture, or gases with addition of up to 3% N2

CONSEQUENCES OF WELDING

- With increased contents of Cr and Mo result in higher susceptible to precipitation of intermetallic phases
- Low sensitivity to hot cracking
- Susceptible to Delay Cracking (high ferrite and hydrogen level combined with high degree constraint)

CONSEQUENCES OF WELDING

- Strength of weld metal always exceeds the min strength of the base metal
- Generally used for good pitting and stress corrosion cracking resistance
- Distortion is lower than that of austenitic grades
- More prone to the formation of porosity than austenitic grades due to high nitrogen content
- PWHT is normally not necessary

WELDING CONSUMABLE SELECTION GUIDE

Steel Grade		Welding Consumable Type		
AISI	Euro-norm No. (BS EN 10088-2)	1st Choice	2nd Choice	3rd Choice
329	1.4460	329		
2RE60	1.4841	2209		
2205	1.4462	2209		
2304	1.4362	2209		
2507	1.4410	2507		
Zeron 100	1.4501	2507		

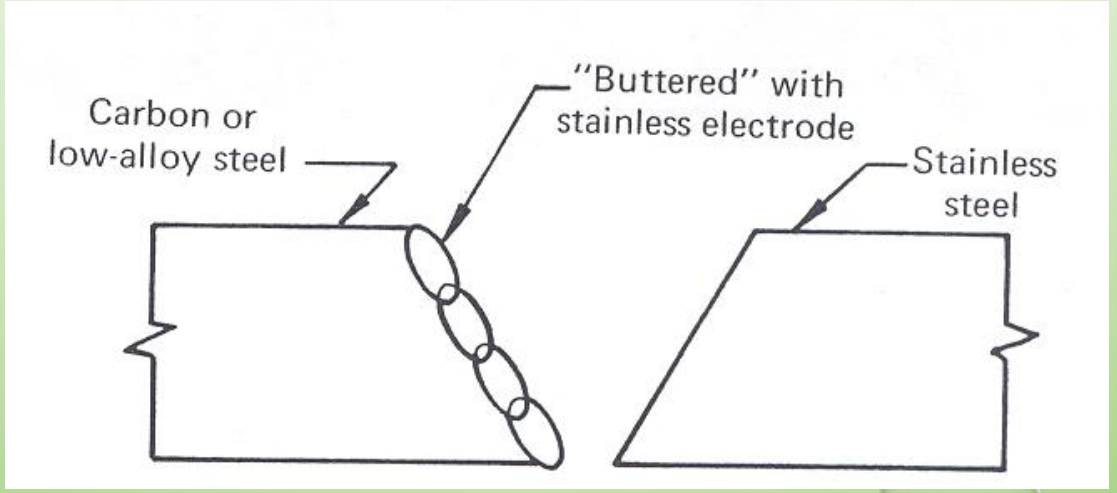
STAINLESS STEELS

TO

OTHER STEELS

JOINING STAINLESS AND OTHER STEELS

- In case of stainless steel join to mild steel
- For example, grade 304 joined to mild steel
- Mild steel is "buttered" with stainless steel "E309" and then filled by suitable grade



EQUIVALENT TYPE OF FILLER METAL FOR WELDING OF STAINLESS STEEL

Steel	304	304L	316	316L	2205	Mild Steel
304	E308	E308L	E308, E316	E308. E316L	E2205	E309
304L		E308L	E308, E316	E308L. E316L	E2205	E309
316			E316	E316L	E2205	E309
316L				E316L	E2205	E309
2205					E2205	E2209

EFFECT OF

ALLOYING ELEMENTS

EFFECTS OF ALLOYING ELEMENTS

C	• Austenite former • Form Cr carbide that lead to inter-granular corrosion
Cr	• Ferrite former • Increase oxidation & corrosion resistance
Ni	• Austenite former • Increase high-temperature strength, corrosion resistance and ductility

EFFECTS OF ALLOYING ELEMENTS

Mo	• Ferrite former • Improve strength at high temperature • Improve corrosion resistance
Mn	• Promote the stability of austenite • Form ferrite at high temperature • Inhibit hot shortness by forming of manganese sulfide
Ti and Nb	• Ferrite former • Reduce susceptibility to inter-granular corrosion • Grain refiner

EFFECTS OF ALLOYING ELEMENTS

N	• Very strong austenite former • Increase strength (at cryogenic temp) • Increase resistance to pitting corrosion

RELEVANT STANDARDS /CODES

STANDARDS / CODES RELATED TO TESTING

Standards	Title
BS EN 10002-1	Tensile test at ambient temperature
BS EN 895	Weld transverse tensile test
BS EN 910	Weld bend test
BS EN 1321	Marco-examinations and micro-examination of welds
BS EN 876	Weld longitudinal tensile test
BS EN 9016	Charpy impact test

STANDARDS / CODES RELATED TO TESTING

Standards	Title
BS EN 970	Visual inspection
BS EN 571-1	Penetrant test
BS EN 1714	Ultrasonic test
BS EN 1435	Radiographic test

STANDARDS RELATED TO WELDING PROCEDURES

Standards	Title
BS EN 1011-3	Welding – recommendations fro welding of metallic material, Part 3 : Arc welding of stainless steels
BS EN ISO 15614-1	Specification and qualification of welding procedures for metallic material – welding procedures test Part 1 : arc and gas welding of steels and arc welding of nickel and nickel alloys

STANDARDS RELATED TO WELDING PROCEDURES

Standards	Title
AWS D1.6	Structural welding code – stainless steels
AWS D10.4	Recommended practices for welding austenitic chromium-nickel stainless piping and tubing

STANDARDS RELATED TO WELDER QUALIFICATION

Standards	Title
BS 4871	Approval testing of welders working to approved welding procedures Part 3 : arc welding of tube to tube-plate joints in metallic materials
BS 4872-1	Approval testing of welders when welding procedure approval is not required Part 1 : fusion welding of steel
BS EN 287-1	Qualification test of welders – fusion welding Part 1 : Steel

THE END