Welding of Austenitic & Duplex Stainless Steels - Overview

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Outokumpu
International Stainless Steel Company

Cloud gate in Millennium Park Chicago, USA

- Outokumpu Group employs some 8000 people in more than 30 countries
  - Main production sites: Sheffield UK, Finland, Sweden, USA
- The Group’s sales of EUR 4.23 billion in 2010
- Manufacture / supply stainless plate, sheet, strip, bar, tube
- Sheffield service centre serving wide-ranging UK customer base

Welding of Stainless Steels

- Stainless Steel Families / Grades
- Brief overview of use of stainless in the nuclear industry
- Welding of austenitic and duplex grades

Stainless Steels

Widely used in nuclear industry

Nuclear Power Plants

Nuclear Waste processing & storage

Steel with addition of minimum 10.5% Chromium,

Corrosion resistance

Heat / Creep resistance

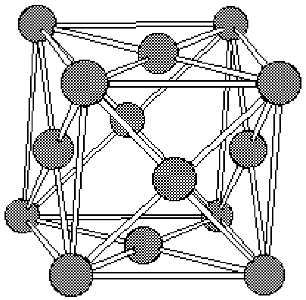
Common Elements in Stainless Steels

Element	Symbol	What improvement it can give to stainless steel
Chromium	Cr	Corrosion resistance
Nickel	Ni	Ductility, toughness, weldability
Molybdenum	Mo	Corrosion resistance
Nitrogen	N	Strength, corrosion resistance
Titanium	Ti	Corrosion resistance near to welds
Sulphur	S	Machine-ability
Carbon	C	Lower carbon gives better corrosion resistance near welds
Manganese	Mn	Alternative to nickel for ductility, toughness, weldability
Silicon	Si	Improved high temperature oxidation resistance
Iron	Fe	

Many of the metallic elements are expensive

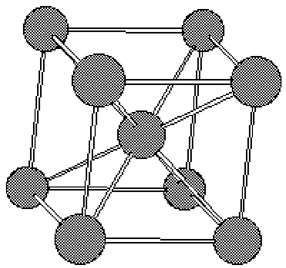
Families of Stainless Steel

Austenitic
(eg 304 = “18/8”
& 316)



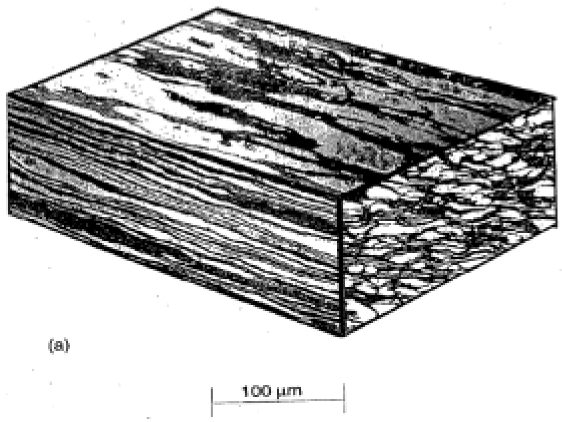
Face Centred Cubic

Ferritic
(eg 430 = “18/0”)



Body Centred Cubic

Duplex
(eg 2205, LDX2101)



Stainless Steel Grades

	Common Name	European Name, EN..	Chemical Composition %, typical main elements				
			Carbon	Nitrogen	Chromium	Nickel	Molybdenum
Austenitic	304L	1.4307	0.02	-	18	8	-
	316L	1.4407	0.02	-	17	10	2
	254SMO	1.4547	0.01	0.2	20	18	6
Duplex	LDX2101	1.4162	0.03	0.22	21	1.5	-
	2205	1.4462	0.02	0.17	22	5.7	3.1
Heat Resistant (austenitic)	310S	1.4845	0.05	-	25	20	-

Nuclear Industry sometimes requires modified standard compositions,
Eg: Low Cobalt; Low Phosphorus; High Boron

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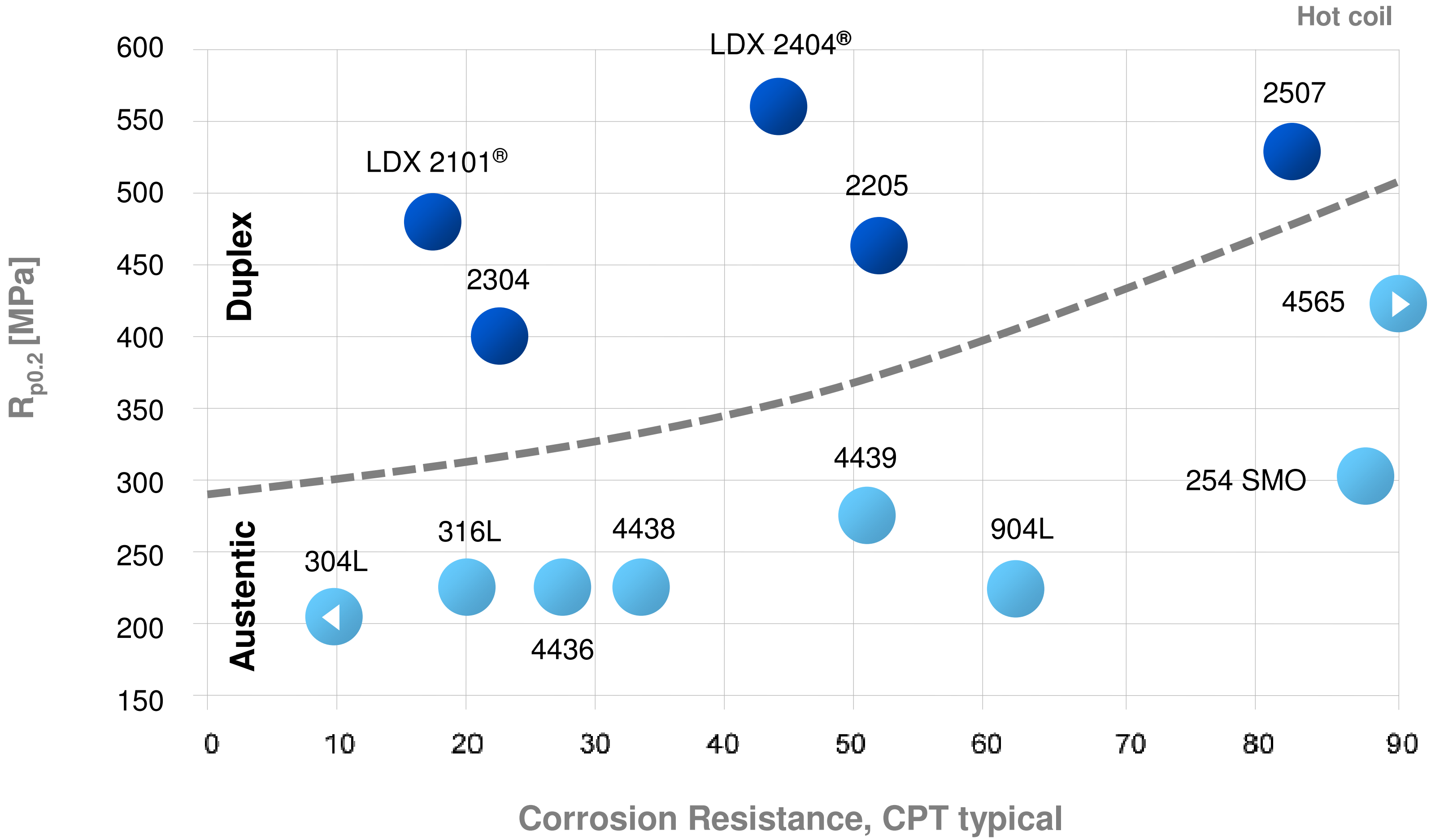
Positioning of Duplex grades

An excellent combination of high strength and corrosion resistance



Some Components using Stainless Steel

Nuclear Island	Turbine Island	Balance of Plant (BOP)
Primary containment	*Secondary support systems*	*Mechanical Equipment*
- Pool liners	- Heating & ventilation systems	- Safety-Related Piping
- Mechanical modules	- Fire Protection systems	- Cooling Water Piping & Handling
Primary support systems	*Secondary Steam Cycle*	- Vertical Heat Exchangers
- Heating & ventilation systems	- Main Turbine	- Horizontal Heat Exchangers
- Fire Protection systems	° Reflective Metal Insulation	- Tanks
Reactor Coolant Systems	- Main Condenser	
- Reactor Internals	° Condenser Tubing / Tubesheets	
- Control Rod Drives	- Moisture Separator-Reheater	**Waste Storage**
- Tubesheets	- Feedwater Heaters	- MOX Fuel Transport baskets
- Safety Injection Accumulator Tanks	*Mechanical Equipment*	- Waste canisters
- Sodium Tanks	- Class 1, 2, 3 Piping	- Waste treatment vessels
- Primary & secondary separators	- Vertical Heat Exchangers	- Wet Fuel Storage Racks
Mechanical Equipment	- Horizontal Heat Exchangers	- Dry Storage Canister
- Class 1, 2, 3 Piping	- Tanks	
- Other Tanks		
° PRESSURIZED RELIEF TANK (X2 CR Ni 19-11)		
° VOLUME CONTROL TANK (304L)		
° REACTOR COOLANT DRAIN TANK (X2 CR Ni Mo 17-12)		

Application example
Plates for Accumulator tanks

- Reactor type: PWR
- Plant (examples):
  - QinShan Phase II, P.R. China
  - Olkiluoto 3, Finland
- Application:
  Accumulator tanks
  - Grade:
    - Z2 CN19-10 Az (QC2)
    - 304L NG
  - C ≤0.035%; Co ≤ 0.06%

Olkiluoto 3, Construction site

Accumulator tank, CPR/EPR

Application example
Plates for steam separators

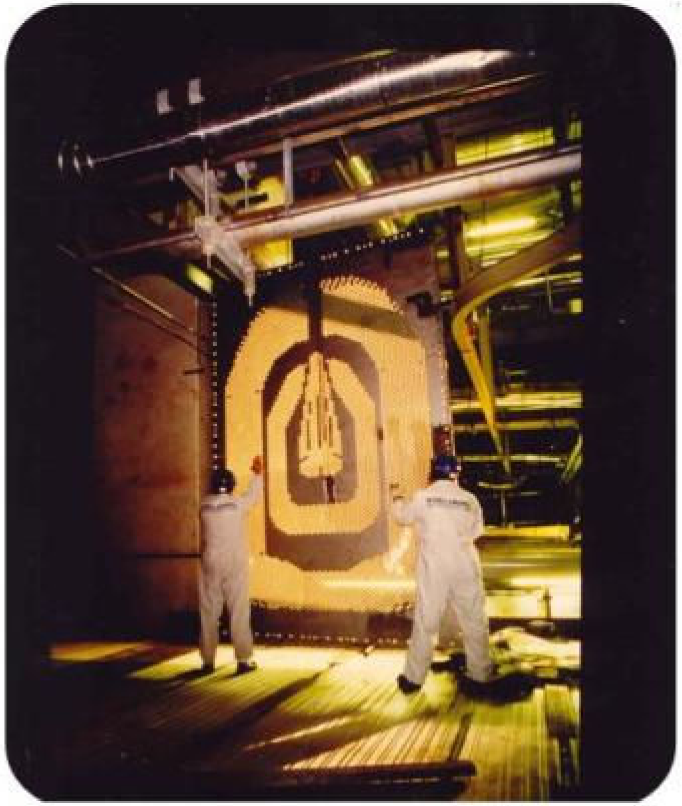
- Reactor type: BWR reactor
- Equipment:
  - Original steam separators
  - Replacement steam separators
- Steel grade: 316L/1.4435
- Basic spec: ASME/EN
- Thick plates: 35 – 85 mm
- Special requirements:
  - Low Co
  - Ultrasonic testing
  - Grain size control
  - Special surface treatment procedure

Steam separator, Oskarshamn Nuclear Power Plant

Application example
254 SMO for seawater cooling condensers

- **Application**:
  - Condenser tube sheets
  - Condenser tubes
  - Strainers
- **Grades**
  - Seawater cooling requires high-alloyed grades.
  - Super-austenitic grades for seawater handling: eg **254 SMO**, **4529**, **4565**.

- High alloyed stainless steels can be used in combination with titanium without risk of galvanic corrosion.



One of 24 condenser tube sheets in 254 SMO installed at Ringhals nuclear power plant on the Swedish west coast .

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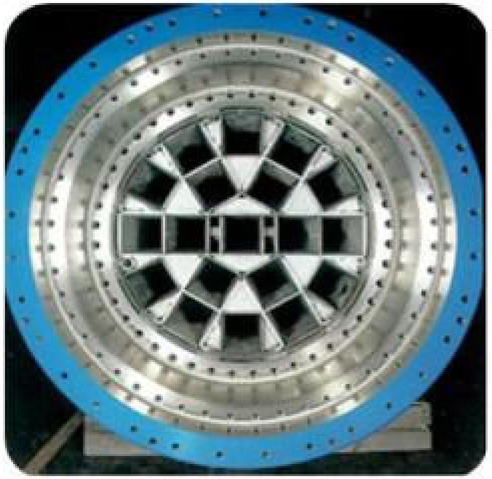
Grades for nuclear applications 2
Radionox – Boron alloyed grades

- **Applications**
  - Fuel storage and handling
  - Storage tanks/caskets, transportation baskets
- **Standards**
  - ASTM A887: Std. Spec. for borated SS plate/sheet for nuclear applications.
  - ASTM C992: Std. Spec. for Boron-Based Neutron Absorbing Materials…
  - Customer's materials specification
- **Grades**
  - Type 304 Borated
- Composition tailored to customer's needs
- Boron levels: 1.00-1.30; 1.20-1.50; 1.70-2.00%



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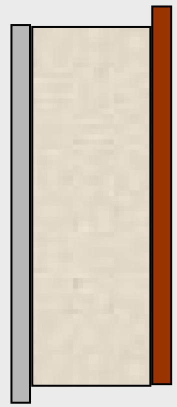
Duplex LDX 2101 in Siemens Westinghouse AP1000 nuclear reactors

- Wall & Floor sandwich panel for “Mechanical Equipment Modules”
- 150 Mechanical Modules per reactor
- LDX2101 duplex inner wall membrane (13 m x 3m plates):
  - Corrosion-resistant water tight inner layer
  - Carbon steel outer plate
  - Concrete sandwich infill



- Sanmen 1 & 2; Haiyang 1 & 2; Vogtle 3 & 4 (China, USA)

Sanmen Units 1 & 2

Nuclear Waste Storage

- Standard Grades, but high integrity fabrication
- 304L
- 316L
- 2205 Duplex

Welding of Stainless Steels

Wide range of suitable arc weld techniques

- Manual Metal Arc MMA (SMAW)
- Tungsten Inert Gas TIG (GTAW)
- Plasma Arc Welding PAW
- Metal Inert/Active Gas MIG/MAG (GMAW)
  - Pulsed MIG/MAG good for duplex steels
- Flux Cored Arc Welding FCAW
- Resistance Spot Welding RSW
- Submerged Arc Welding SAW
- Laser Beam Welding LBW

Welding of Standard Austenitic Grades

- Generally easy to weld, with
  - little risk of hydrogen cracking,
  - Some risk of hot cracking
  - but can distort
  - Coefficient of thermal expansion (x1.5 steel)
  - Low thermal conductivity (1/3 steel)
  - High electrical resistance (x5 steel)

- Practical

  Facilities: power; Resource: welder and equipment

  Process: position and access

– Quality and H&S

- Financial

– Labour and capital cost

– Duty cycle and deposition rate

Metallurgical Issues

- Hot (solidification) cracking
  - Largely controlled by consumable chemistry
  - Aim for small amount of ferrite (5-10%) in weld metal (primary ferrite solidification)
  - "Fully Austenitic" grades (eg grades 254SMO, 310/S) greater risk
  - Welding speed, cooling rate and restraint play a role
- Chromium carbide formation c.400-700℃
  - cooling through or heat treatment in critical temperature range
  - can lead to intergranular corrosion
  - more of a problem with high carbon grades, eg 310, much less of an issue when welding modern low carbon 'L' grades

Weld process design:

Standard Austenitic grades 304L, 316L

- No pre- or post- weld heat treatment usually needed
- Use suitable joint design (bevelled in thick section)
  - Butt joints preferred to overlap joints
- Can be welded autogenously, or use (over alloyed)matching-filler wire eg 308L, 316L
- Tolerant to wide range of weld heat input levels
- HI generally driven by weld pool control rather than metallurgy
- HI level relative to metal thickness/distortion

- Post weld cleaning using mechanical / chemical methods

Shielding and Backing Gas

- Primarily
  - protection of the molten pool from air, minimise oxidation

- Also
  - influence on the arc's physical properties:
    - electrical, flow dynamics,, thermal, etc..
    - determine viscosity and surface tension, droplet transfer and weld pool behaviour
  - metallurgical reactions with filler and base material
  - influences penetration and weld geometry

Austenitic Steels

- Argon - most commonly used for TIG in UK
  - Heavier than air - good shielding in PA position
  - Easy arc ignition

- • Helium
  - – Lighter than air, Higher welding voltage, hotter arc
  - – Higher depth of penetration or travel speed

Austenitic Steels

- Active components eg   for MIG

- CO2
  - Higher welding voltage, hot arc
  - Higher penetration and speed, arc stabilition

- • O2
  - Lower welding voltage cool arc
  - Arc stabilisation: smooth welds, low spatter

- Full penetration welds with smooth weld bead, minimum spatter
  - Crevices are a corrosion initiation site

Workshop Practice

- Clean working environment
  - Avoidance of carbon pick-up (oil, grease, shop dirt)
  - Avoidance of mild steel pick-up
  - Degrease/clean all surfaces to at least~50mm from joint line
  - Avoid using mild-steel contaminated tools
  - Segregation of work
  - Careful storage and handling of materials/components
    - Protect steel racking
    - Cover forks on fork trucks
  - Avoid draughts (close the doors)
  - Chloride-free marker pens for identification

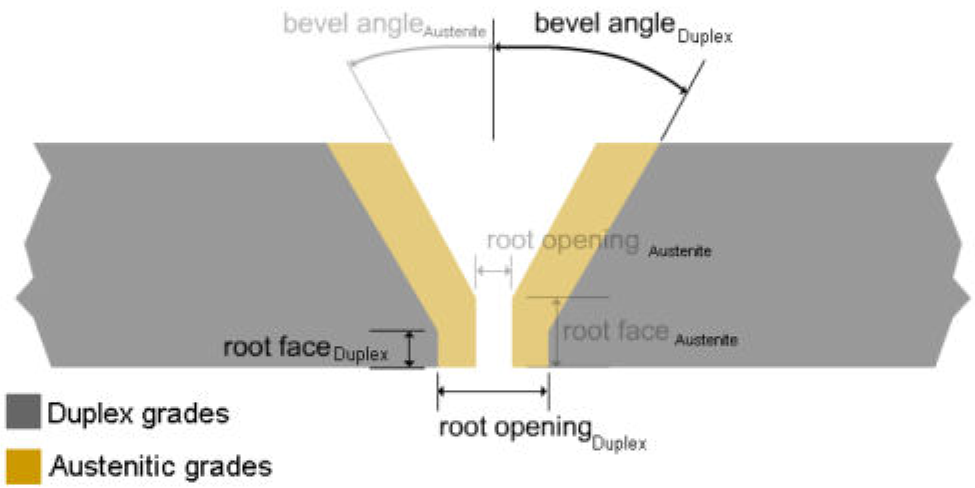
Welding of Duplex Grades

- Workshop cleanliness practices same
- Essentially same welding equipment
  - (modern pulsed MIG)
- No pre- or post weld heat treatment
  - AVOID POST WELD HEAT TREATMENT
- Post weld cleaning similar to austenitics

- Some differences in welding process detail.

Joint design – Austenitics & Duplex

- Use suitable joint configuration and bevelling
  - Reduced penetration with duplex
  - Reduced fluidity with duplex
    Wider joint preparation +10°
  - Tack weld duplex closer and longer
  - less distortion with duplex



- Avoid too thick weld beads to avoid porosity

Metallurgy of Welding Duplex Stainless Steels

More complex than austenitic steels

Need to :

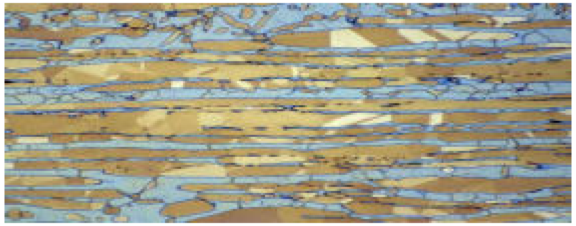
Maintain Austenite : Ferrite balance

Avoid precipitation of deleterious phases
eg Sigma phase

Potentially severely detrimental to mechanical properties, toughness and corrosion resistance

Duplex Microstructure in welding

Challenge: Maintain roughly equal amounts of ferrite and austenite



Risk with thin materials: Generate too high content of ferrite (>75%)

Controlled by two main factors

Chemical Composition of steel & welding (filler) wire

Ferrite Formers	Austenite Formers
Chromium	Nickel
Molybdenum	Manganese
Iron	Nitrogen
Silicon	Carbon

Cooling rate during welding

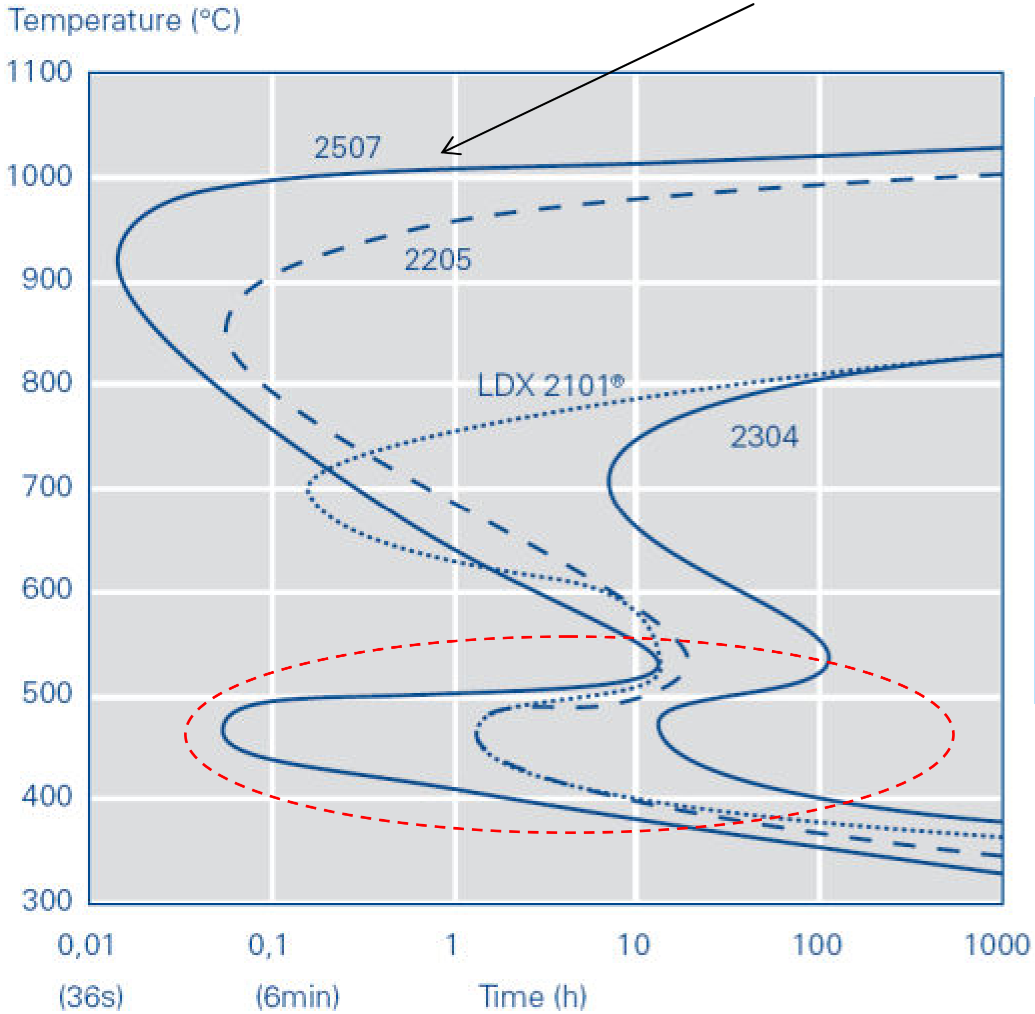
Faster cooling = higher ferrite content

Cooling rate controlled in welding by the heat input : –

welding current, voltage and speed.

Temperature

254 SMO® can also form sigma phase



Intermetallic phases at 600-900ºC

Ferrite decomposition at 350-525ºC

These temperatures should be avoided

Can reduce
- Corrosion resistance
- Toughness

Low risk at normal welding operations

Max interpass temperature 150ºC
(100 ºC for 2507 and 254 SMO®)

Curves for 50% reduction of impact toughness compared with quench annealed condition

Filler wire and Heat Input

LDX 2101

- Available filler: ISO 23 7 N L or 22 9 3 N L
- HI: 0.2-1.5 kJ/mm
- Autogenous welding possible (TIG, Laser, RSW) – rapid austenite formation
- Avoid SAW with large fusion – low Ni may reduce impact toughness

2304

- Use filler: ISO 23 7 N L or 22 9 3 N L
- HI: 0.5-2.5 kJ/mm
- Avoid rapid cooling for austenite formation (0.10% N)

2205

- Use filler: ISO 22 9 3 N L
- HI: 0.4-3.5 kJ/mm

2507

- Use filler: ISO 25 9 3 Cu N L
- HI: 0.2-1.0 (1.5) kJ/mm – risk of embrittlement and decreased corrosion

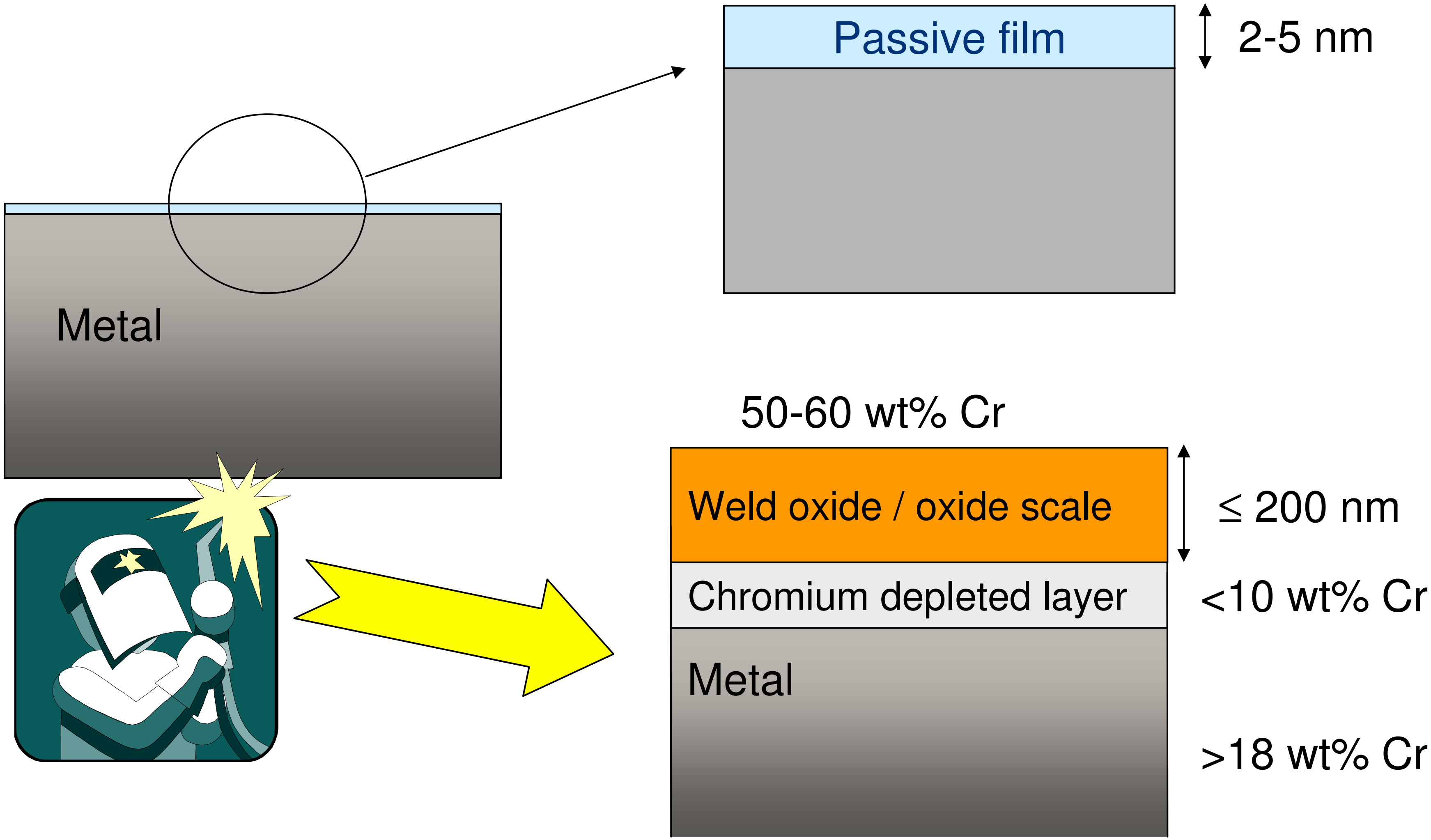
Shielding and backing gases
TIG - Duplex

- Argon
- Argon + 30% helium to improve fluidity

- TIG welds can benefit from 2 -2.5% nitrogen addition to shielding gas
  - helps maintains nitrogen level in HAZ
  - Too high nitrogen is detrimental

- Backing gas
  - argon
  - nitrogen + 5 – 10% hydrogen
  - nitrogen

Post weld cleaning of weld oxide



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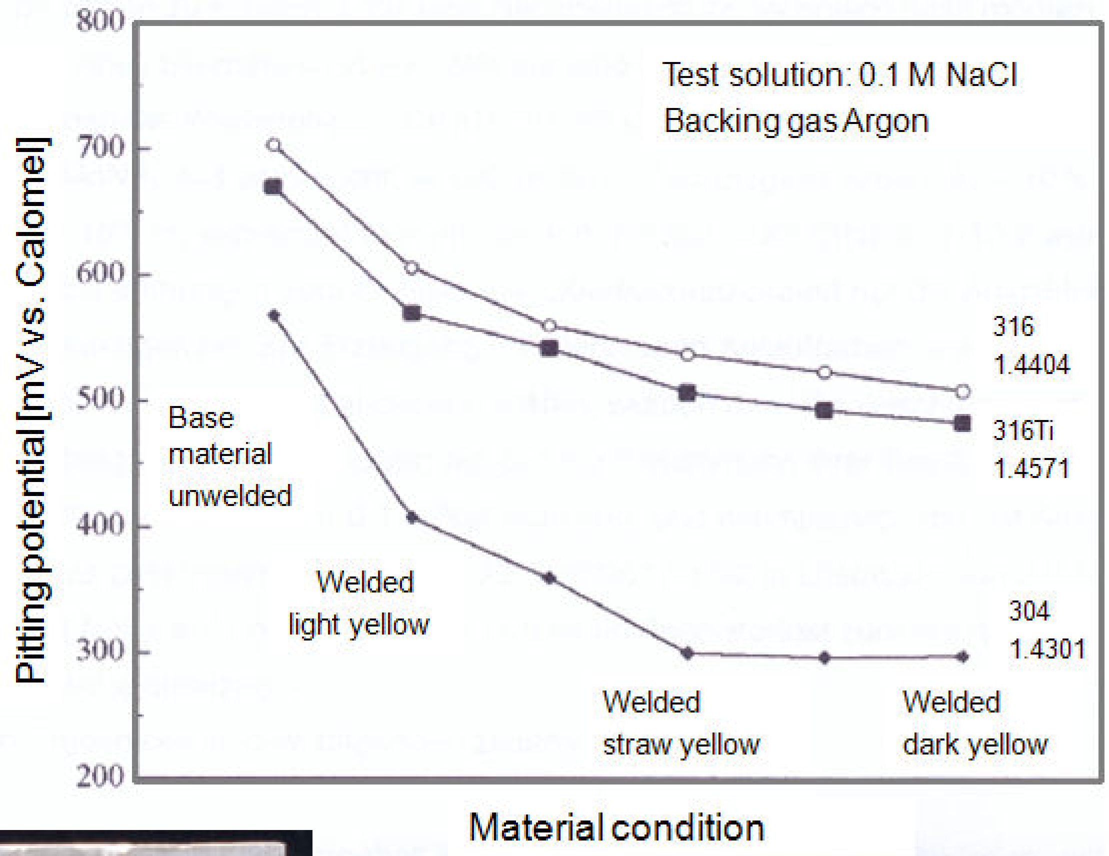
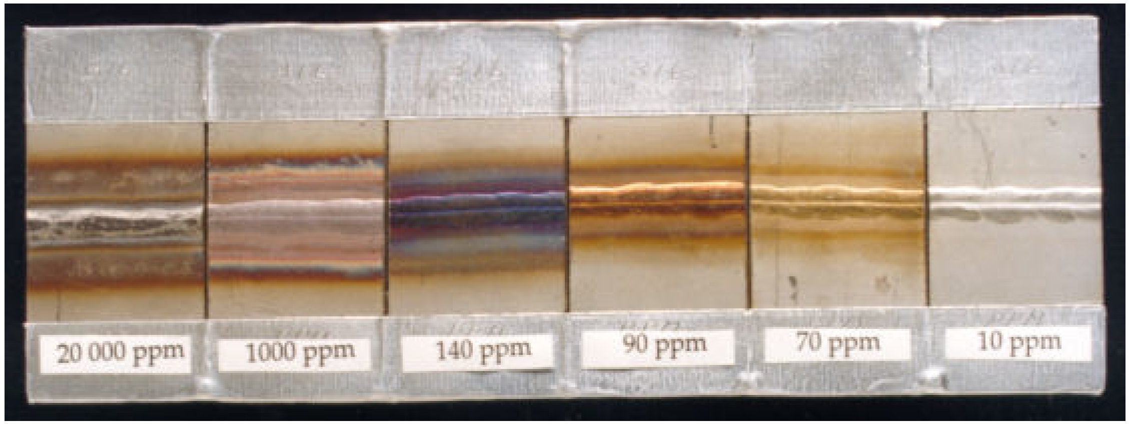
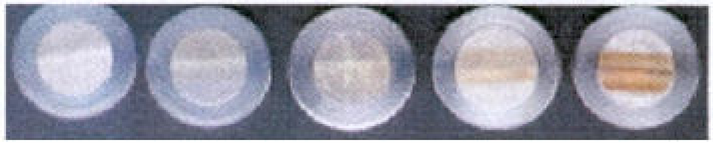
Backing gas



Holmberg and Larén (2001)





Köstermann (2001)

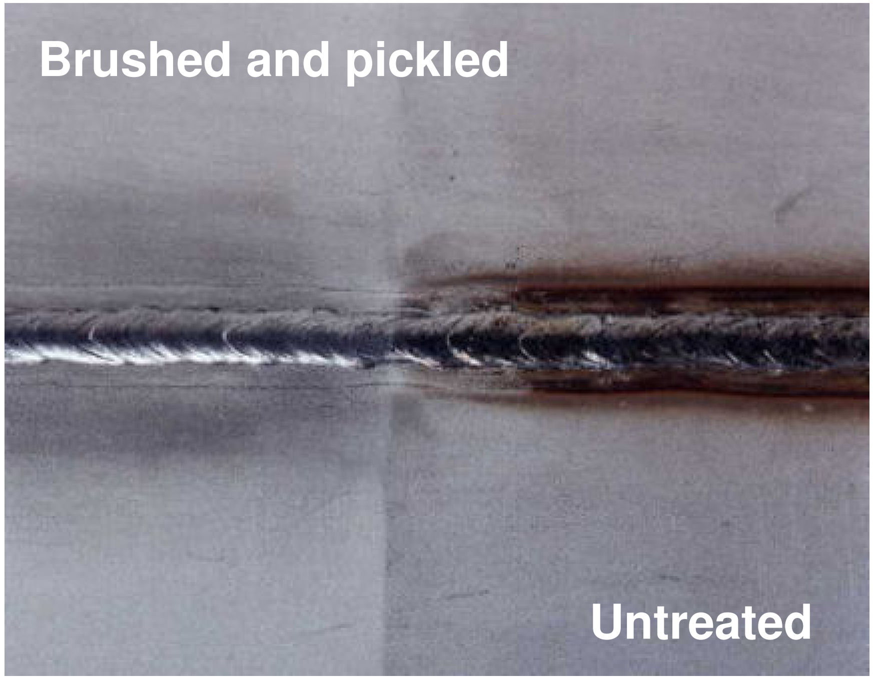
Importance of postweld cleaning

- Mechanical
  - Blasting
  - Grinding
  - Brushing
  - Polishing

Only use stainless steel tools!

Finer surface → better corrosion resistance

- Chemical cleaning
  - Pickling
- Mechanical + chemical
  - Optimal



Maintain corrosion resistance!

Summary

- Austenitic and increasingly duplex steels are often selected for nuclear applications
  - Corrosion resistance, + high strength for duplex

- Welding is a critical operation

- 304L, 316L focus is on clean workshop environment, weld pool control and post-weld cleaning

- Duplex steels have additional, metallurgical considerations in weld procedure design

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