Stainless Steels

Module 3D

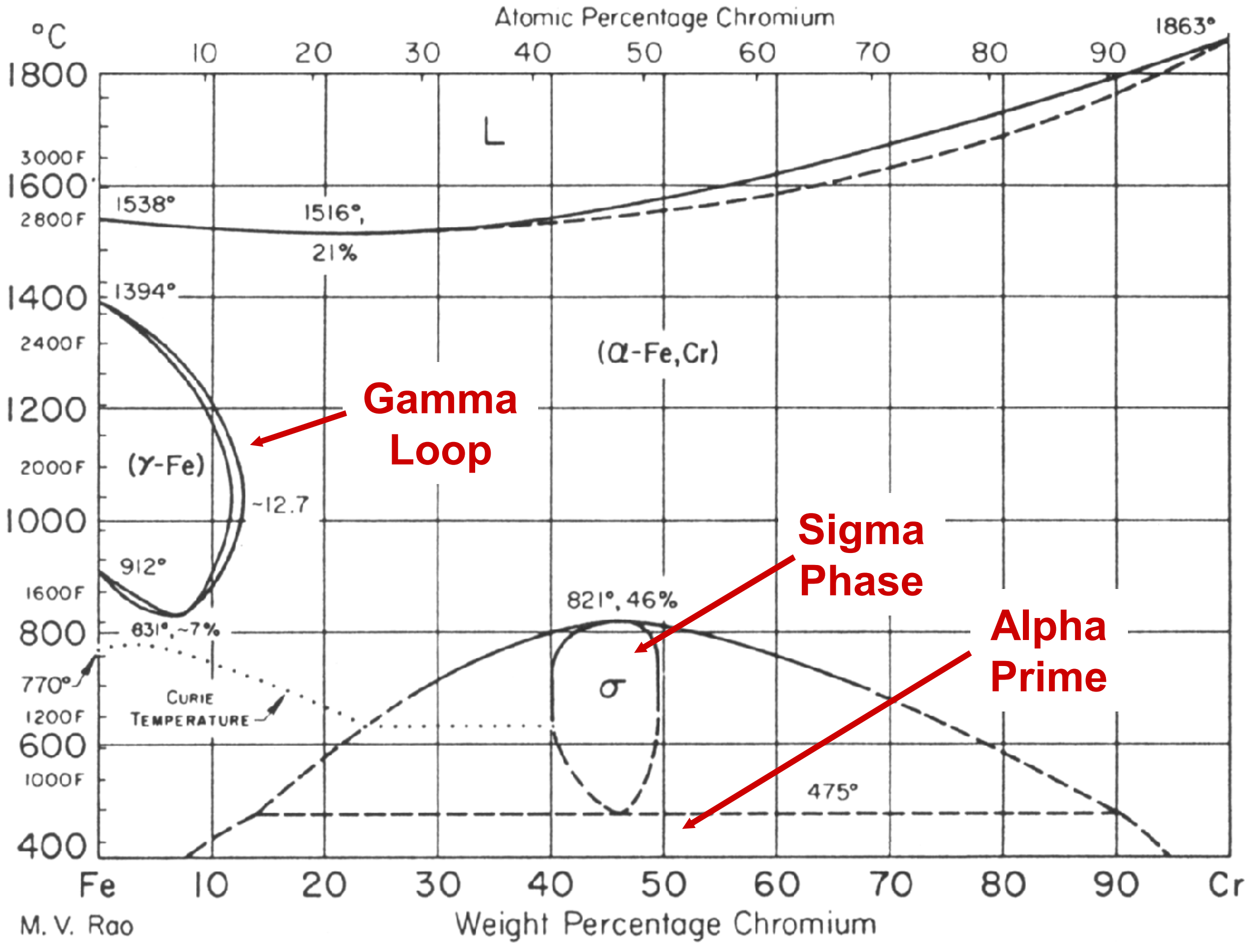
Stainless Steels

- Iron alloyed with greater than 12% chromium
- Chromium-rich oxide forms a continuous layer on the surface to prevent corrosion in ambient conditions
- Classified by their microstructure
  - Martensitic
  - Ferritic
  - Austenitic
  - Duplex (austenite + ferrite)
- Engineering properties
  - Resistance to discoloration (stainless)
  - Corrosion resistance
  - High temperature oxidation resistance
  - Wide range of strength and ductility
  - Generally good fabricability
  - Weldability

Classification of Stainless Steels

- Classified by microstructure
- Classifications
  - Martensitic (4XX)
  - Ferritic (4XX)
  - Austenitic (2XX, 3XX)
  - Duplex
  - Precipitation Hardenable (PH)

Fe-Cr Binary Phase Diagram



Gamma Loop

Sigma Phase

Alpha Prime

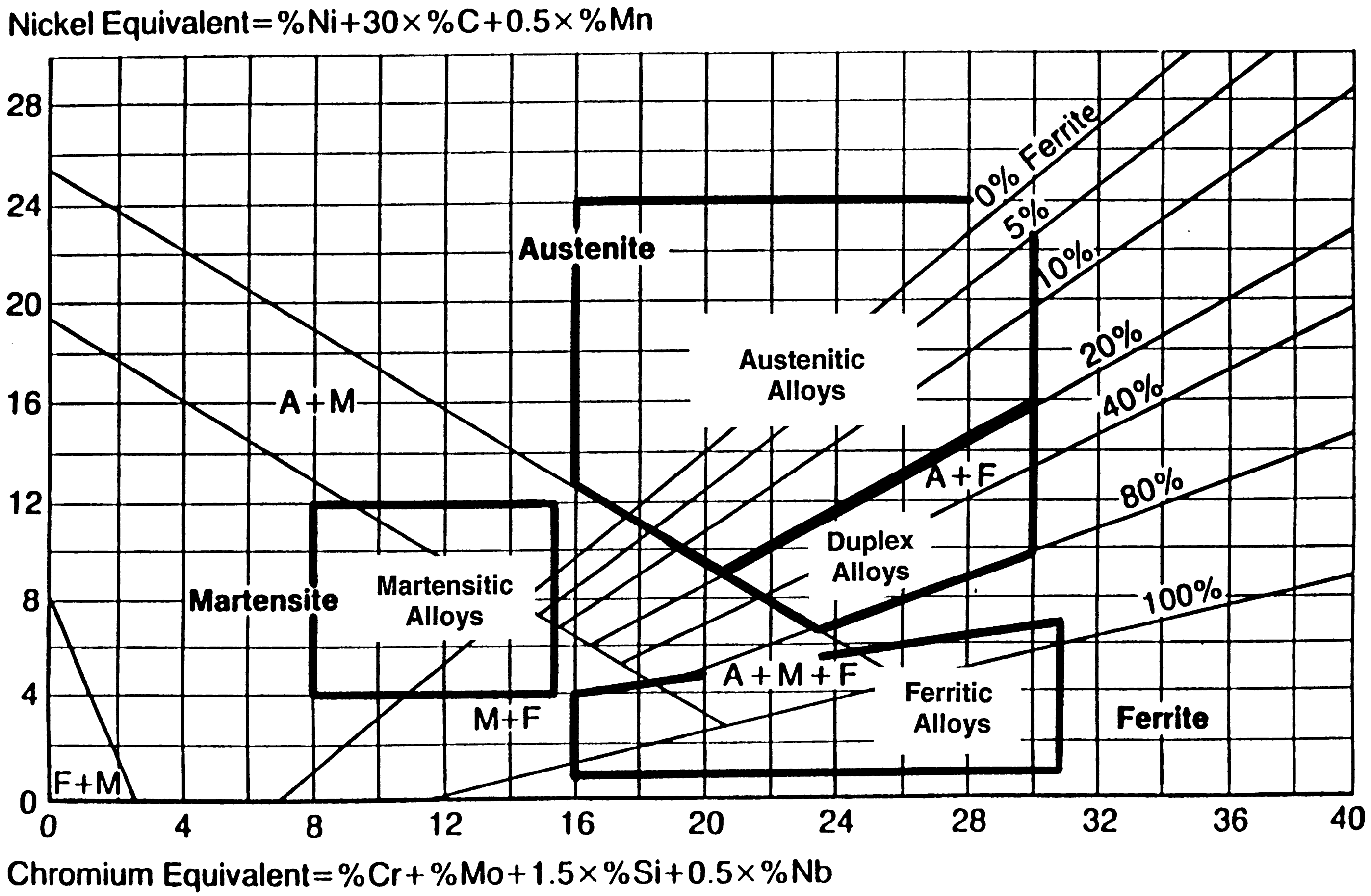
Alloying Element Effects

- Austenite formers
  - Nickel
  - Manganese
  - Carbon
  - Nitrogen
  - Copper
  - Cobalt
- Ferrite formers
  - Aluminum
  - Titanium
  - Vanadium
  - Chromium
  - Molybdenum
  - Niobium
  - Silicon

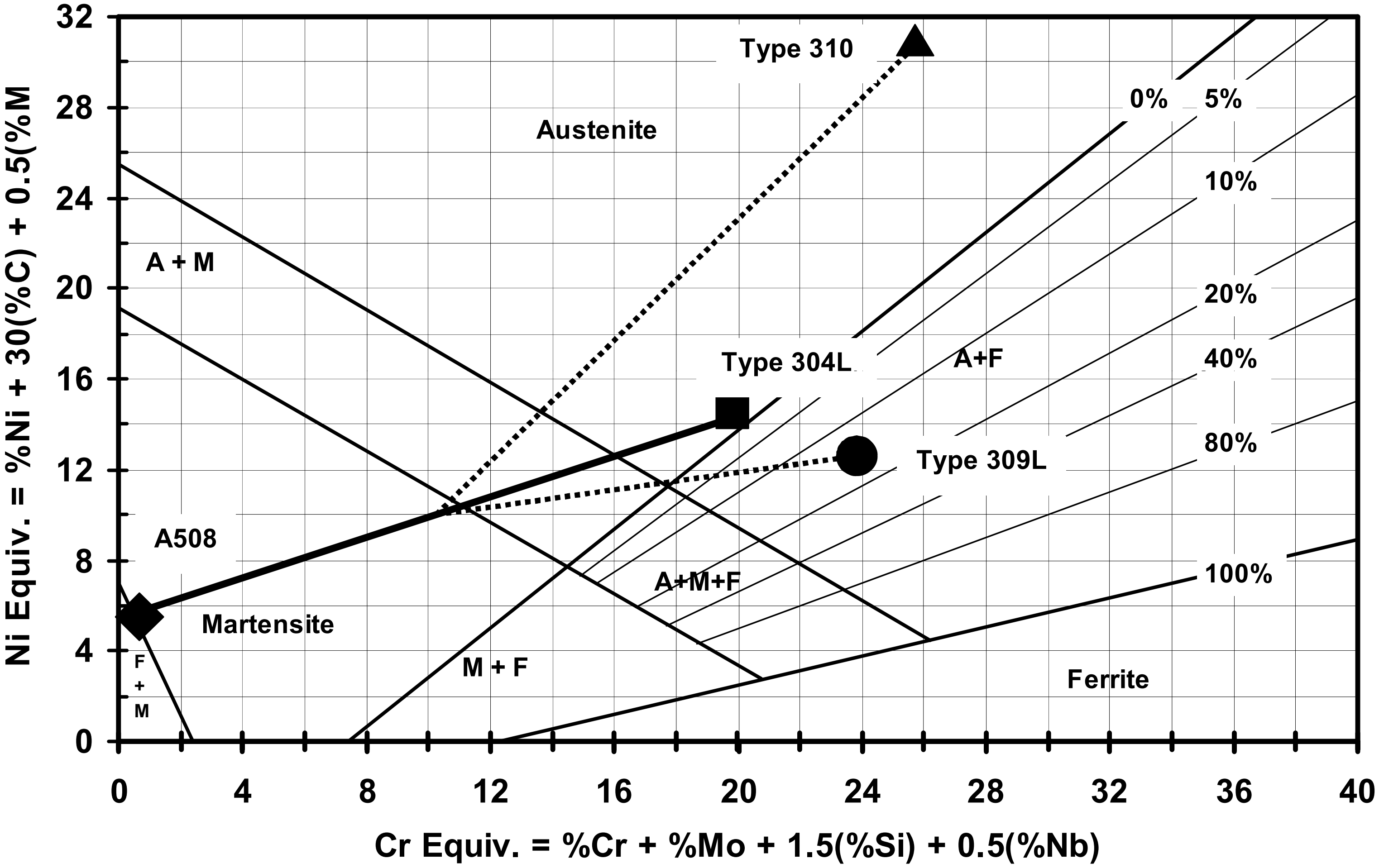
Equivalency Relationships

Source	Year	Used for	Cr-Equivalent, wt%	Ni-equivalent, wt%
Schaeffler	1949	All stainless steels	Cr + Mo + 1.5 Si + 0.5Nb	Ni + 0.5Mn + 30C
Delong *et al*	1956	Austenitics	Cr + Mo + 1.5 Si + 0.5Nb	Ni + 0.5Mn + 30C + 30N
Kaltenhauser	1971	Ferritics	Cr + 6Si + 8Ti + 4Mo + 2Al	40(C + N) + 2Mn + 4Ni
Hull	1973	Austenitics	Cr + 1.21Mo + 0.48Si +0.14Nb + 2.27V + 2.20Ti + 0.21Ta + 2.48Al	Ni + $(0.11Mn - 0.0086Mn^2)$ + 24.5C + 14.2N + 0.41Co + 0.44Cu
Hammar/Svennson	1979	Austenitics	Cr + 1.37 Mo + 1.5Si + 2Nb + 3Ti	Ni + 0.31Mn + 22C + 14.2N + Cu
WRC-1992	1992	Austenitics and duplex	Cr + Mo + 0.7Nb	Ni + 35C + 20N + 0.25Cu
Balmforth/Lippold	2000	Ferritics and martensitics	Cr + 2Mo + 10(Al + Ti)	Ni + 35C + 20N

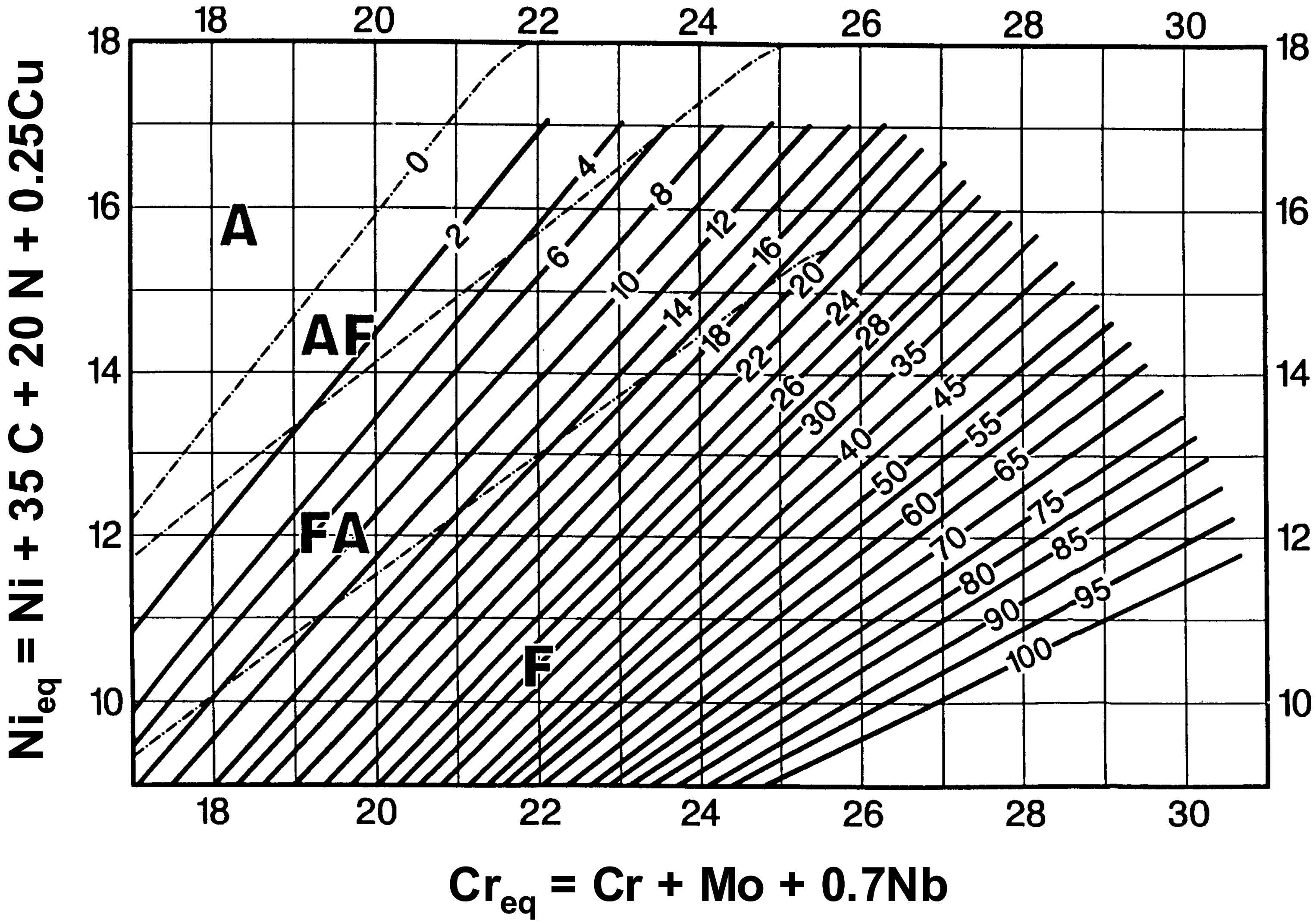
The Schaeffler Diagram



Use of the Schaeffler Diagram



WRC-1992 Diagram

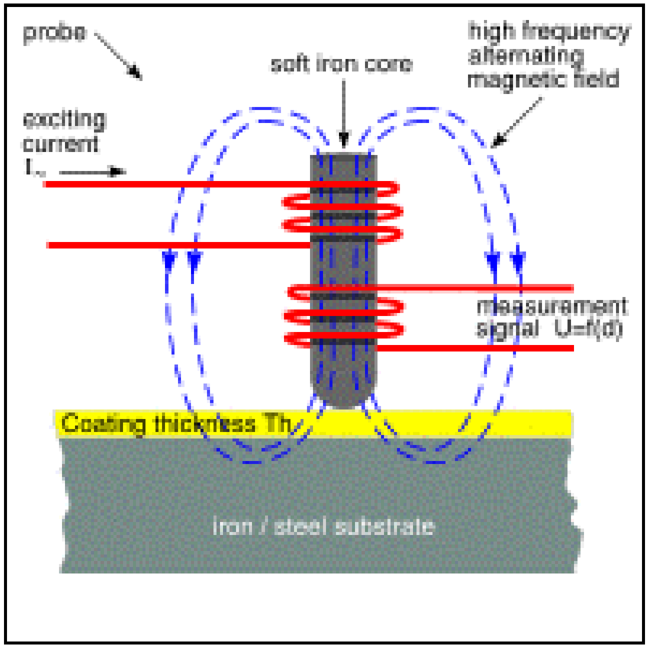


Ferrite Measurement

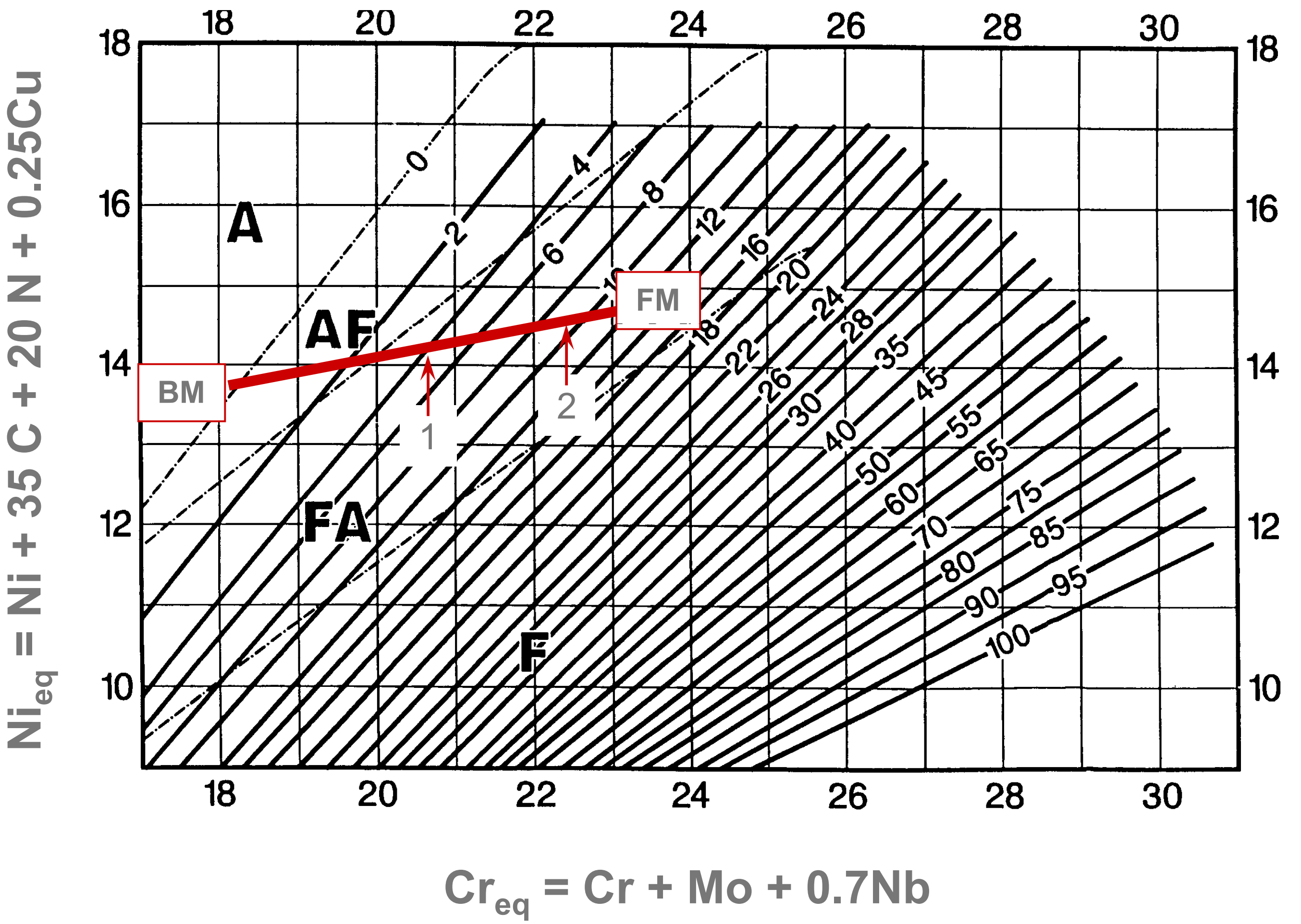
- Metallographic techniques
  - Volume percent ferrite
  - Expensive, tedious, inaccurate, generally destructive
- Magnetic instruments
  - Ferrite is ferromagnetic
  - Magnetic tearing force (MagneGage and Severn Gage)
  - FeritScope – Magnetic Inductive Method
  - Calibrated using AWS A4.2-98
  - Values in ferrite number (FN) not volume percent
  - Nondestructive

FeritScope™

- Nondestructive method for ferrite content measurement
- IIW – AWS/ANSI approved
- Magnetic inductive method

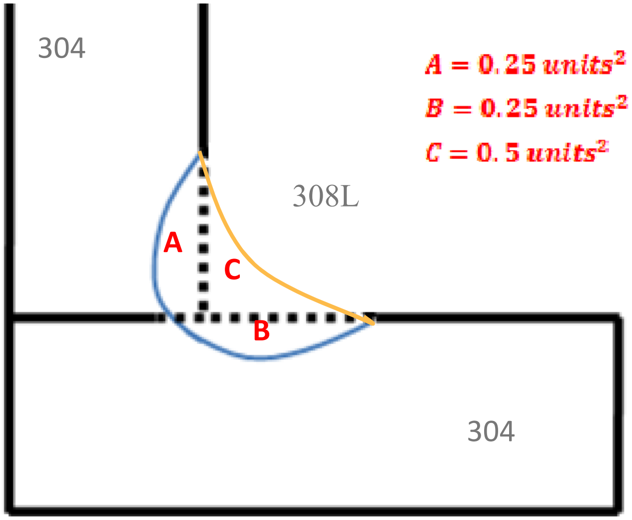


Determining FN and Solidification Mode



Determining Ferrite Number

High Dilution



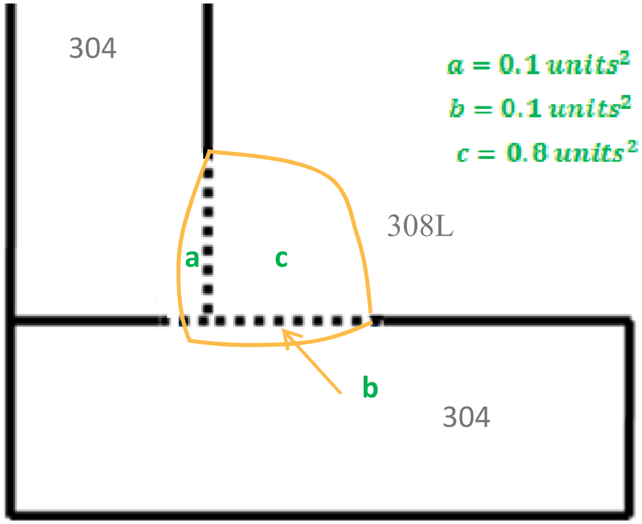
$A = 0.25\ units^2$

$B = 0.25\ units^2$

$C = 0.5\ units^2$

Figure 1

Low Dilution



$a = 0.1\ units^2$

$b = 0.1\ units^2$

$c = 0.8\ units^2$

Figure 2

$$High\ Dilution\ \% = \frac{base\ metal\ area}{weld\ metal\ (nugget\ area)} = \frac{A+B}{A+B+C}$$

$$= \frac{0.25\ units^2 + 0.25\ units^2}{0.25\ units^2 + 0.25\ units^2 + 0.5\ units^2}$$

$$= \frac{0.5\ units^2}{1\ unit^2} = 50\%$$

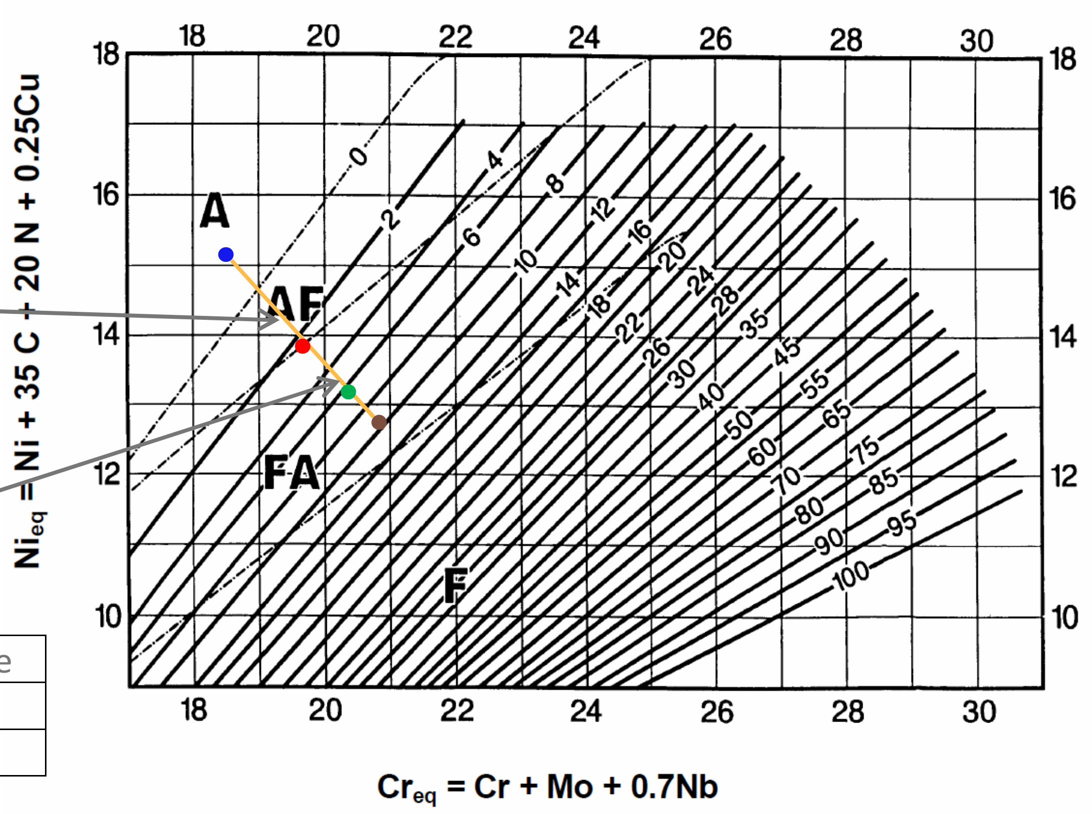
$$Low\ Dilution\ \% = \frac{base\ metal\ area}{weld\ metal\ (nugget\ area)} = \frac{a+b}{a+b+c}$$

$$= \frac{0.1\ units^2 + 0.1\ units^2}{0.1\ units^2 + 0.1\ units^2 + 0.8\ units^2}$$

$$= \frac{0.2\ units^2}{1\ unit^2} = 20\%$$

Notice the difference in dilution percentages due to the size of weld metal area (or the nugget size). Because a larger amount of filler metal is illustrated in Figure 2 than Figure 1, the percent of dilution is lowered.

Determining Ferrite Number



High Dilution (50%)
FN = 3

Low Dilution (10%)
FN = 7

Material	Cr Equivalence	Ni Equivalence
304	18.50	14.90
308L	20.75	12.80

Material	C	Mn	P	S	Si	Cr	Ni	Mo	N
304	0.06	1.5	0.03	0.01	0.6	18.5	12	-	0.04
308L	0.04	1.5	0.03	0.01	0.6	20	11	0.75	0.02

$$Cr_{eq} = \%Cr + \%Mo + 0.7 * (\%Nb)$$

$$Cr_{eq}^{304} = 18.5 + 0 + 0 = 18.5$$

$$Cr_{eq}^{308L} = 20 + 0.75 + 0 = 20.75$$

$$Ni_{eq} = \%Ni + 35 * (\%C) + 20 * (\%N) + 0.25 * (\%Cu)$$

$$Ni_{eq}^{304} = 12 + 35 * (0.06) + 20 * (0.04) + 0 = 14.90$$

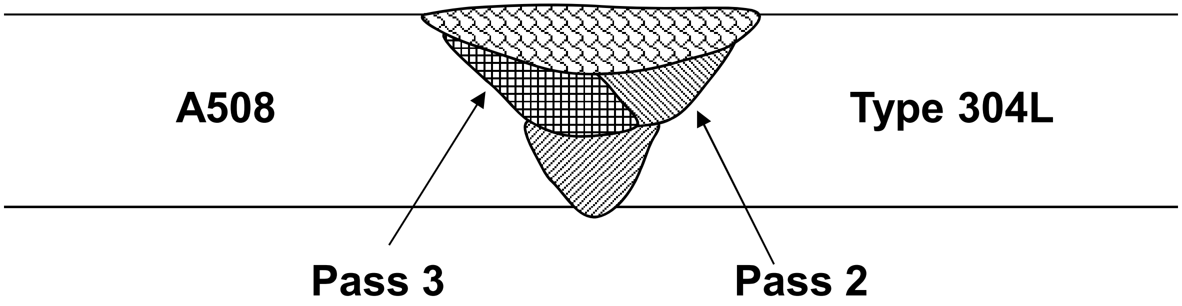
$$Ni_{eq}^{308L} = 11 + 35 * (0.04) + 20 * (0.02) = 12.80$$

Ferrite Number Determination Example

- Determine the FN of each pass in a four pass weld
    - A508 Steel to Type 304L S.S. using Type 308L filler metal
    - Schematic illustrates the weld pass sequence
    - The tables show the dilution level in each pass and the composition of the three materials

Pass #	Percent Dilution				
	A508	304L	Pass 1	Pass 2	Pass 3
1	20	20	-	-	-
2	-	15	15	-	-
3	15	-	10	15	-
4	5	5	-	15	15

Composition (wt.%)										
	Cr	Ni	Mn	Si	Mo	Nb	C	N	S	P	Cu
A508	0	0.4	1.35	0.4	0.1	0	0.3	0	0.03	0.045	0
304L	18.5	11	2	1	0	0.01	0.03	0.05	0.01	0.035	0.01
308L Filler	19.5	10.5	1.25	1	0.75	0	0.04	0.03	0.01	0.03	0.1



Ferrite Number Determination Example

- Step 1: Use WRC 1992 diagram to determine Ni_{eq} and Cr_{eq} for A508, Type 304L, and ER308L

$$Ni_{EQ} = Ni + 35C + 20N + 0.25Cu$$

$$Cr_{EQ} = Cr + Mo + 0.7Nb$$

$$Ni_{EQ}^{A508} = 0.4 + 35 \times 0.3 + 20 \times 0 + 0.25 \times 0 = 10.9$$

$$Cr_{EQ}^{A508} = 0 + 0.1 + 0.7 \times 0 = 0.1$$

$$Ni_{EQ}^{304L} = 11 + 35 \times 0.03 + 20 \times 0.05 + 0.25 \times 0.01 = 13.1$$

$$Cr_{EQ}^{304L} = 18.5 + 0 + 0.7 \times 0.01 = 18.5$$

$$Ni_{EQ}^{ER308L} = 10.5 + 35 \times 0.04 + 20 \times 0.03 + 0.25 \times 0.1 = 12.4$$

$$Cr_{EQ}^{ER308L} = 19.5 + 0.75 + 0.7 \times 0 = 20.3$$

Ferrite Number Determination Example

- Step 2: Use above Ni$_{eq}$ and Cr$_{eq}$ along with dilution% to calculate the Ni$_{eq}$ and Cr$_{eq}$ for each pass

$$Ni_{EQ}^{Pass1} = 0.2 \times Ni_{EQ}^{A508} + 0.2 \times Ni_{EQ}^{304L} + 0.6 \times Ni_{EQ}^{ER308L} = 12.2$$

$$Cr_{EQ}^{Pass1} = 0.2 \times Cr_{EQ}^{A508} + 0.2 \times Cr_{EQ}^{304L} + 0.6 \times Cr_{EQ}^{ER308L} = 15.9$$

$$Ni_{EQ}^{Pass2} = 0.15 \times Ni_{EQ}^{304L} + 0.15 \times Ni_{EQ}^{Pass1} + 0.7 \times Ni_{EQ}^{ER308L} = 12.5$$

$$Cr_{EQ}^{Pass2} = 0.15 \times Cr_{EQ}^{304L} + 0.15 \times Cr_{EQ}^{Pass1} + 0.7 \times Cr_{EQ}^{ER308L} = 19.3$$

$$Ni_{EQ}^{Pass3} = 0.15 \times Ni_{EQ}^{A508} + 0.1 \times Ni_{EQ}^{Pass1} + 0.15 \times Ni_{EQ}^{Pass2} + 0.6 \times Ni_{EQ}^{ER308L} = 12.2$$

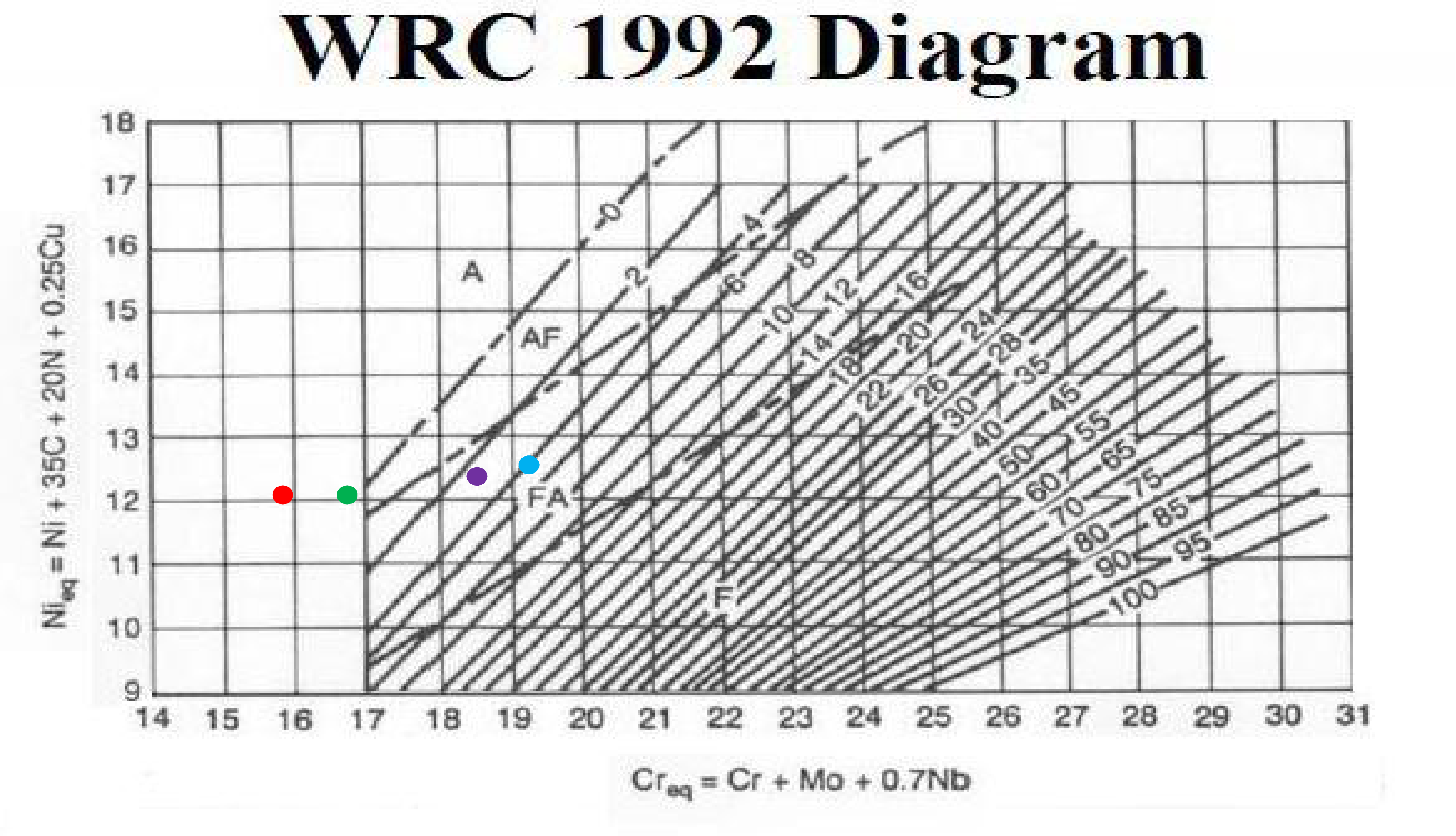
$$Cr_{EQ}^{Pass3} = 0.15 \times Cr_{EQ}^{A508} + 0.1 \times Cr_{EQ}^{Pass1} + 0.15 \times Cr_{EQ}^{Pass2} + 0.6 \times Cr_{EQ}^{ER308L} = 16.7$$

$$Ni_{EQ}^{Pass4} = 0.05 \times Ni_{EQ}^{A508} + 0.05 \times Ni_{EQ}^{304L} + 0.15 \times Ni_{EQ}^{Pass2} + 0.15 \times Ni_{EQ}^{Pass3} + 0.6 \times Ni_{EQ}^{ER308L} = 12.4$$

$$Cr_{EQ}^{Pass2} = 0.05 \times Cr_{EQ}^{A508} + 0.05 \times Cr_{EQ}^{304L} + 0.15 \times Cr_{EQ}^{Pass2} + 0.15 \times Cr_{EQ}^{Pass3} + 0.6 \times Cr_{EQ}^{ER308L} = 18.5$$

Ferrite Number Determination Example

- Step 3: Plot on Extended WRC 1992 Diagram to show FN



Alloy Constitution and Standard Alloys

- Composition Range
  - Standard alloys, 11.5 - 14 wt% Cr
  - Specialty alloys, 14 - 18 wt% Cr
  - 0.1 - 0.25 wt% C, 0.6 - 1.2 wt% C for cutlery grades
  - Mo, V, W - high temperature strength, improve corrosion resistance
  - Martensitic structure with some ferrite and carbides
- Standard Alloys

410	“workhorse alloy”
410NiMo	higher strength version of 410
416 (Se)	free machining grade
420	slightly higher Cr
422	contains Mo, V, W
440A,B,C	higher Cr, higher C

- Service temperatures - up to 1200ºF (650ºC)

Industrial Uses

- Applications
  - Power generation
    - Blades and vanes for steam and gas turbines
    - Main steam nozzles and valve seats (erosion resistance)
  - Wear and corrosion resistance
    - Rolls in pulp and paper, steel mills
    - Cutlery
- Limitations
  - Service temperature normally up to 1200°F (650°C)
  - Corrosion resistance not as good as higher Cr stainless steels
  - Poor weldability in higher carbon alloys

Steam turbine stage

Weldability Issues

- Cracking
  - Solidification cracking susceptibility generally low
  - Hydrogen-induced cracking, particularly for higher C grades (> 0.20 wt% C)
- Poor mechanical properties as welded
  - Low ductility
  - Low toughness
- Reheat cracking possible
  - Postweld aging promotes carbide precipitation along prior austenite GBs

Composition Range

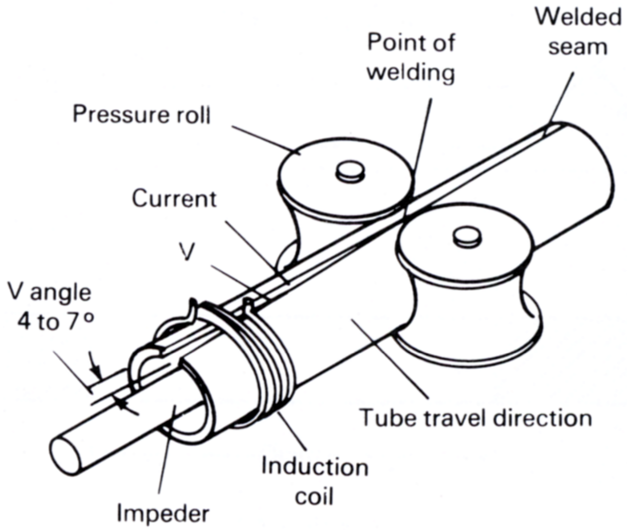
- Based on Fe-Cr system
- Composition range
  - 9-30 wt% chromium
  - 0-3 wt% nickel
  - 1 -2 wt% manganese
  - 0.3-0.6 wt% silicon
  - 0.02-0.1 wt% carbon
  - additions of Ti, Nb, Al, and Mo
- Microstructure – ferrite, martensite, and carbides

Standard Alloys

- First Generation – steels with “free’ carbon
  - 405, 11.5-14.5Cr, 0.08C max, contains Al
  - 430, 16-18Cr, 0.12C max. “workhorse” alloy
  - 442, 18-23Cr, 0.2C max
- Second Generation – steels with strong carbide formers
  - 409, 10.5-11.75Cr, 0.03-0.08C max, contains Ti and Nb
  - 436, 16-18Cr, 0.12C max, contains Mo and Nb
  - 439, 17-19Cr, 0.03C max, contains Ti
  - 468, 18-20Cr, 0.03C max, contain Ti and Nb
- Third Generation – steels with very low C and high Cr
  - 444, 17.5-19.5Cr, 0.025C max, contains Ti
  - 29-4, 28-30Cr, 0.01C max, 0.02N max, contains Mo
  - Many specialty grades – “superferritics”

Industrial Uses

- Applications
  - Dependent on chromium content
  - Automotive exhaust systems
    - 409, 439, 468
  - Automotive decorative
    - 430, 434, 439
  - Piping and vessels for Cl-containing environments
    - High-Cr alloys
  - Food handling
    - 430
- Limitations
  - Service temperature up to 420ºC (750°F)
  - Toughness and ductility limitations
  - Corrosion resistance in lower Cr alloys



High Frequency Welding

AISI 409, 439 and 468

30 – 60 m/min
(100 – 200 ft/min)

Welding Considerations

- Preheat
  - Dependent on alloy type and thickness (low and medium Cr)
  - Control residual stresses and martensite formation
  - May promote grain growth
  - When employed 150 - 260ºC (300 - 500ºF)
- PWHT
  - 730 - 845ºC (1350 - 1550ºF)
  - Tempers residual martensite
  - Dissolves carbides and nitrides
  - Reduces residual stresses
- Filler metals
  - Matching 409, 430, 439, 446, or specialty austenitic 308, 309, 310
  - Ni-based - Inconel™ , Hastelloy™ types (high Cr alloys)

Weldability Issues

- Cracking
  - Weld solidification and liquation cracking
  - Hydrogen-induced cracking
  - IGSCC in service
- High temperature embrittlement (grain growth)
- Intermediate temperature embrittlement
  - S-phase formation
  - “885°F embrittlement”
- Carbide precipitation
  - Formation of Cr-rich carbides
  - \Localized loss of corrosion resistance

Alloy Constitution and Standard Alloys

- Based on Fe-Cr-Ni system
- Composition range (wt%)
  - 16 - 25 chromium
  - 8 - 20 nickel
  - 1 -2 manganese
  - 0.5 - 3 silicon
  - 0.02 - 0.08 carbon (< 0.04 designated “L” grades)
  - 0 - 2 molybdenum
  - 0 - 0.15 nitrogen
  - 0 - 2 Ti and Nb
- Microstructure – austenite with some ferrite

Alloy Constitution and Standard Alloys

- 201-205 Low Cr. Ni partially replaced by Mn-N
- 301-302 Low Cr grades
- 303 Free machining grade, contains high sulfur
- 304 “Workhorse grade”
- 304LLow carbon to avoid carbide precipitation
- 316 – 317 Contains Mo (localized corrosion resistance)
- 321 Stabilized grade, contains Ti
- 347 Stabilized grade, contains Nb and Ta
- 348 Stabilized grade, contains Nb and Ta (Nuclear)
- 310 Fully austenitic - high Cr, high Ni
  (High temperature applications)
- 384 High Ni – Reduce cold work hardening

Industrial Applications

- Structural
  - Piping systems
  - Pressure containment
- Corrosion protection
  - Cladding on structural and pressure vessel steels
  - High temperature applications up to 1800°F (980°C)
- Architectural/Decorative
  - Gateway Arch in St. Louis
  - Air Force Memorial in Arlington, VA
- Kitchen/Sanitary
  - Sinks, racks, etc.
  - Commercial kitchen equipment
  - Medical products – pacemakers, needles

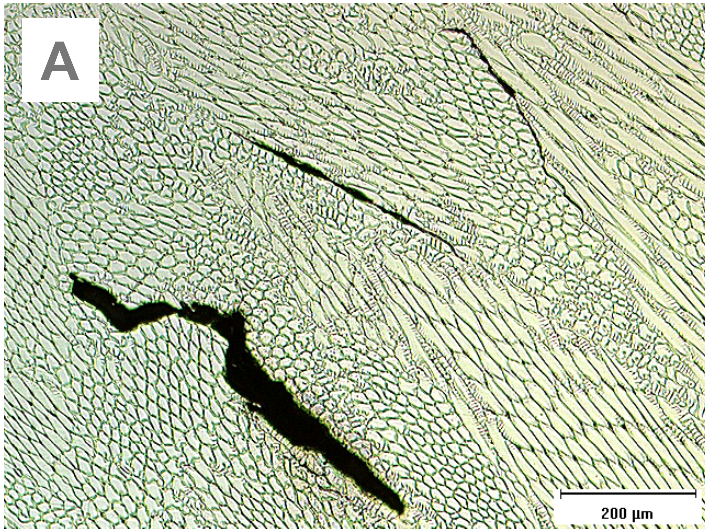
Welding Considerations

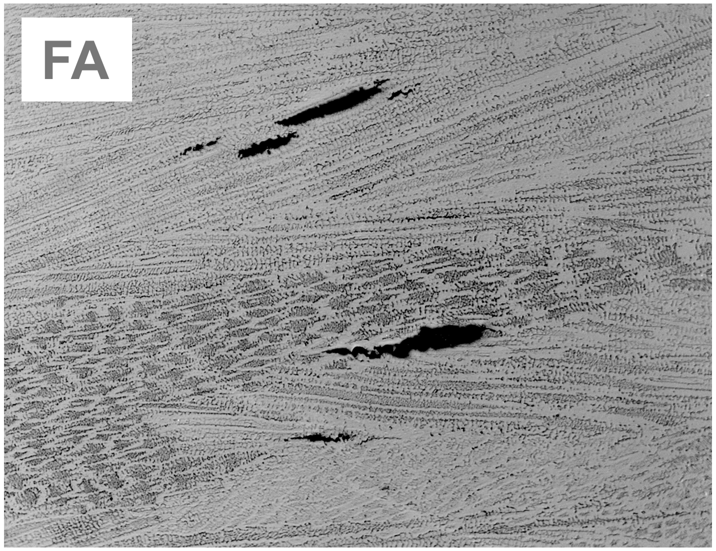
- Preheat
  - Preheat generally not required
  - Interpass 350°F (177°C) maximum
- PWHT
  - None required in thinner sections
  - Stress relief, 1200°F (650°C)
    - must consider carbide and sigma precipitation
  - Solution anneal, 1800-2000°F (980-1095°C)
- Filler metals
  - Matching or near-matching
  - 308, 309 for solidification cracking control
  - Ni-base for corrosion or transition

Weldability Issues

- Solidification cracking
- Liquation cracking
  - Heat-affected zone
  - Weld metal (multipass welds)
- Reheat (stress relief) cracking
- Ductility-dip cracking
- Cu-contamination cracking
- Corrosion
  - Intergranular attack (“sensitization”)
  - Intergranular stress corrosion cracking (IGSCC)
  - Transgranular SCC (TGSCC)
- Intermediate temperature embrittlement
- Lack of penetration (fluidity problems)

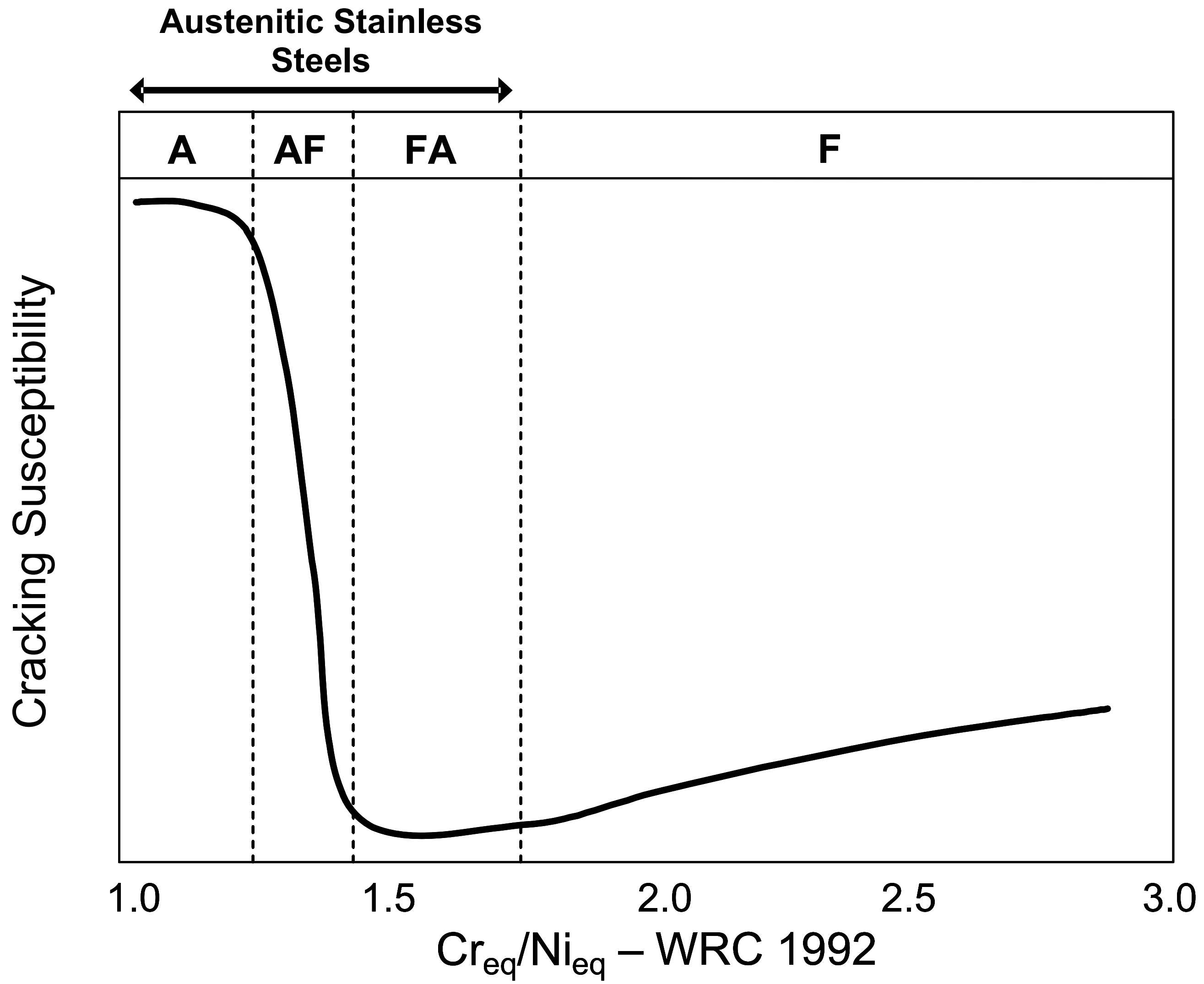
Weld Solidification Cracking





- Influence of solidification mode
  - Primary austenite most susceptible
  - Primary ferrite has very high resistance
- Impurity content
  - Sulfur, phosphorus, boron
  - Strong partitioning during solidification
  - Eutectic films and boundary wetting
- Restraint
  - Large contraction stresses with A and AF solidification
  - Effect of thick sections

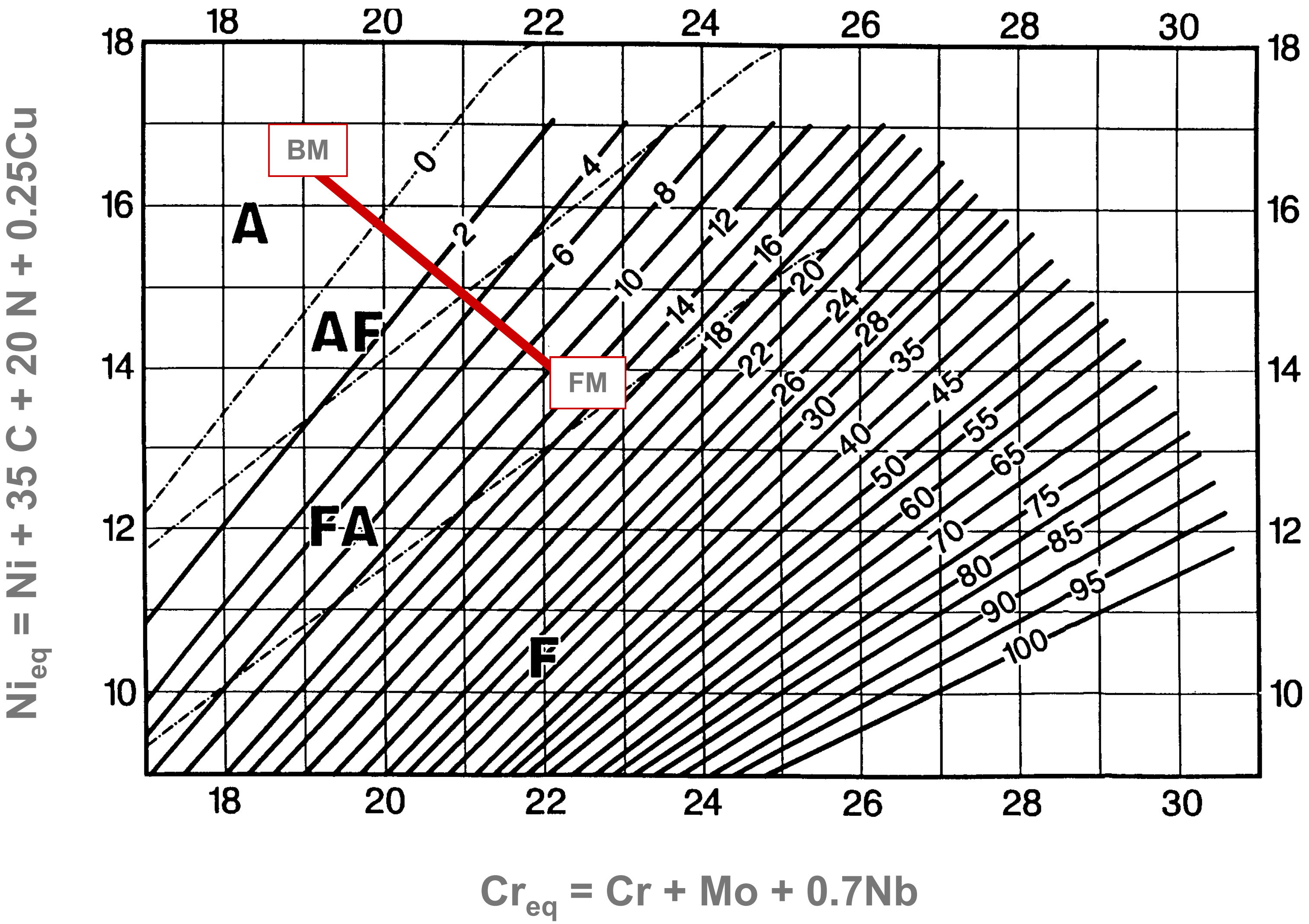
Weld Solidification Cracking vs. Composition



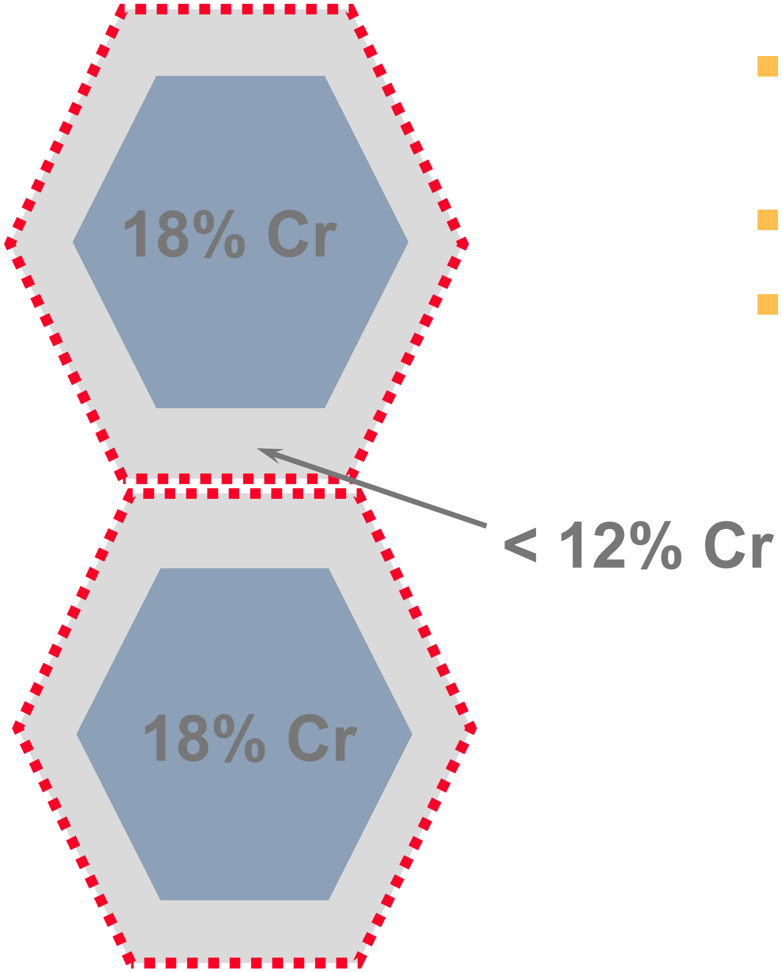
Preventing Weld Solidification Cracking

- Control solidification behavior
  - Selection of base and filler metals
  - Filler metal dilution
  - Use of predictive diagrams
- Reduce impurity levels
  - Low levels of S, P, and B
  - Critical for primary austenite solidification (A and AF)
- Minimize restraint
  - Fixturing
  - Welding procedures

Controlling FN and Solidification Mode

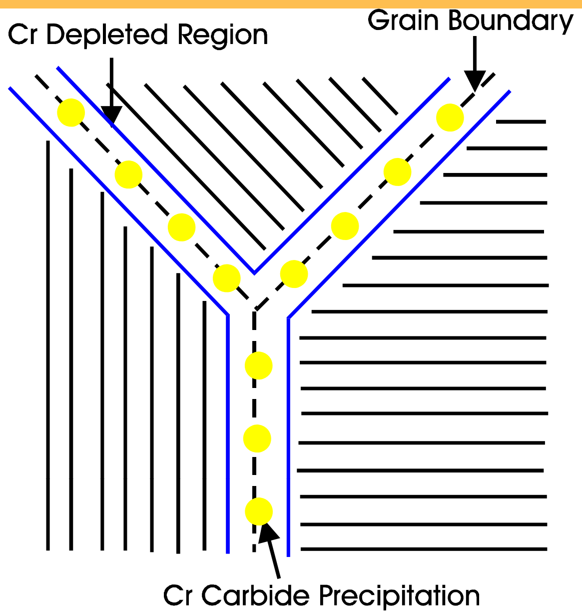


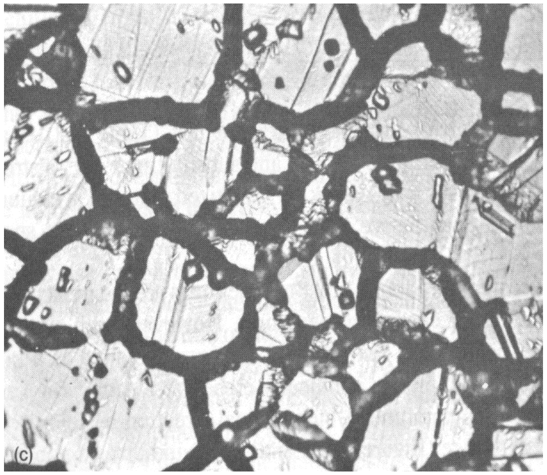
“Sensitization” of Austenitic Stainless Steels



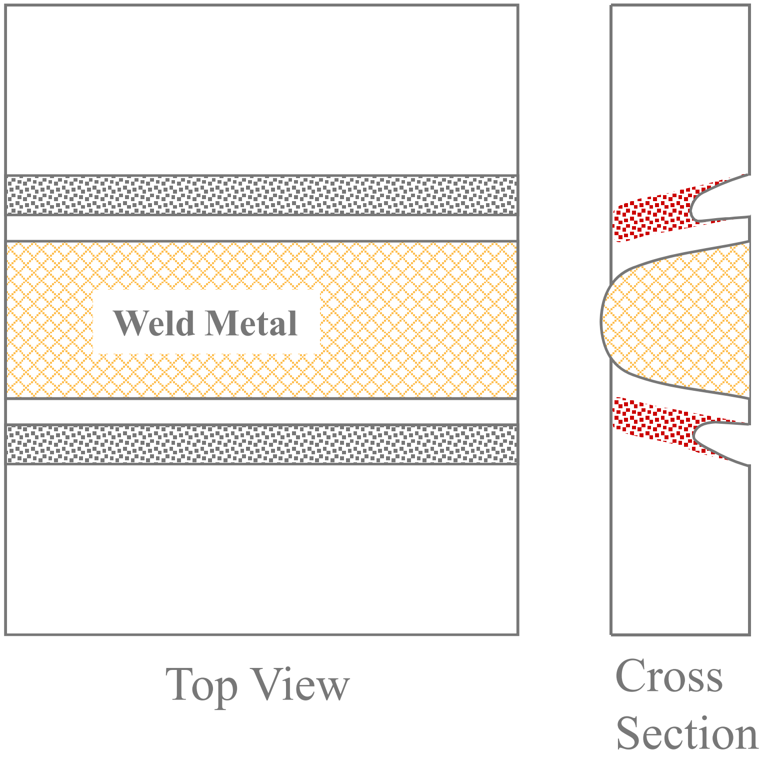
- 800°-1600°F (425°- 870°C)
- $Cr_{23}C_6$ particles form at the grain boundaries; Cr drops < 12%
- Grain boundary corrosion
- Stabilized or low-C grades
  - Maximum 0.1%carbon for standard grades (304)
  - Maximum 0.04% carbon for L grades (304L)
  - Ti or Nb additions form stable MC carbides

Example of Intergranular Attack

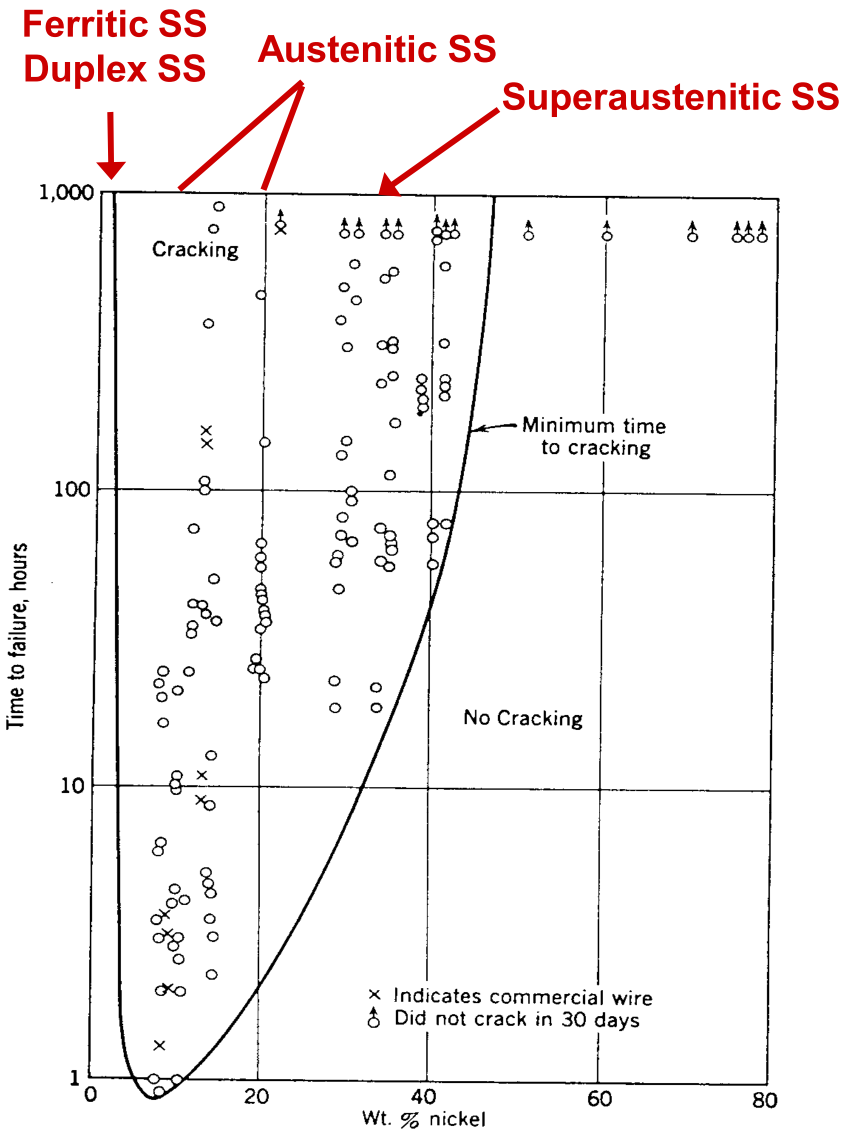




Grain boundary attack in Type 304

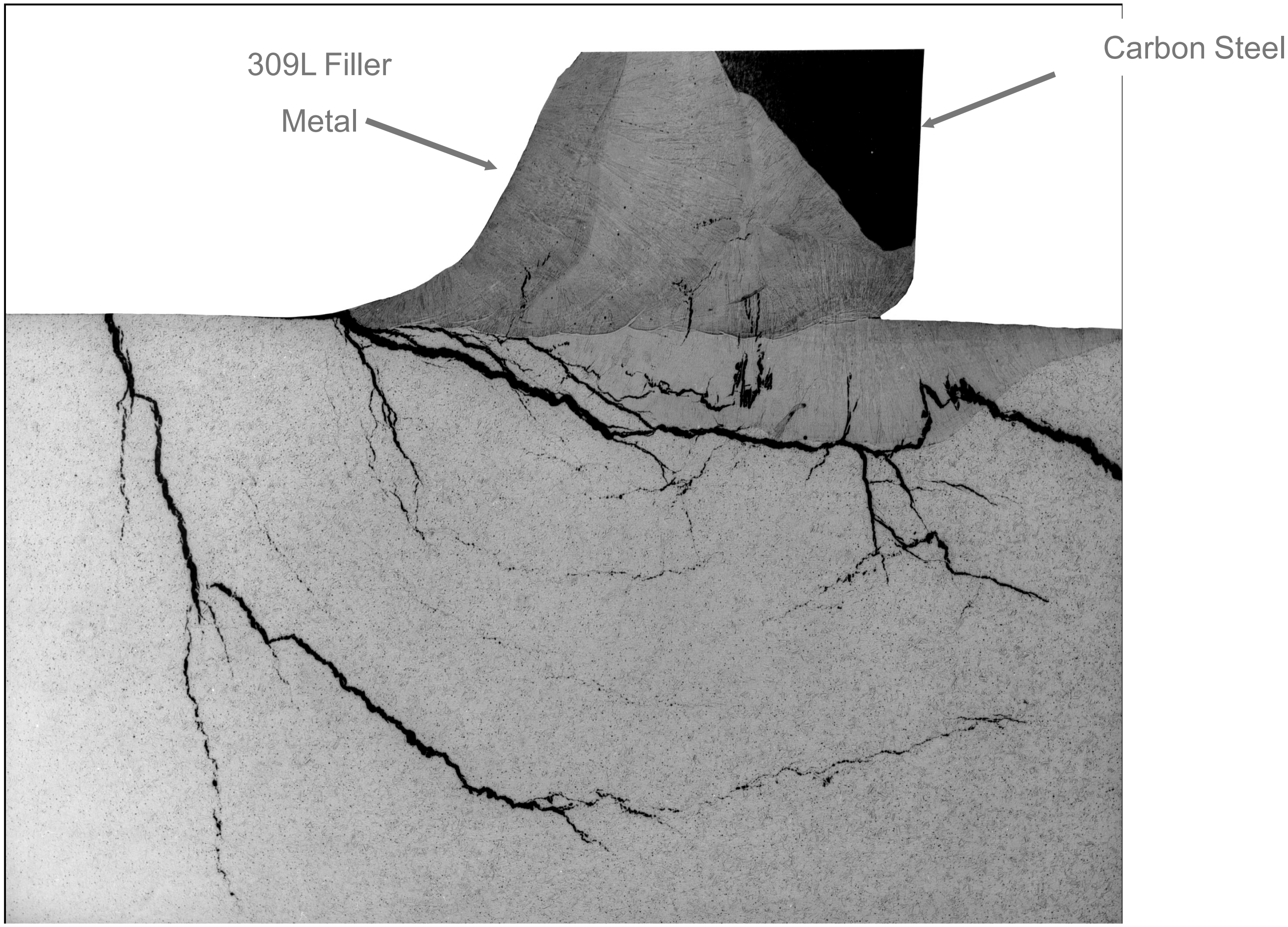


Stress Corrosion Cracking



- “Copson curve” for SCC resistance vs. Ni-content
- Cl-containing environments
- High residual stresses in and around welds
- Stress concentrations
- Minimum at 8-12 wt% Ni

Transgranular SCC in Type 316 Tubesheet



Alloy Constitution and Standard Alloys

- Composition Range

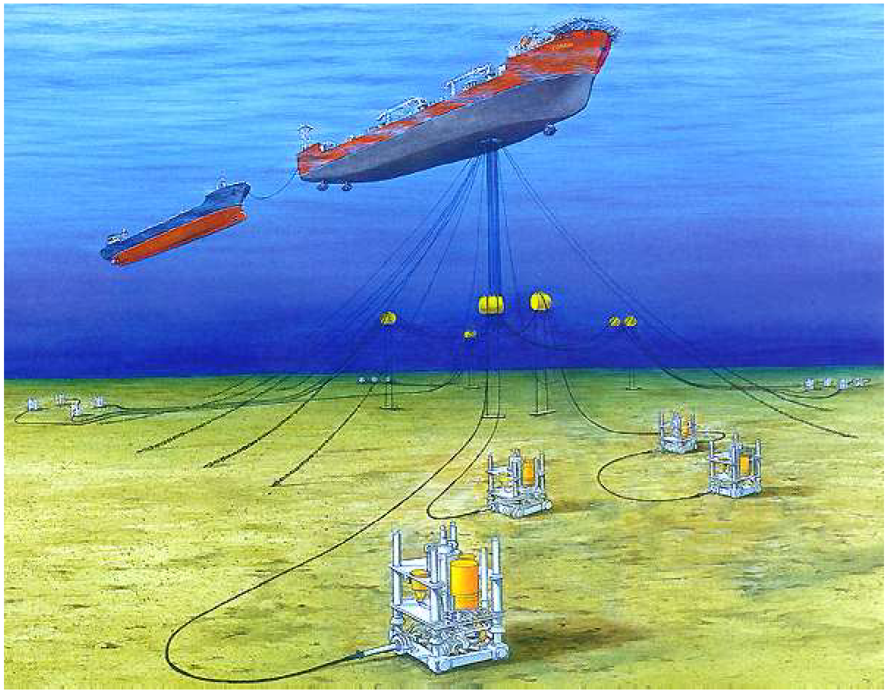
Chromium	20 - 30 wt%
Nickel	4 - 10 wt%
Manganese	1 - 2 wt%
Silicon	1 wt% max
Carbon	0.08 wt% max
Nitrogen	0.25 wt% max
Molybdenum	2 - 5 wt%
Copper	0 - 2 wt%
Tungsten	0 - 3 wt%

- Balanced ferrite + austenite microstructure

- 22 Cr Alloys
  - 2304 Fe - 23Cr - 4Ni - 0.1N
  - 2205 Fe - 22Cr - 5.5Ni – 3Mo - 0.15N
- 25 Cr Alloys
  - Ferralium 255
  - Uranus 52N
- "Superduplex" Alloys
  - SAF 2507
  - Zeron 100
  - Uranus 52N+
  - Sumitomo DP-3W

Industrial Uses

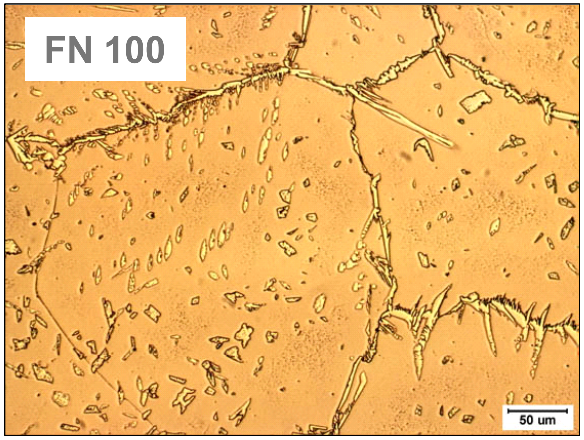
- Applications
  - Pipelines, particularly for “sour” service
  - Umbilical systems – Offshore Oil production
  - Chemical plants
  - Pulp and paper mills
- Advantages
  - Higher strength and corrosion resistance than austenitics
  - Lower CTE and higher thermal conductivity
- Limitations
  - Restricted to 300°C (570°F) maximum service temperature
  - Weld process control is critical to avoid loss of corrosion resistance and properties

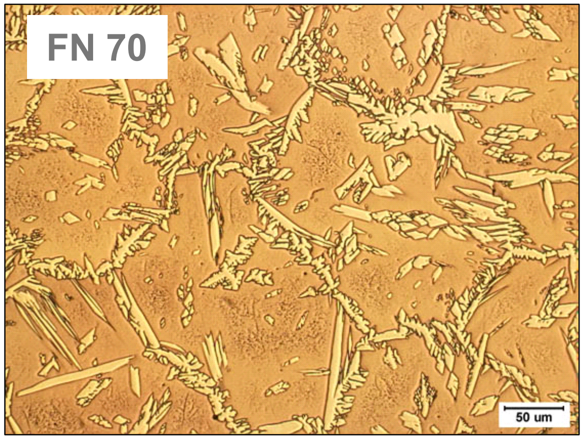


Undersea collection lines for oil and gas

Welding Considerations

- Small heat input window to control ferrite-to-austenite transformation
- Preheat
  - None required
- PWHT
  - Not recommended due to possible embrittlement
- Filler metals
  - Matching (with Ni-"boost")
  - Austenitic or nickel-base (dissimilar joints)





Weldability Issues

- Solidification and HAZ/WM liquation cracking
  - Low to medium susceptibility
  - Dependent on impurity content
- Hydrogen-induced cracking
  - May occur if FN > 90
  - Low hydrogen practice recommended
- Control of ferrite / austenite balance in HAZ
  - For FN > 90
    - Lower toughness and ductility
    - Reduced corrosion resistance
  - Austenite provides ductility and high toughness
- Intermediate temperature embrittlement

Nickel-Base Alloys

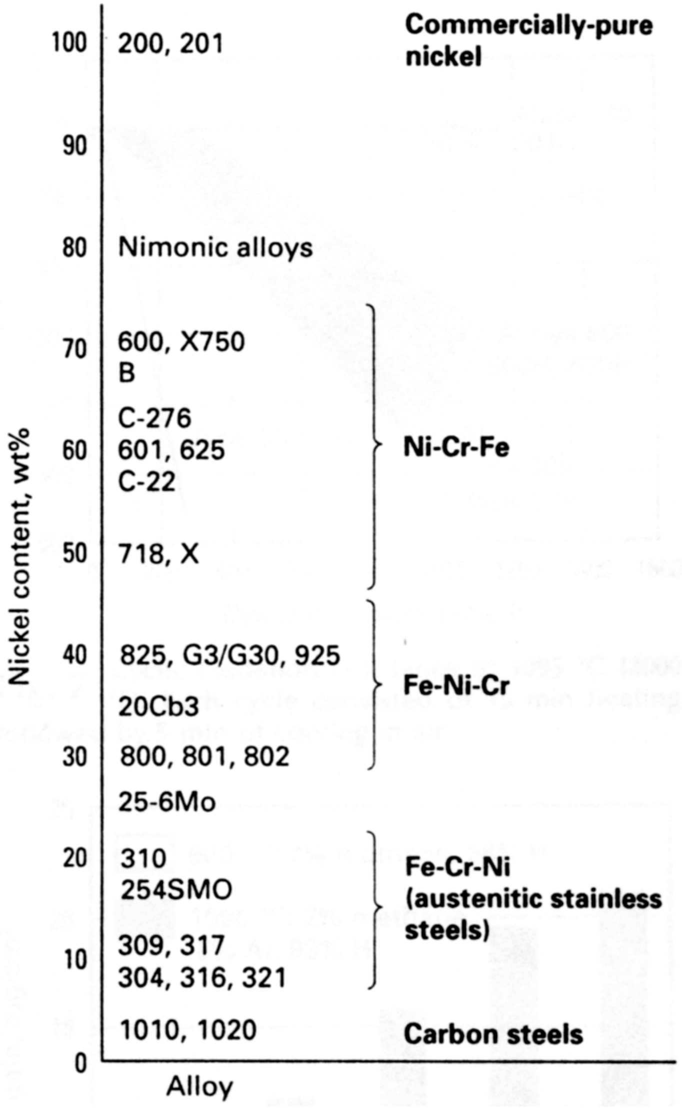
Module 3E

Characteristics of Nickel Alloys

- Excellent corrosion resistance
- Medium to high strength
  - Strengthened by solid solution and precipitation
  - Good strength at temperatures above 1200ºF (650ºC)
- Austenitic microstructure
- May be difficult to fabricate
- Very expensive

Classes of Ni-Base Alloys

- Commercially pure Ni (Low alloy) – Chemical
  - Alloy 200 (99Ni)
- Ni-Cu Alloys – Chemical, marine
  - Alloy 400 and K500
- Ni-Cr, Ni-Cr-Fe
  - Alloys 600, 718, and C22
- Fe-Ni-Cr – Piping, heat exchangers, nuclear, oil production
  - Alloys 800 and 925
- Controlled expansion alloys – Turbines, precision equipment
  - Alloy 902
- Ni-Fe (Low expansion) – Electronic
  - Invar or Alloy 36



Classes of Ni-Base Alloys

- Solid-Solution Strengthened Alloys (Cr, Mo, Fe, W)
  - Alloy 600 (15.5Cr, 8Fe)
  - Alloy 625 (21.5Cr, 2.5Fe, 9Mo, 3.5Nb)
  - Alloy 690 (27Cr, 9Fe)
  - Hastelloy X (22Cr, 18.5Fe, 9Mo, 2Al, 0.6W)
  - Haynes 230 (22Cr, 2Fe, 2Mo, 14W)
- Precipitation-Hardened Alloys (“Superalloys”)
  - Alloy 718 (19Cr, 18.5Fe, 3Mo, 5Nb, 0.9Ti, 0.5Al)
  - Inconel 713C (12.5Cr, 4.2Mo, 2Nb, 0.8Ti, 6Al)
  - Waspaloy (19.5Cr, 2Fe, 4Mo, 13.5Co, 3Ti, 1.4Al)
  - Inconel 939 (23Cr, 19Co, 4Ti, 2Al, 1.5Ta, 1Nb, 0.15C)

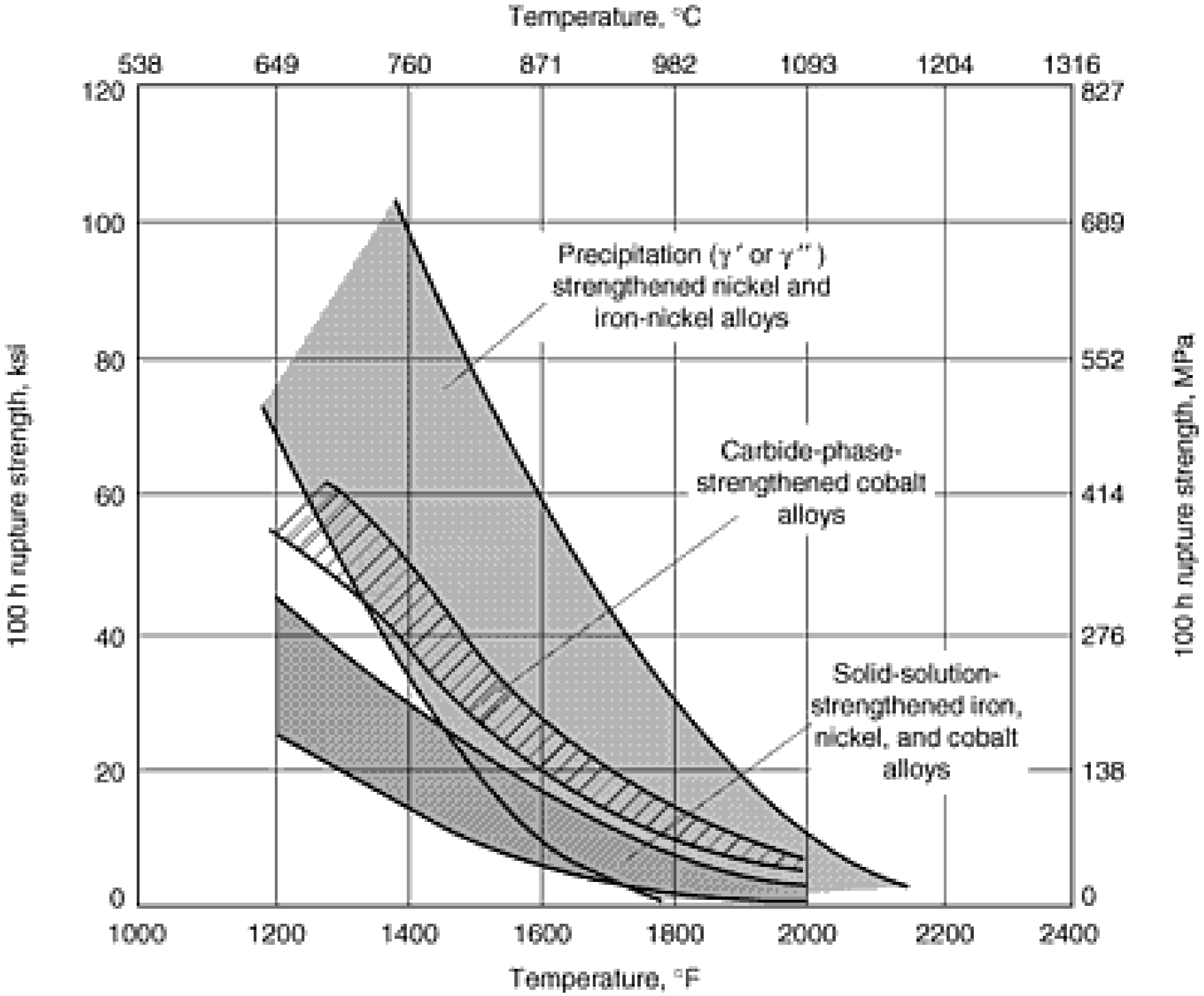
Commercial Uses

- Heat treatment equipment
- Heating elements
- Turbine engines
- Chemical plants
- Pulp and paper industry
- High temperature waste incinerators
- Transition joints between carbon steel and stainless steel
- Cladding over steel for corrosion protection

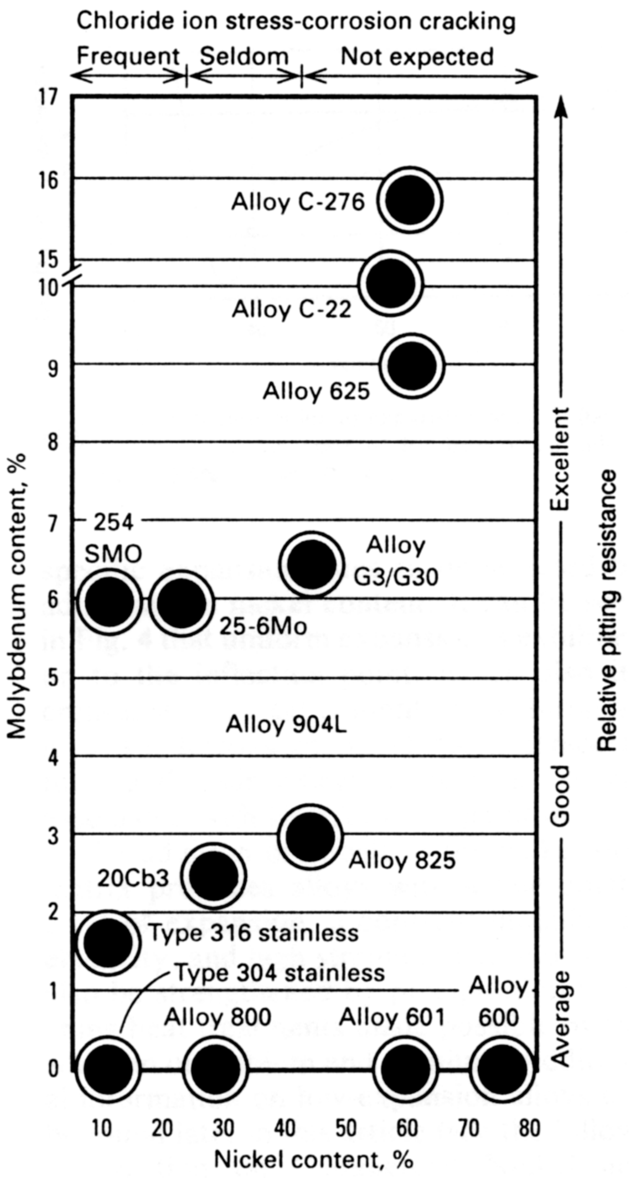
Alloy Selection Criteria

- Strength
  - PH alloys can have reasonable strength to temperatures approaching 1800oF (980oC)
  - Room temperature strength may exceed 200 ksi
- Ductility
  - Generally good over wide range of temperatures
  - May be a ductility dip in some alloys at elevated temperature
- Fracture Toughness
  - No transition
  - Excellent at cryogenic temperature
- Corrosion Resistance
- Cost

Strength vs. Temperature



Corrosion Resistance Effect of Mo



Microstructure and Constitution

- Single phase, FCC structure
- High levels of chromium for corrosion resistance
- Strengthened by
  - Solid solution (Cr, Mo, Fe, W)
  - Precipitation strengthening (Ti, Al, Nb))
- Carbide formers (Ti, Nb, Cr, Mo)
- Embrittling phases
  - Laves - (Ni, Fe, Co)2 (Nb, Ti, Mo)
  - Sigma (σ) - FeCr, FeCrMo
  - Mu (μ) – Co_7W_6, $(FeCo)_7(MoW)_6$
- Very complex systems

Effect of Alloys Elements on Superalloys

Effect	Elements
Solid-solution strengtheners	Co, Cr, Fe, Mo, W, Ta, Re
Carbide form: MC	W, Ta, Ti, Mo, Nb, Hf
Carbide form: M_7C_3	Cr
Carbide form: $M_{23}C_6$	Cr, Mo, W
Carbide form: M_6C	Mo, W, Nb
Forms γ' $Ni_3(Al,Ti)$	Al, Ti
Raises solvus temperature of γ'	Co
Hardening precipitates and/or intermetallics	Al, Ti, Nb
Oxidation resistance	Al, Cr, Y, La, Ce
Improve hot corrosion resistance	La, Th
Sulfidation resistance	Cr, Co, Si
Improves creep properties	B, Ta
Increases rupture strength	B
Grain-boundary refiners	B, C, Zr, Hf
Retard γ' coarsening	Re

Strengthening Precipitates

- Solution heat treatment and aging
- Exhibit C-curve precipitation behavior
- Volume fraction may be very high in some alloys
- Precipitate types
  - Gamma-prime (g’) - Ni3(Ti,Al), FCC (Ordered), spherical or cubic
  - Eta (η) - Ni3Ti, HCP, cellular or acicular
  - Gamma-double prime (g”) - Ni3Nb, BCT (Ordered), disk-shaped
  - Delta (δ) – Ni3Nb, Orthorhombic (Ordered), acicular or cellular

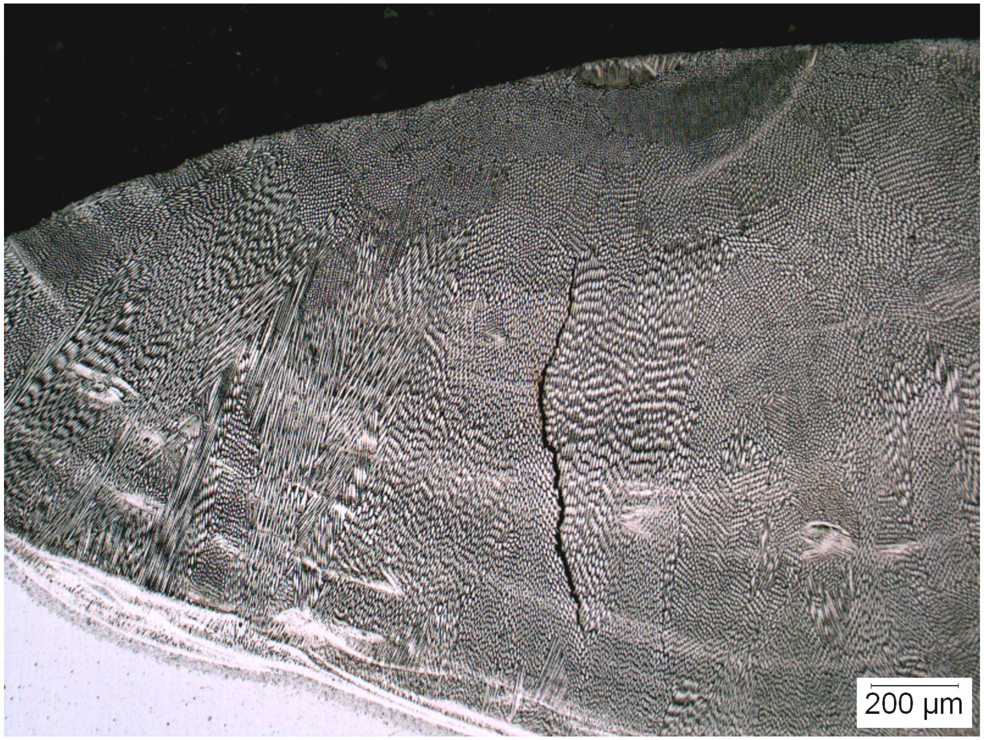
Weldability Issues

- Weld solidification cracking
- HAZ and WM liquation cracking
- Strain-age cracking
- Ductility-dip cracking
- Joint efficiency
- WM Segregation (high Mo) – Effect on corrosion
- Sensitization (May happen but is not serious)
- Porosity (May happen but is not serious)

Effect of Composition

- Austenitic solidification and microstructure
  - segregation
  - limited solid diffusion
  - liquid film wetting
- Most alloying elements partition to the liquid (k<1)
  - Ti, Nb, Al, and B
  - formation of low melting eutectic constituents (e.g. Laves)
  - suppression of solidification temperature by 200-300ºC
- Impurity levels (S, P) normally low
- Effect of boron

Weld Solidification Crack



Filler Metal 52 deposited on 304 stainless steel

- Form along solidification grain boundaries
- Presence of liquid films
- Wetting of austenite-austenite boundaries
- High inherent restraint

Avoiding Solidification Cracking

- Most alloys are inherently susceptible
- Minimize restraint
    - Joint design
    - Base metal in solution-annealed condition
    - Increase number of fill passes (multipass welds)
- Use crack resistant filler metals

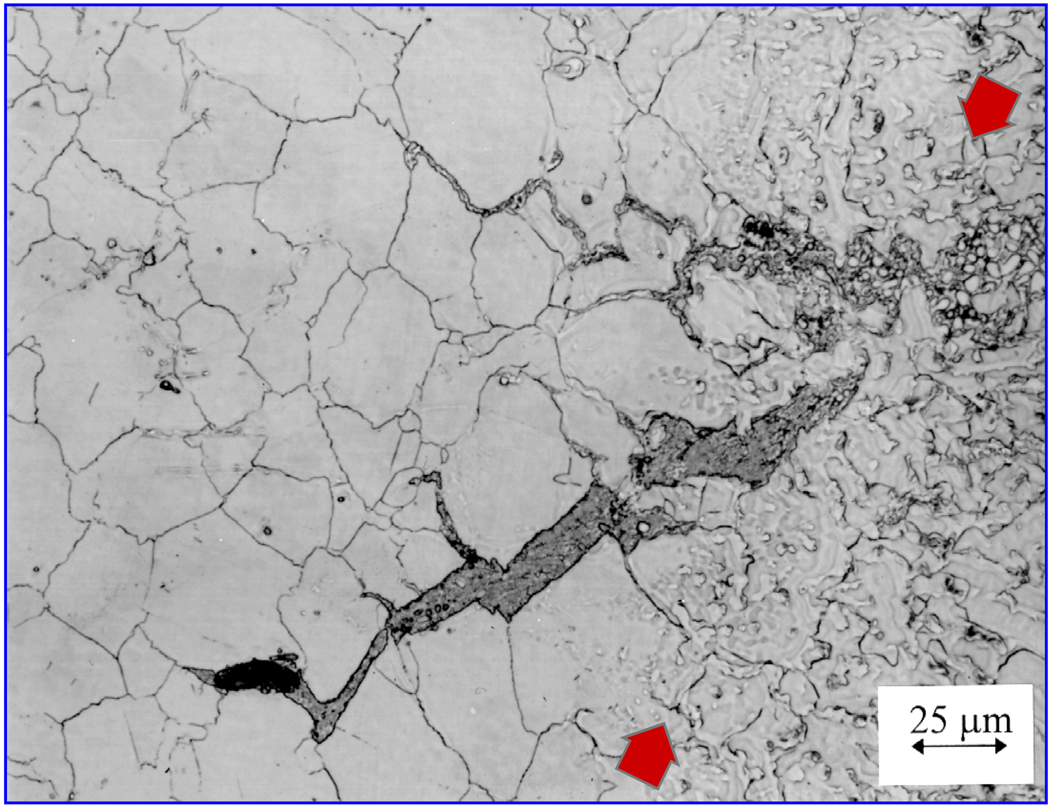
E/ER NiCrMo-3	Alloy 625
E/ER NiCrMo-4	Hastelloy C-276
E/ER Ni-1	Nickel 141

Characteristics

- Segregation mechanism
  - Impurity or alloy segregation at grain boundaries
  - Wetting of austenite grain boundaries
- Penetration mechanism in alloys with Nb additions
  - Nb added to form g” strengthening precipitate
  - NbC undergoes constitutional liquation
  - “Penetration” of liquid along mobile grain boundaries
- Adjacent to the fusion boundary in the HAZ
  - Dependent on weld thermal cycle
  - Discrete liquation temperature range

HAZ Liquation Crack in Alloy 718

- Constitutional liquation of NbC
- Mobile grain boundaries
- Liquid penetration along grain boundaries

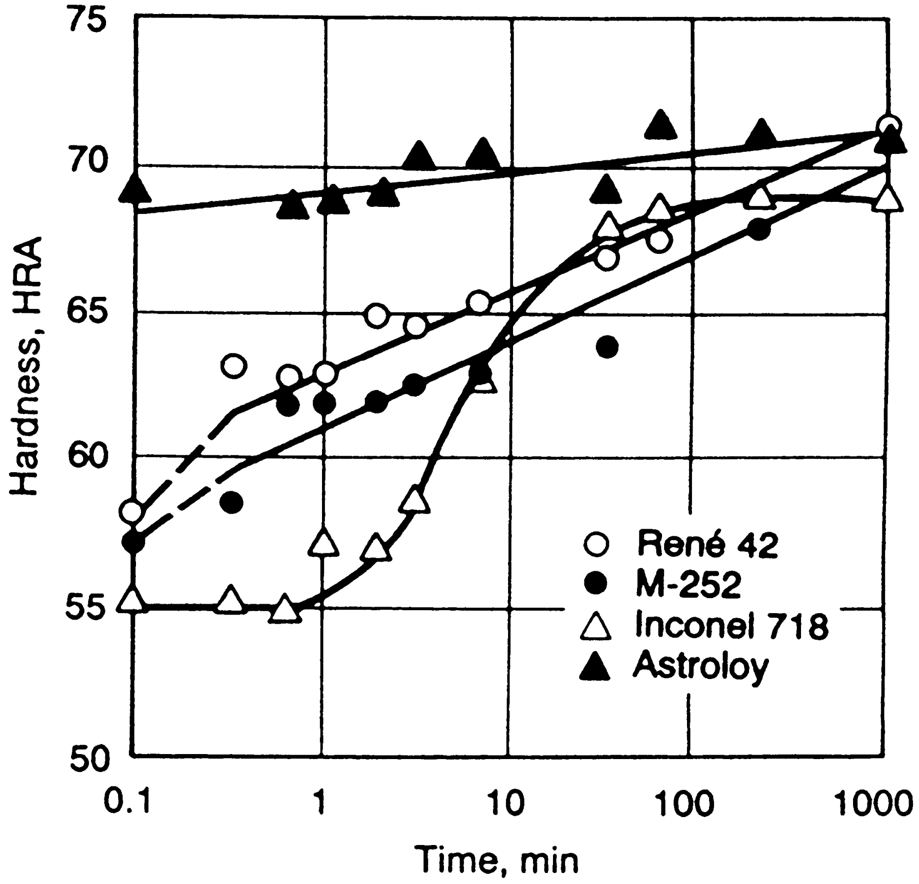


Alloy 718

How to Control

- Reduce HAZ grain size
  - Use fine grained base metal
  - Minimize weld heat input
- Reduce impurity levels (S, P, and B)
- Minimize restraint
  - Weld in solution-annealed condition
  - Adjust process and/or procedures
- “Buttering” of substrate
  - Eliminates susceptible microstructure
  - Not cost effective

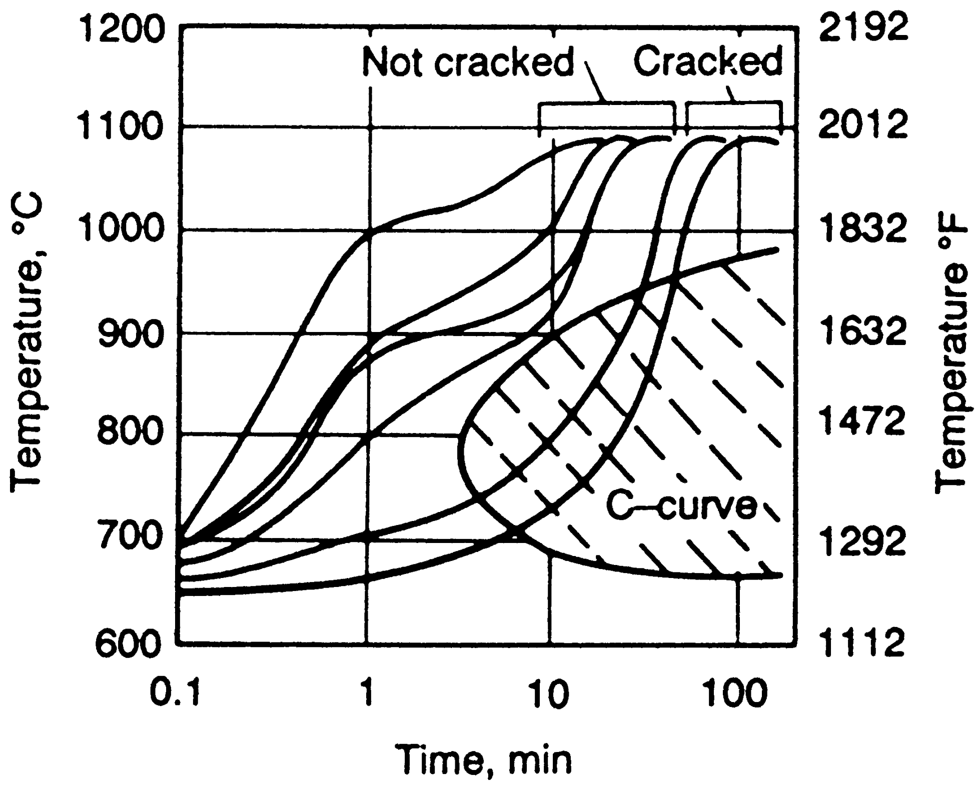
Characteristics



- Cracking occurs in the solid-state along HAZ grain boundaries
- Normally during PWHT
- Alloys that harden rapidly during aging are most susceptible

from ASM Handbook, Vol. 6

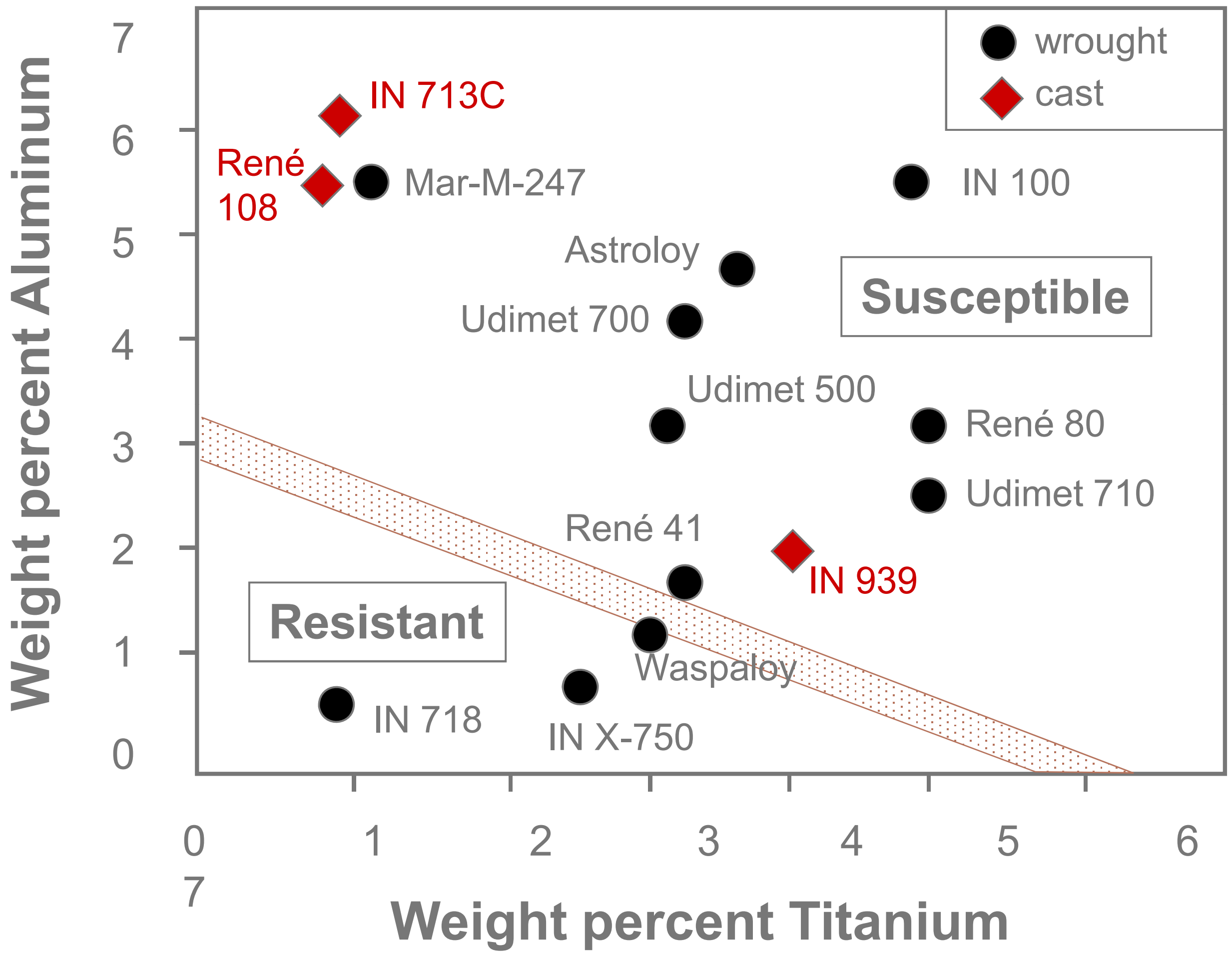
Mechanism



from ASM Handbook, Vol.6

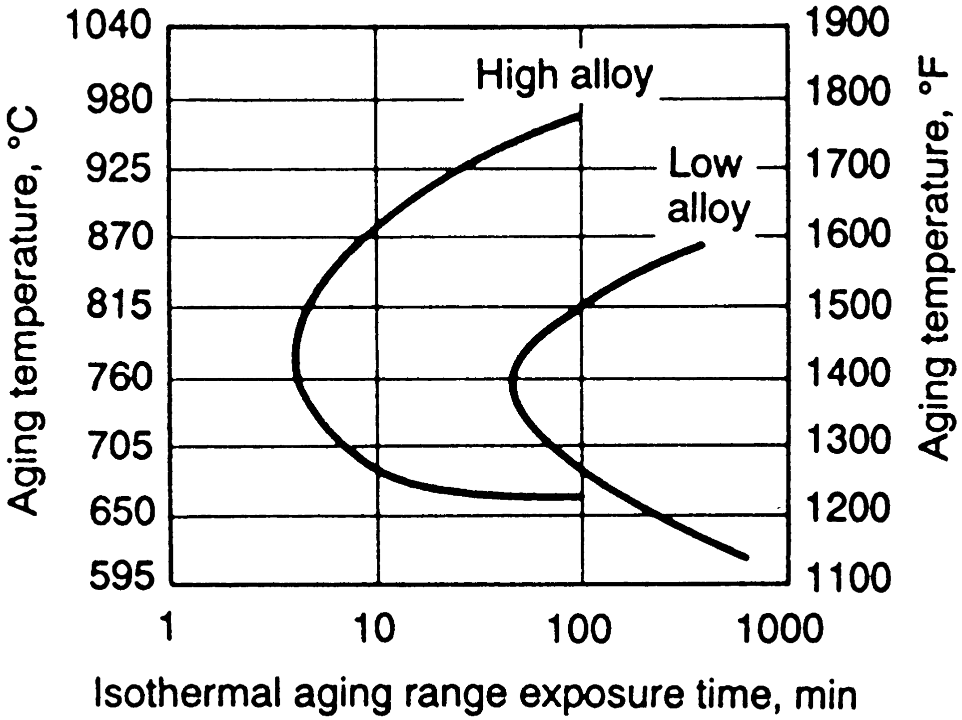
- Precipitates are solutionized and grain growth occurs in the HAZ during welding
- During reheating
  - Intragranular precipitation
  - Relief of residual stresses
  - Localization of strain at the grain boundaries

Effect of Ti and Al



Adapted from Shira and Prager, WRC Bulletin

Preventing Cracking



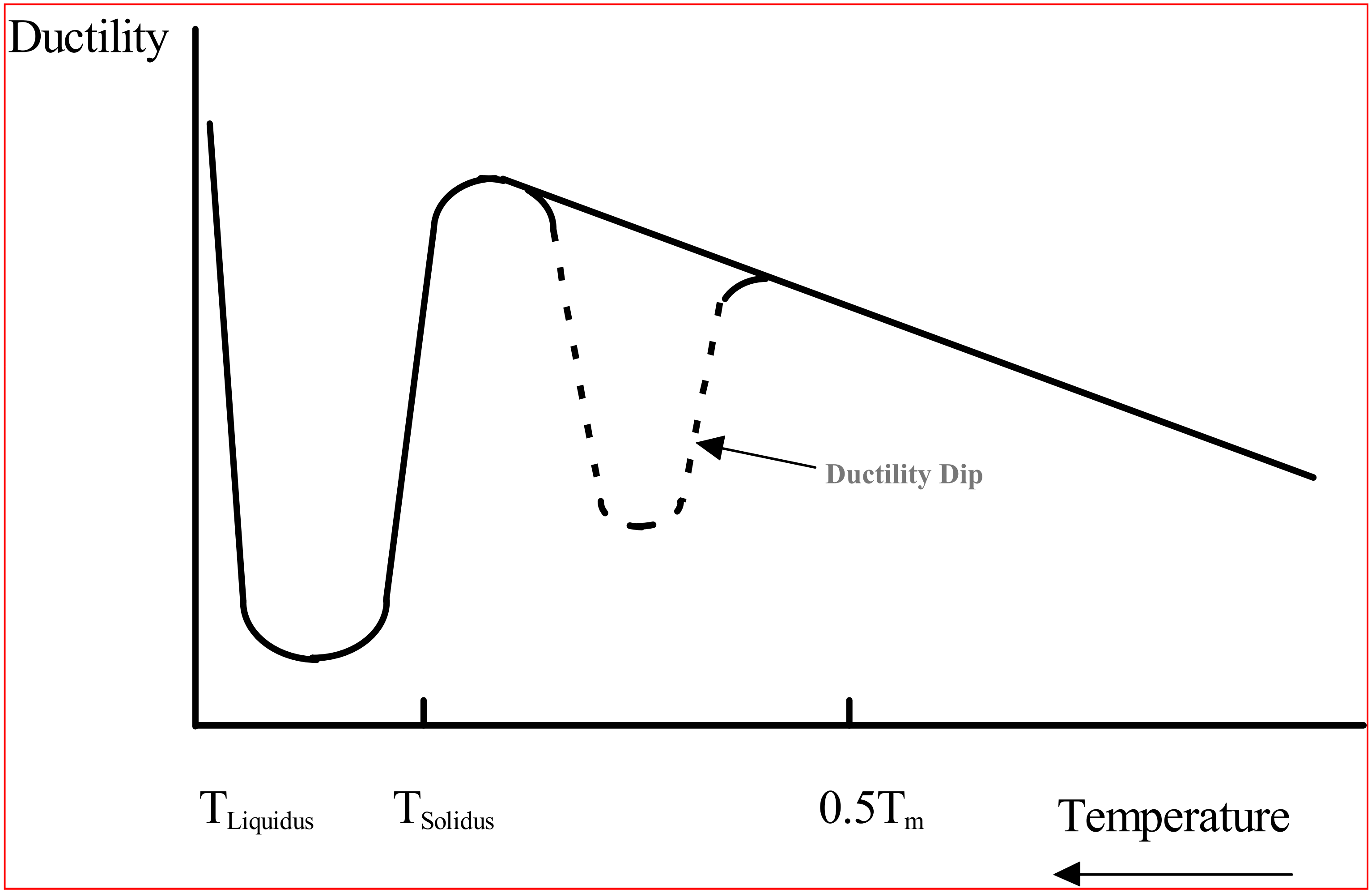
from ASM Handbook, Vol. 6

- Select resistant material (low Ti + Al)
- Heat rapidly during PWHT to avoid “nose” of precipitation curve
- Heat and hold below nose of curve to reduce residual stress
- Design issues

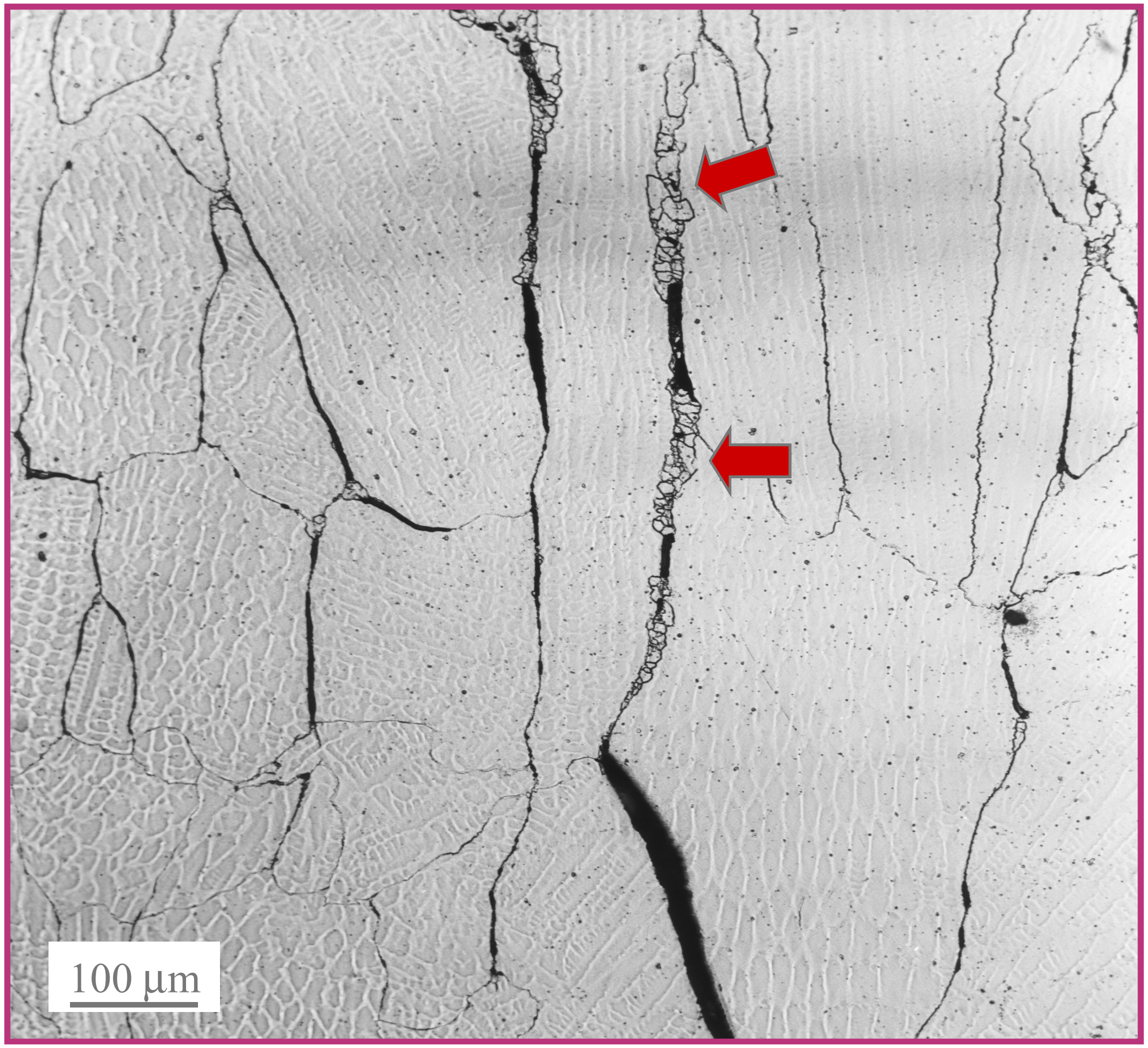
Characteristics

- Occurs in the solid-state at Ts > T > 0.5Ts
- Grain boundary phenomenon
- Weld metal or HAZ
- Fully austenitic materials
  - Stainless steels
  - Ni-base alloys
  - Copper alloys
- High purity (low S + P)

Ductility versus Temperature



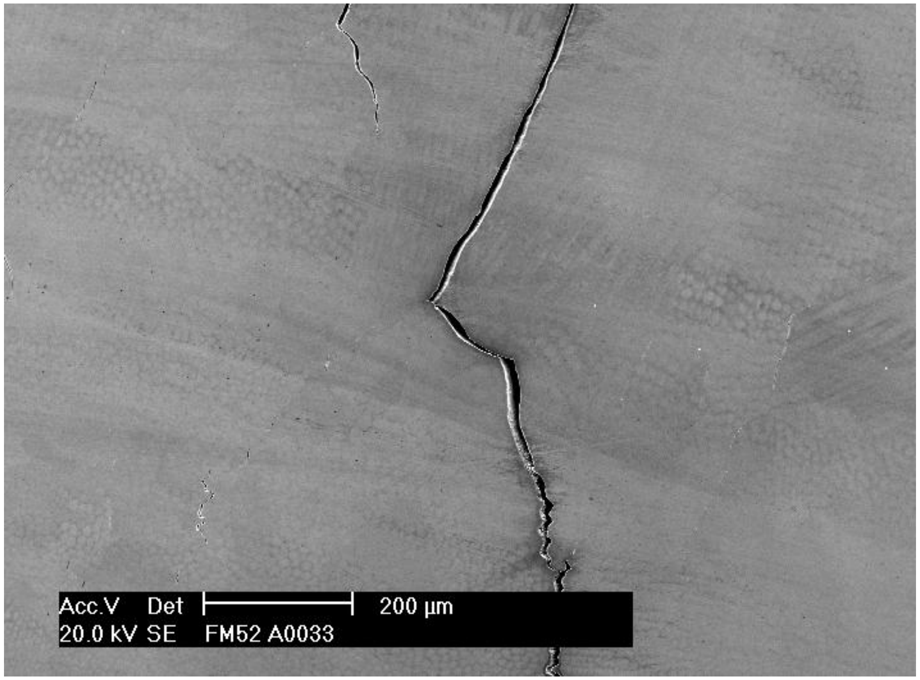
Ductility Dip Cracking In Alloy 52 Weld Metal



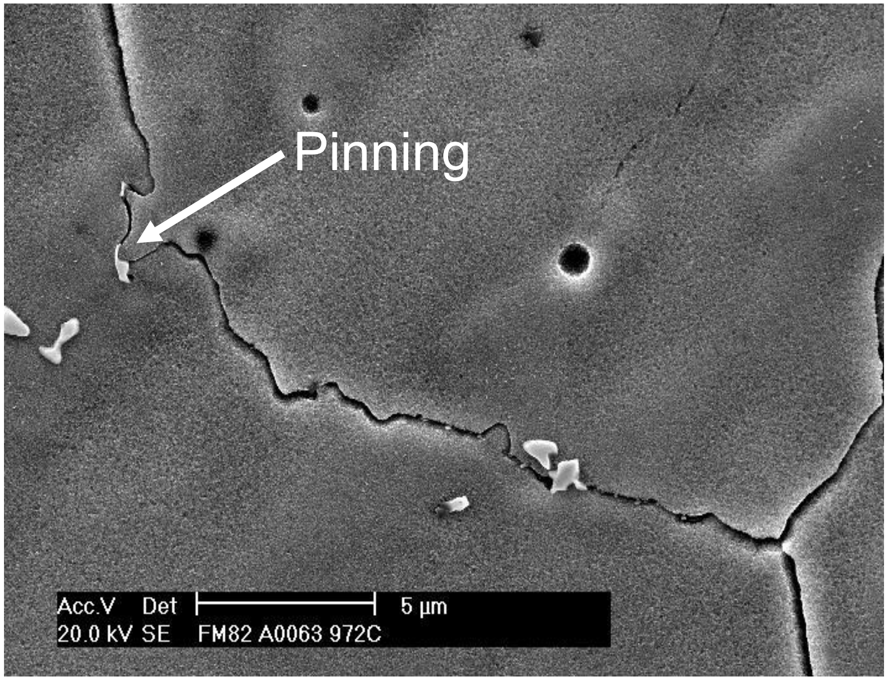
Mechanism

- Rapid grain growth
  - Single phase austenite
  - No boundary pinning
- Grain boundary strain localization
- Intergranular cracking with little ductility
- Fracture behavior
  - Smooth IG at high temperature
  - Ductile IG at lower temperatures

Nature of the Grain Boundaries



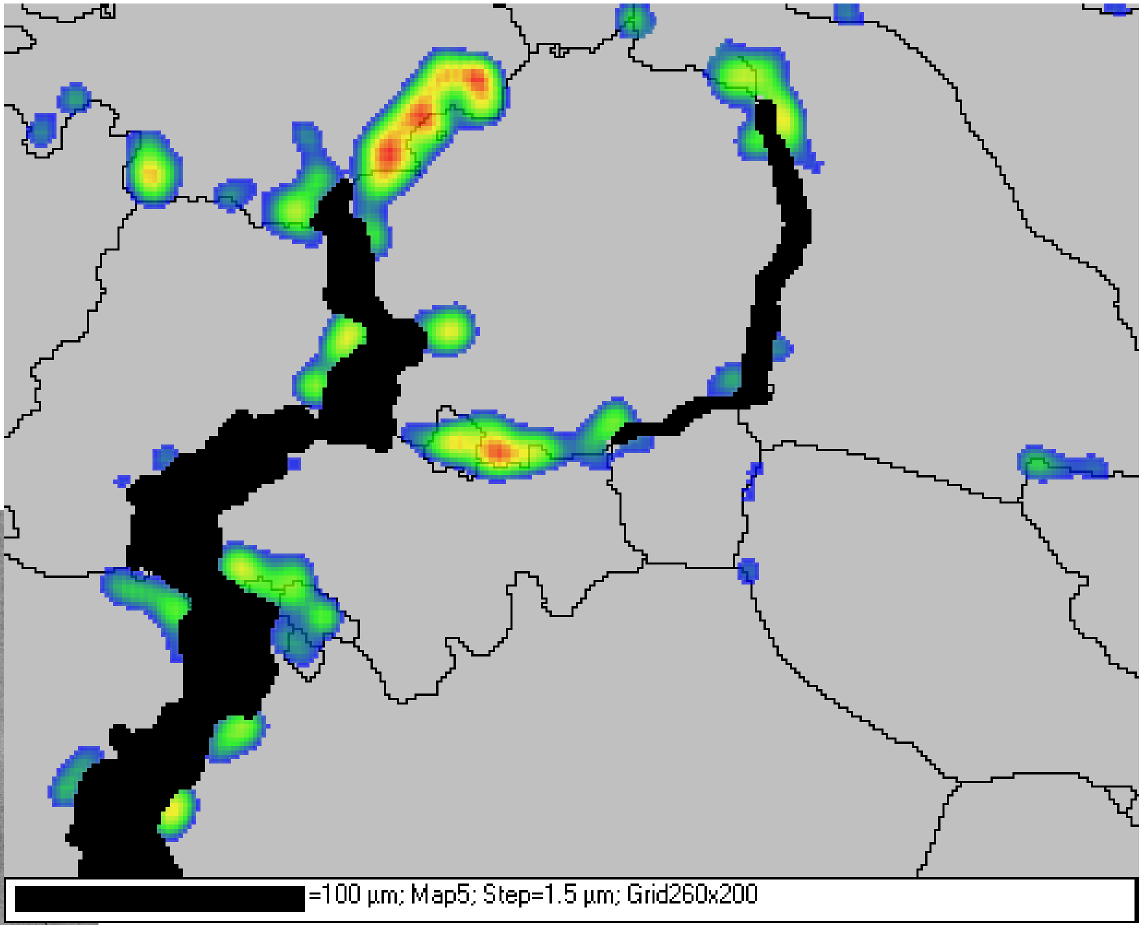
FM-52 Straight GBs

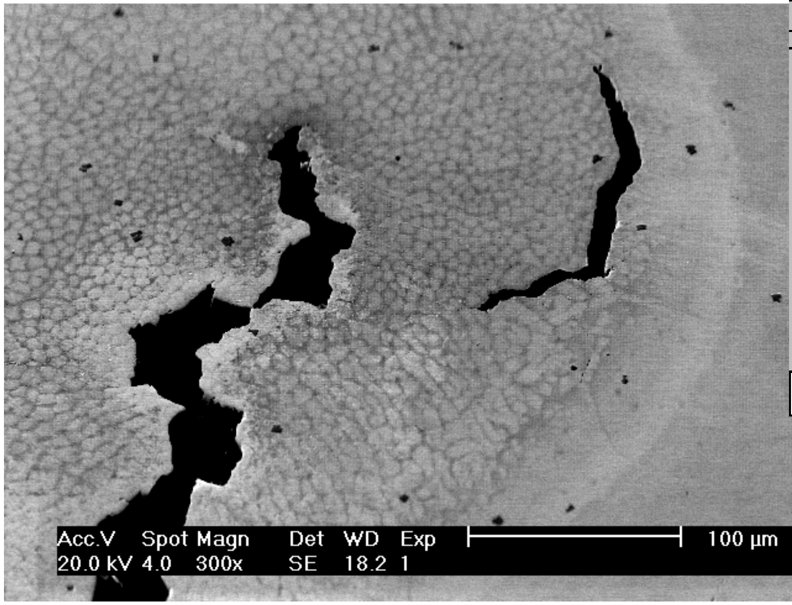


FM-82 Tortuous GBs

Grain Boundary Strain Localization

Micro strains measured
on the SEM





FM-82 DDC

Prevention

- Select resistant materials
  - Fine grain size or grain growth inhibitors
  - Two phase microstructure (weld metal eutectic)
- Minimize restraint
  - Multipass weld techniques
  - Weld design
- Mechanism is still not fully understood

Controlling Joint Efficiency

- Weld metal and HAZ are effectively solution annealed after welding
- Significant softening in precipitation-strengthened alloys
- Strength recovery
  - Full SHT and age
  - Postweld age
- Use of HED processes
  - Minimize extent of HAZ softening
  - Optimize aging response

Ni-based Overlays on Stainless Steel

PWSCC and Mitigation Techniques

- MRP-139, Rev. 1 - Primary System Piping Butt Weld Inspection and Evaluation Guideline, December 2008
- MRP-169, Rev. 1 – Technical Basis for Preemptive Weld Overlays for Alloy 82/182 Butt Welds in PWRs, June 2008
- MRP-220 – Review of Stress Corrosion Cracking of Alloys 182 and 82 in PWR Primary Water Service, October 2007
- MRP-237, Rev. 1 – Resistance of Alloys 690, 52 and 152 to Primary Water Stress Corrosion Cracking, August 2008

Nickel Weld Metals and Base Metals used in PWRs

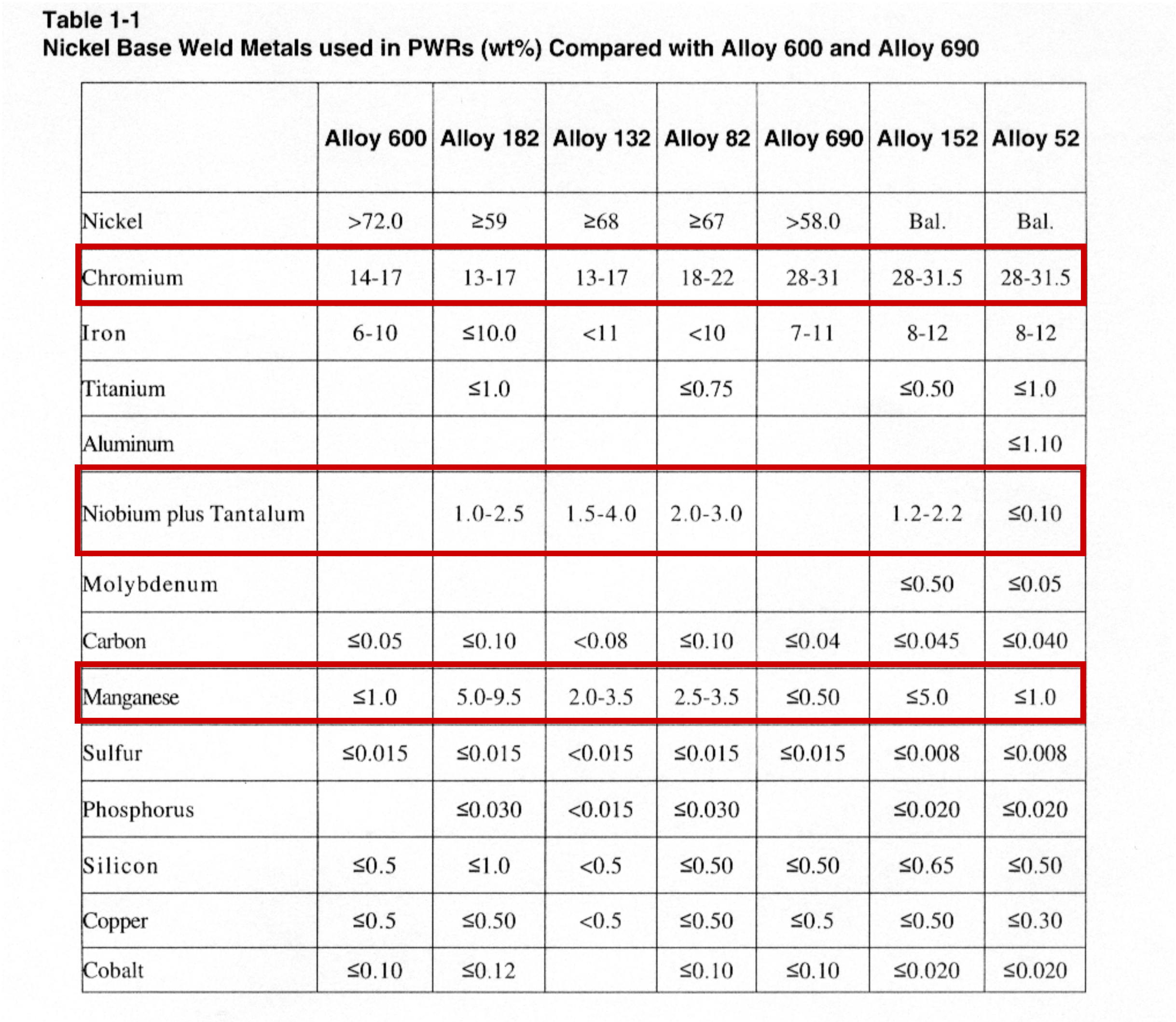


Table 1-1
Nickel Base Weld Metals used in PWRs (wt%) Compared with Alloy 600 and Alloy 690

	Alloy 600	Alloy 182	Alloy 132	Alloy 82	Alloy 690	Alloy 152	Alloy 52
Nickel	>72.0	≥59	≥68	≥67	>58.0	Bal.	Bal.
Chromium	14-17	13-17	13-17	18-22	28-31	28-31.5	28-31.5
Iron	6-10	≤10.0	<11	<10	7-11	8-12	8-12
Titanium		≤1.0		≤0.75		≤0.50	≤1.0
Aluminum							≤1.10
Niobium plus Tantalum		1.0-2.5	1.5-4.0	2.0-3.0		1.2-2.2	≤0.10
Molybdenum						≤0.50	≤0.05
Carbon	≤0.05	≤0.10	<0.08	≤0.10	≤0.04	≤0.045	≤0.040
Manganese	≤1.0	5.0-9.5	2.0-3.5	2.5-3.5	≤0.50	≤5.0	≤1.0
Sulfur	≤0.015	≤0.015	<0.015	≤0.015	≤0.015	≤0.008	≤0.008
Phosphorus		≤0.030	<0.015	≤0.030		≤0.020	≤0.020
Silicon	≤0.5	≤1.0	<0.5	≤0.50	≤0.50	≤0.65	≤0.50
Copper	≤0.5	≤0.50	<0.5	≤0.50	≤0.5	≤0.50	≤0.30
Cobalt	≤0.10	≤0.12		≤0.10	≤0.10	≤0.020	≤0.020

MRP-220, Table 1-1

Incidents of PWSCC

- More than 300 cracks welds detected since 1994
- Wolf Creek (Autumn 2006)
  - Pressurizer nozzle
  - 5 circumferential indications
  - 8 to 166 degrees around circumference
  - Up to 31% through wall
- Farley 2 (Spring 2007)
  - Pressurizer nozzle
- Tsuraga 2 and Mihama 2 (Autumn 2007)
  - Steam generator nozzle to safe end welds
  - Axial and circumferential welds
- Davis Besse (2007)
  - Near through wall crack opened during PWOL

Source: MRP-220

Locations of PWSCC in PWR Primary Circuit

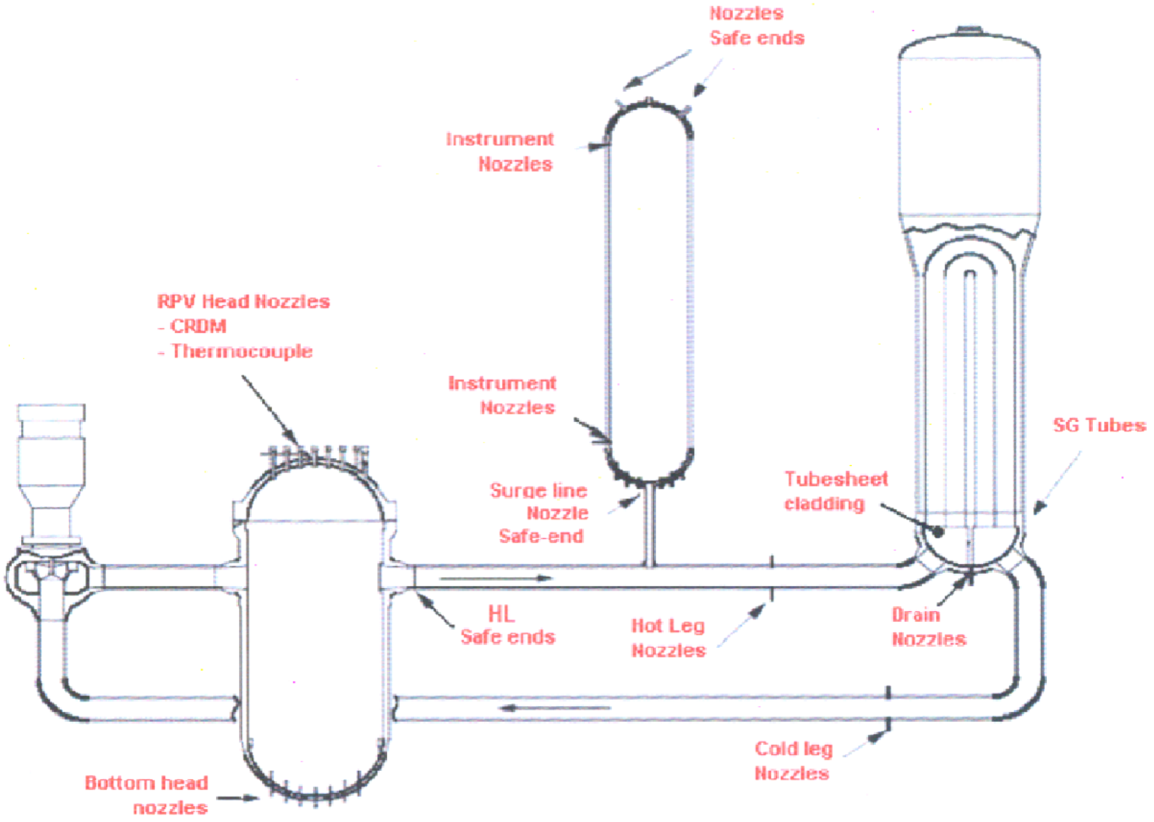
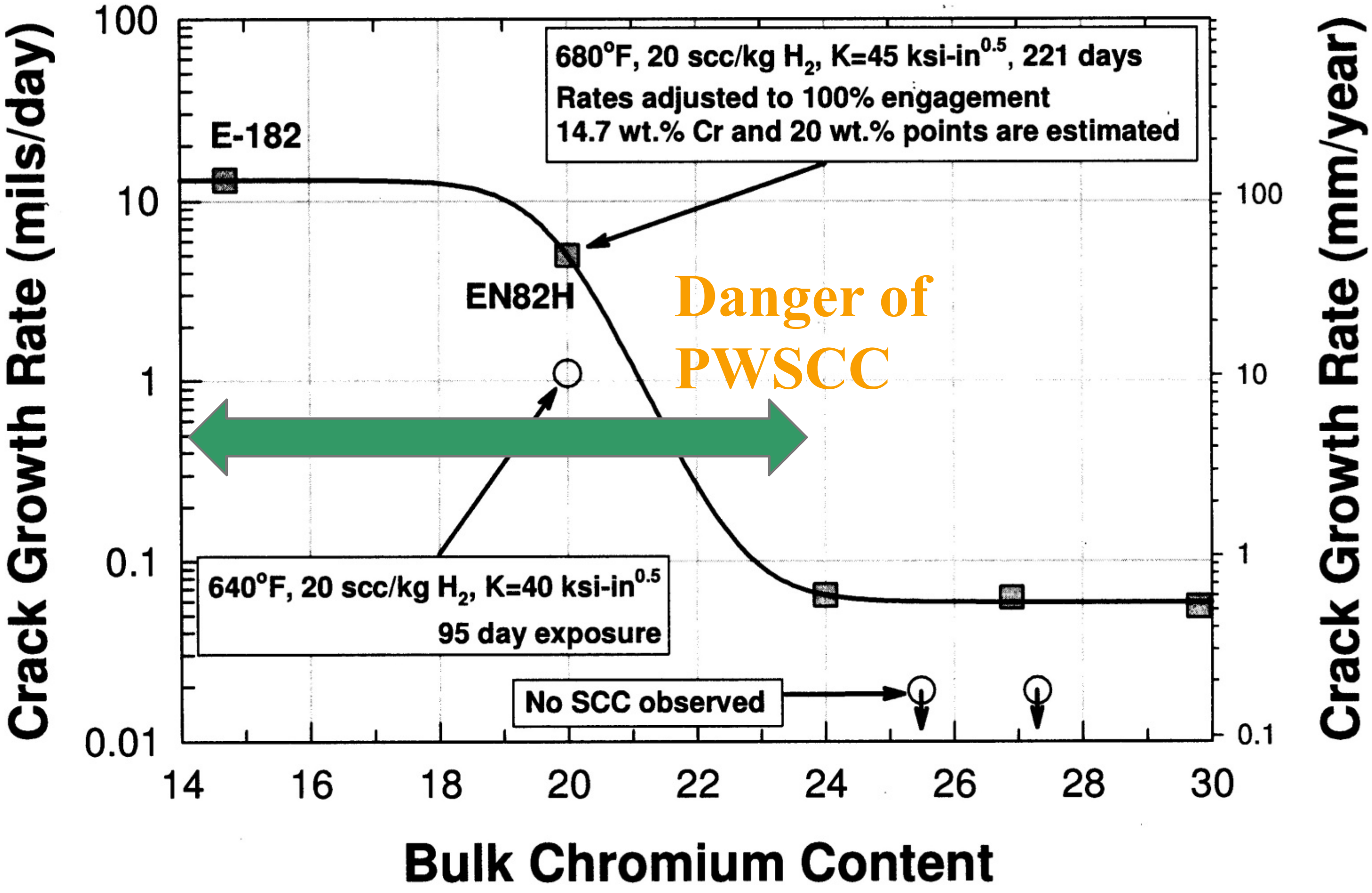


Figure 2-1
Location of Cracked Nickel-Base Welds in the Primary Circuit of PWR Units

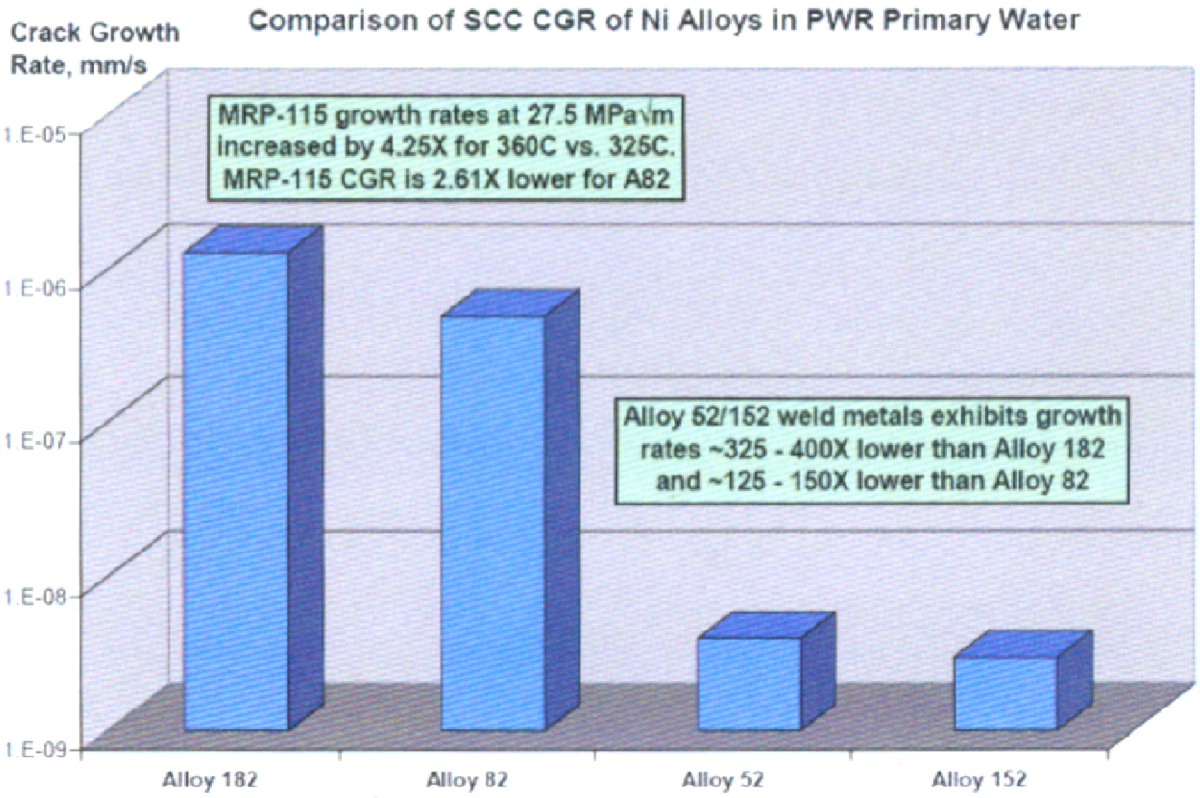
MRP-139, Figure 2-1`

PWSCC as Function of Composition



From Etien et al., Corrosion 2008, Paper 08597

PWSCC as Function of Composition



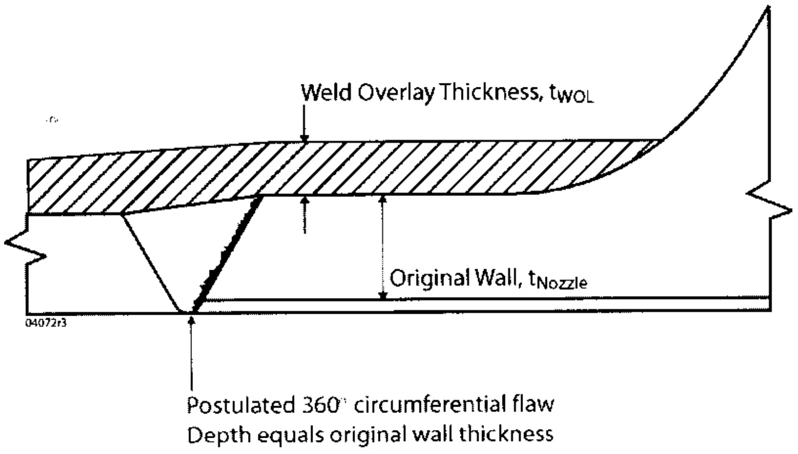
Comparison of SCC CGR of Ni Alloys in PWR Primary Water

MRP-115 growth rates at 27.5 MPa$\sqrt{m}$ increased by 4.25X for 360C vs. 325C. MRP-115 CGR is 2.61X lower for A82

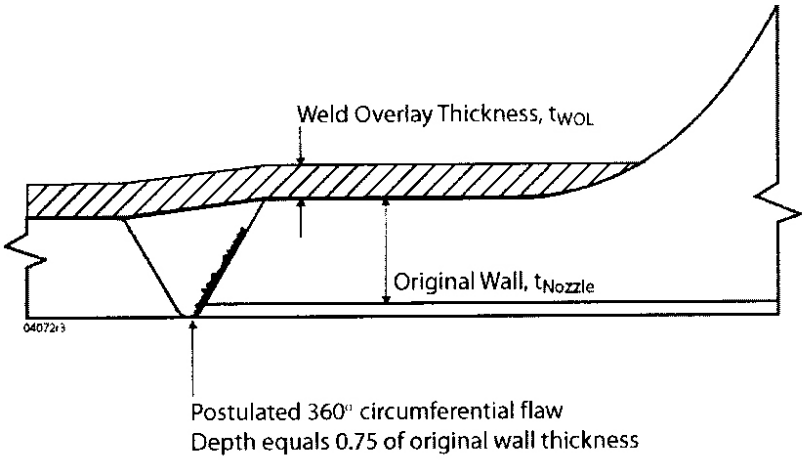
Alloy 52/152 weld metals exhibits growth rates ~325 - 400X lower than Alloy 182 and ~125 - 150X lower than Alloy 82

MRP-237, Figure 2-30 (from GE-GRC)

The Antidote – SWOL or PWOL



a) Full Structural Weld Overlay (FSWOL)



b) Optimized WOL (OWOL)

MRP-169, Figure 4-2

Summary of Weld Overlay Design Types

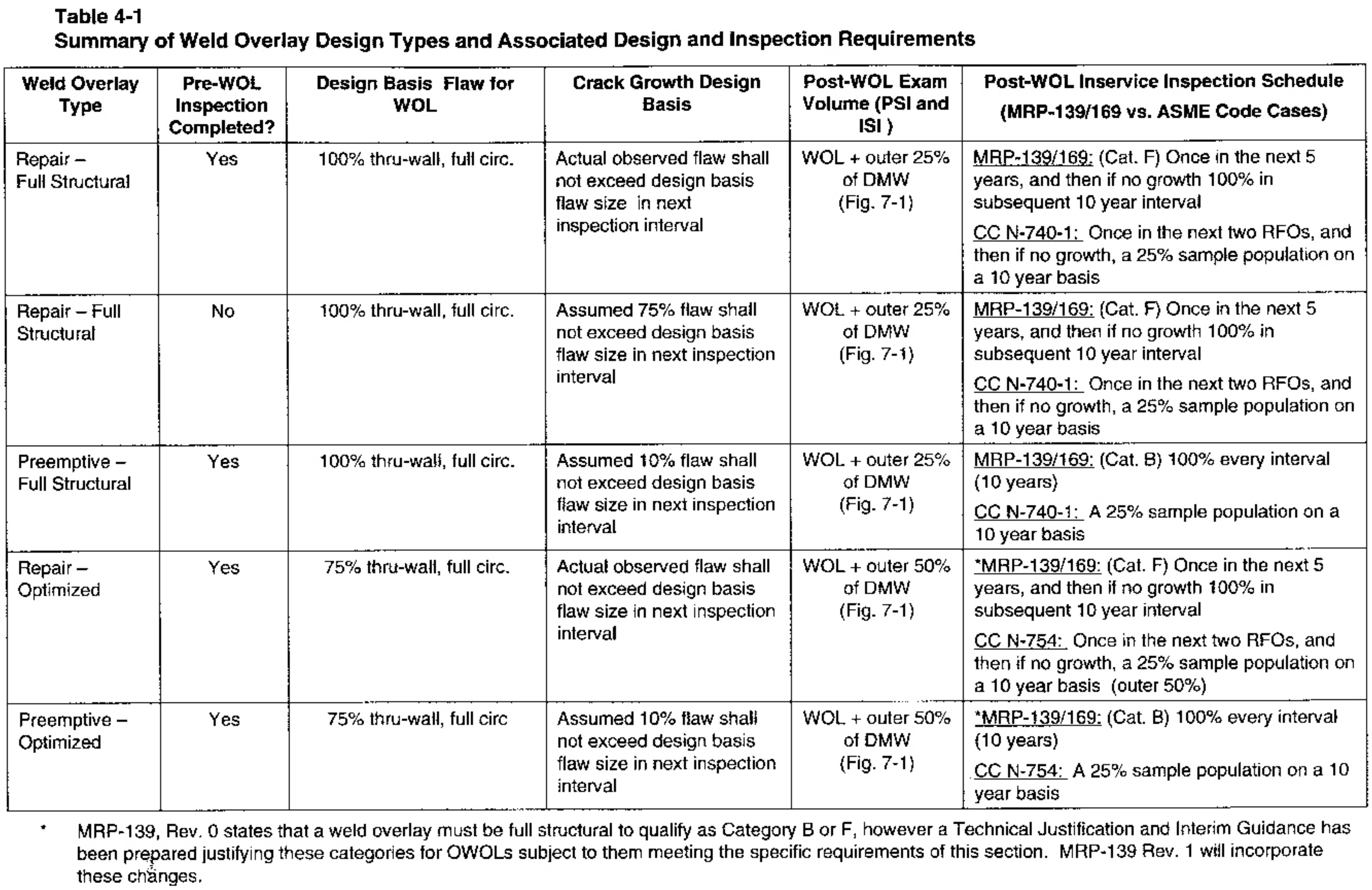


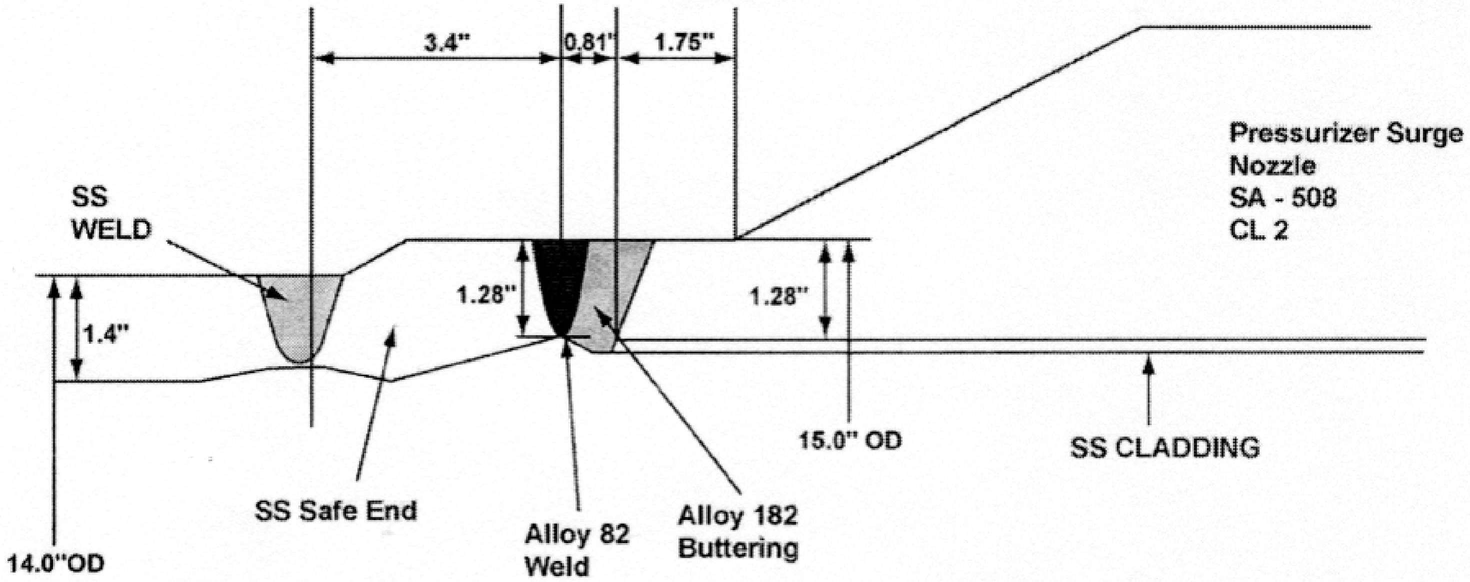
Table 4-1
Summary of Weld Overlay Design Types and Associated Design and Inspection Requirements

Weld Overlay Type	Pre-WOL Inspection Completed?	Design Basis Flaw for WOL	Crack Growth Design Basis	Post-WOL Exam Volume (PSI and ISI)	Post-WOL Inservice Inspection Schedule (MRP-139/169 vs. ASME Code Cases)
Repair – Full Structural	Yes	100% thru-wall, full circ.	Actual observed flaw shall not exceed design basis flaw size in next inspection interval	WOL + outer 25% of DMW (Fig. 7-1)	MRP-139/169: (Cat. F) Once in the next 5 years, and then if no growth 100% in subsequent 10 year interval CC N-740-1: Once in the next two RFOs, and then if no growth, a 25% sample population on a 10 year basis
Repair – Full Structural	No	100% thru-wall, full circ.	Assumed 75% flaw shall not exceed design basis flaw size in next inspection interval	WOL + outer 25% of DMW (Fig. 7-1)	MRP-139/169: (Cat. F) Once in the next 5 years, and then if no growth 100% in subsequent 10 year interval CC N-740-1: Once in the next two RFOs, and then if no growth, a 25% sample population on a 10 year basis
Preemptive – Full Structural	Yes	100% thru-wall, full circ.	Assumed 10% flaw shall not exceed design basis flaw size in next inspection interval	WOL + outer 25% of DMW (Fig. 7-1)	MRP-139/169: (Cat. B) 100% every interval (10 years) CC N-740-1: A 25% sample population on a 10 year basis
Repair – Optimized	Yes	75% thru-wall, full circ.	Actual observed flaw shall not exceed design basis flaw size in next inspection interval	WOL + outer 50% of DMW (Fig. 7-1)	*MRP-139/169: (Cat. F) Once in the next 5 years, and then if no growth 100% in subsequent 10 year interval CC N-754: Once in the next two RFOs, and then if no growth, a 25% sample population on a 10 year basis (outer 50%)
Preemptive – Optimized	Yes	75% thru-wall, full circ	Assumed 10% flaw shall not exceed design basis flaw size in next inspection interval	WOL + outer 50% of DMW (Fig. 7-1)	*MRP-139/169: (Cat. B) 100% every interval (10 years) CC N-754: A 25% sample population on a 10 year basis

* MRP-139, Rev. 0 states that a weld overlay must be full structural to qualify as Category B or F, however a Technical Justification and Interim Guidance has been prepared justifying these categories for OWOLs subject to them meeting the specific requirements of this section. MRP-139 Rev. 1 will incorporate these changes.

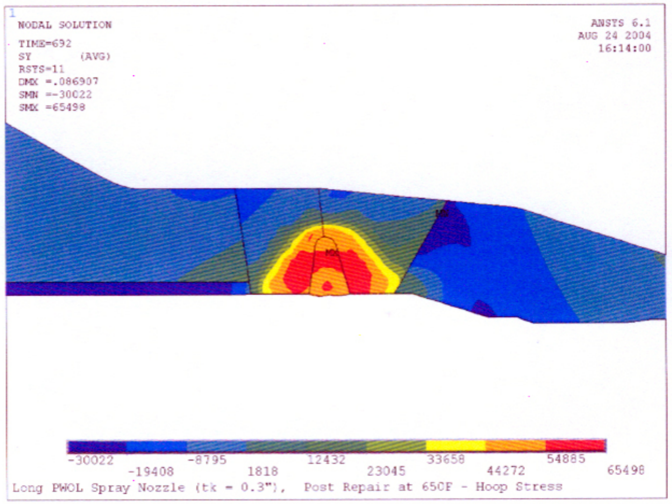
MRP-169, Table 4-1

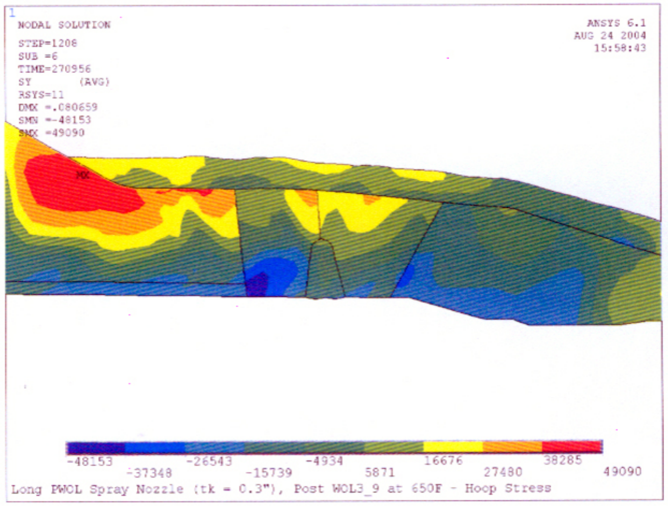
Example – Pressurizer Nozzle

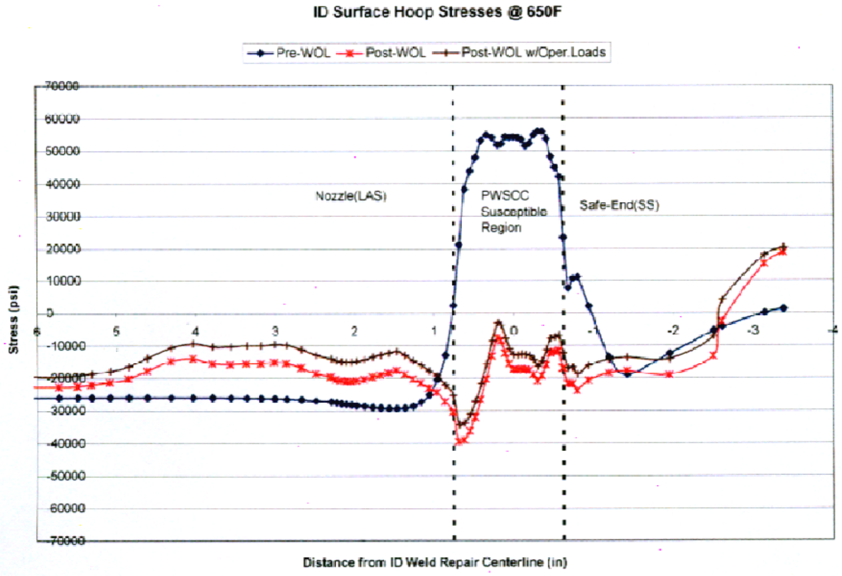


MRP-169, Figure 8-2

Stress Analysis

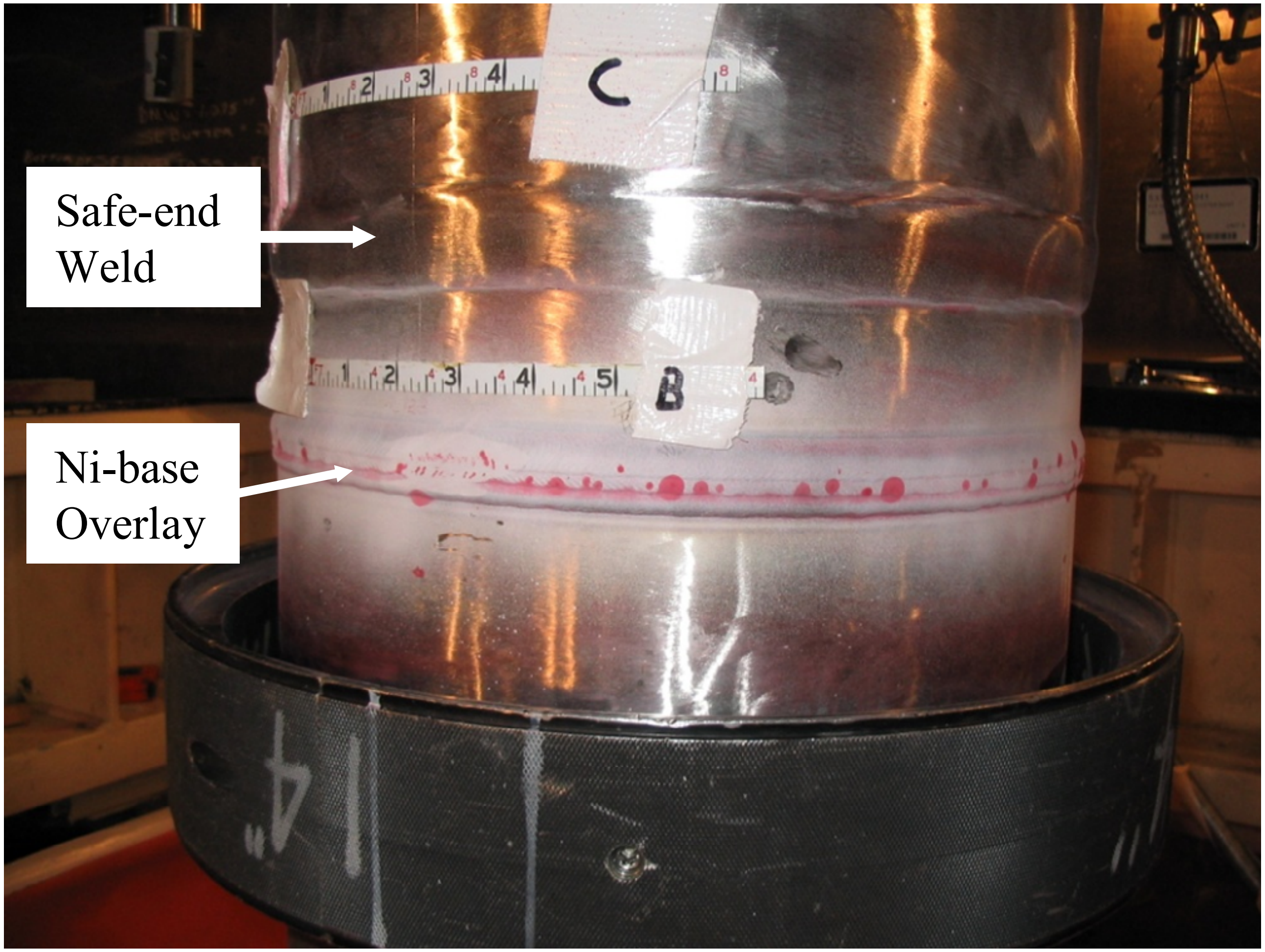






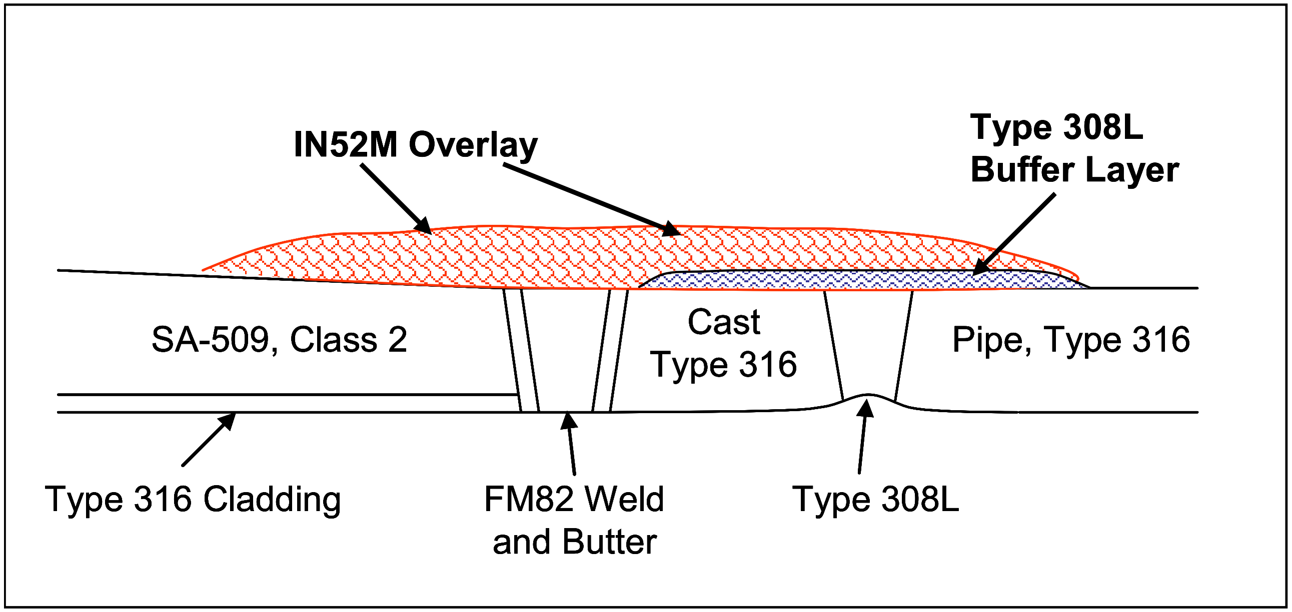
MRP-169, Figures 8-9 and 8-10

Then – A Problem



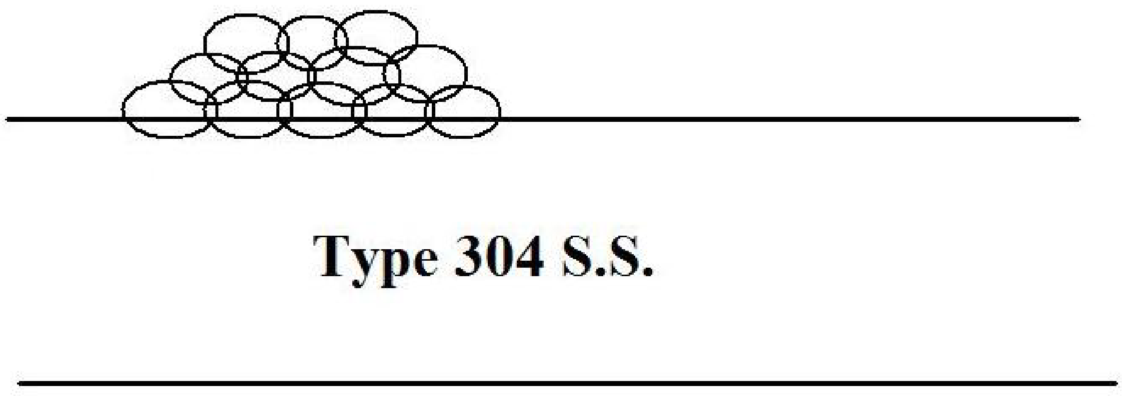
Use of Stainless Steel Buffer Layers

- Solidification cracking of overlays applied to some stainless steels
- Root cause – high sulfur levels of the stainless steel
- Solution – add stainless steel buffer layer



Use of Stainless Steel Buffer Layers

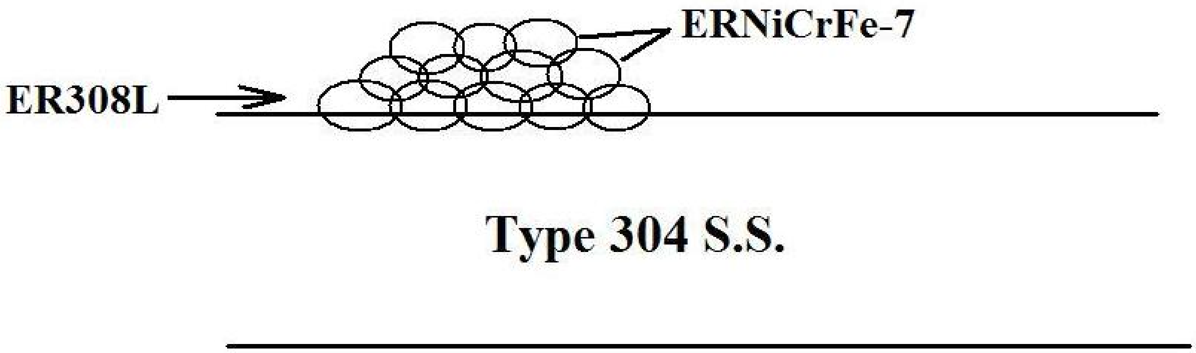
- You are overlaying Type 304 S.S. pipe with Inconel Filler Metal 52 (ERNiCrFe-7), shown in the Figure below. When depositing the layer of IN52 you encounter solidification cracking. Why does this occur?
  - The table gives the composition of the base and filler metal



Compositions (wt.%)

	Cr	Ni	Mn	Si	Mo	Nb	C	N	S	P	Cu	Ti
304	18.8	12	1.2	0.5	0.2	0	0.08	0.06			0.01	0
ERNiCrFe-7	30	43	1	1	0.5	0.1	0.04	0	0.01	0.02	0.3	1

Use of Stainless Steel Buffer Layers



Compositions (wt.%)

	Cr	Ni	Mn	Si	Mo	Nb	C	N	S	P	Cu	Ti
304	18.8	12	1.2	0.5	0.2	0	0.08	0.06	0.04	0.045	0.01	0
ER308L	19.5	10.5	1.25	1	0.75	0	0.04	0.03	0.01	0.04	0.1	0
ERNiCrFe-7	30	43	1	1	0.5	0.1	0.04	0	0.01	0.02	0.3	1

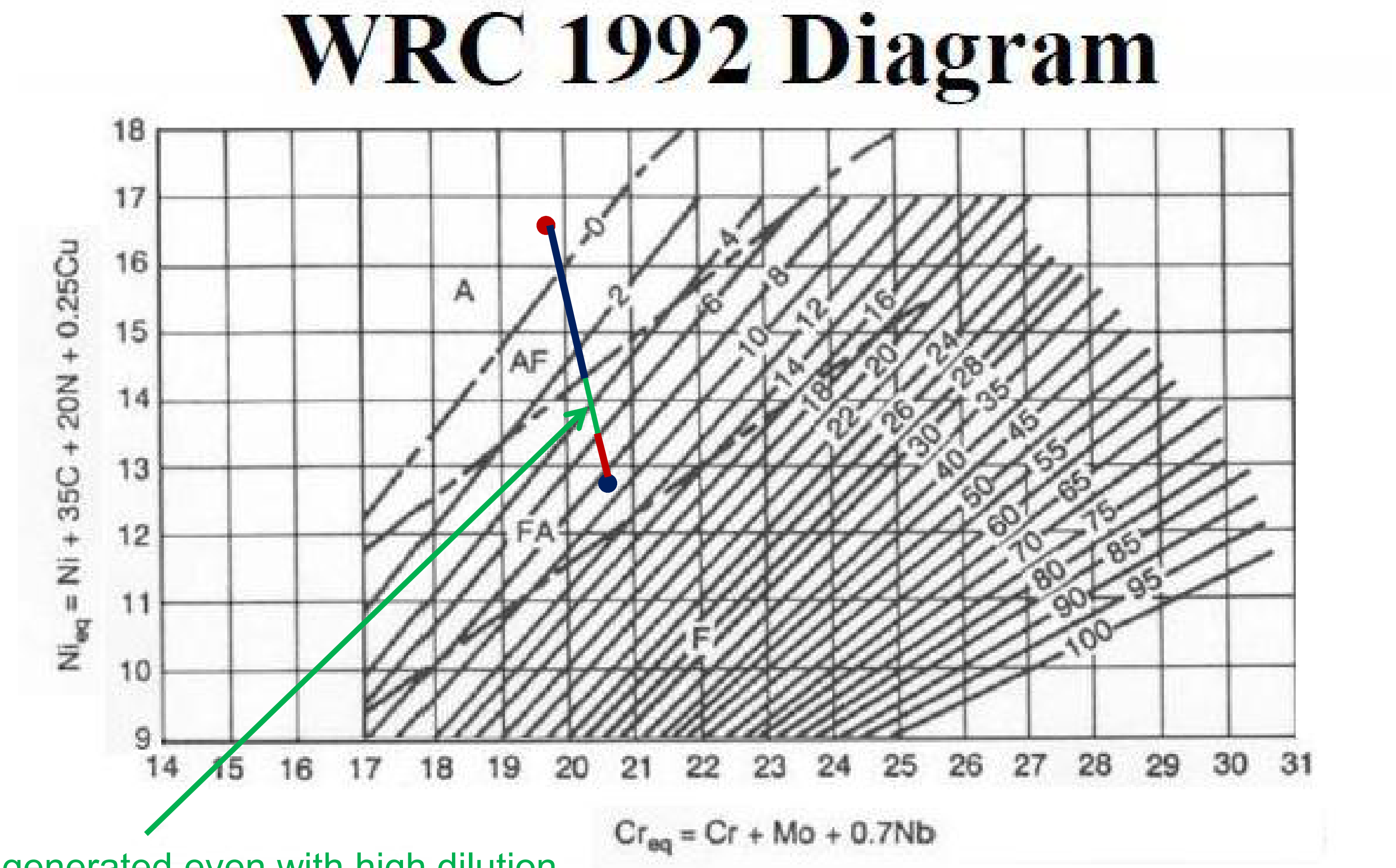
$$Ni_{EQ}^{304} = 12 + 35 \times 0.08 + 20 \times 0.06 + 0.25 \times 0.01 = 16$$

$$Cr_{EQ}^{304} = 18.8 + 0.2 + 0.7 \times 0 = 20$$

$$Ni_{EQ}^{ER308L} = 10.5 + 35 \times 0.04 + 20 \times 0.03 + 0.25 \times 0.1 = 12.5$$

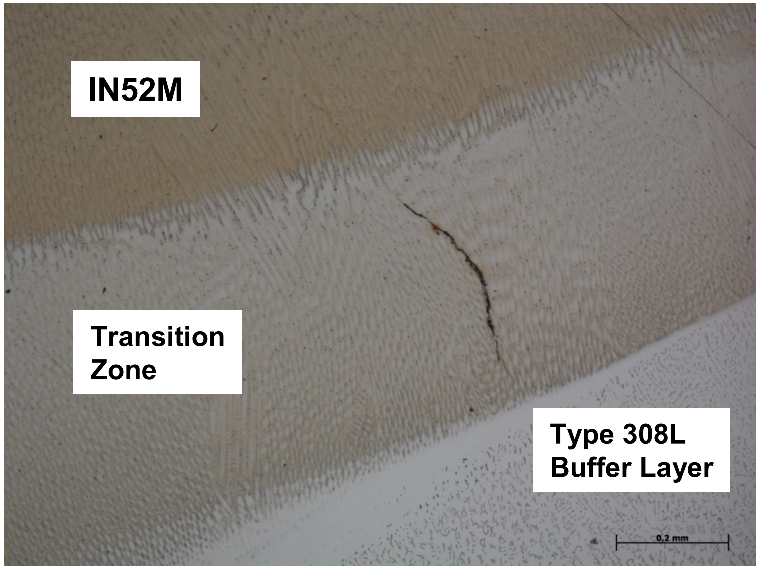
$$Cr_{EQ}^{ER308L} = 19.5 + 1.25 + 0.7 \times 0 = 20.75$$

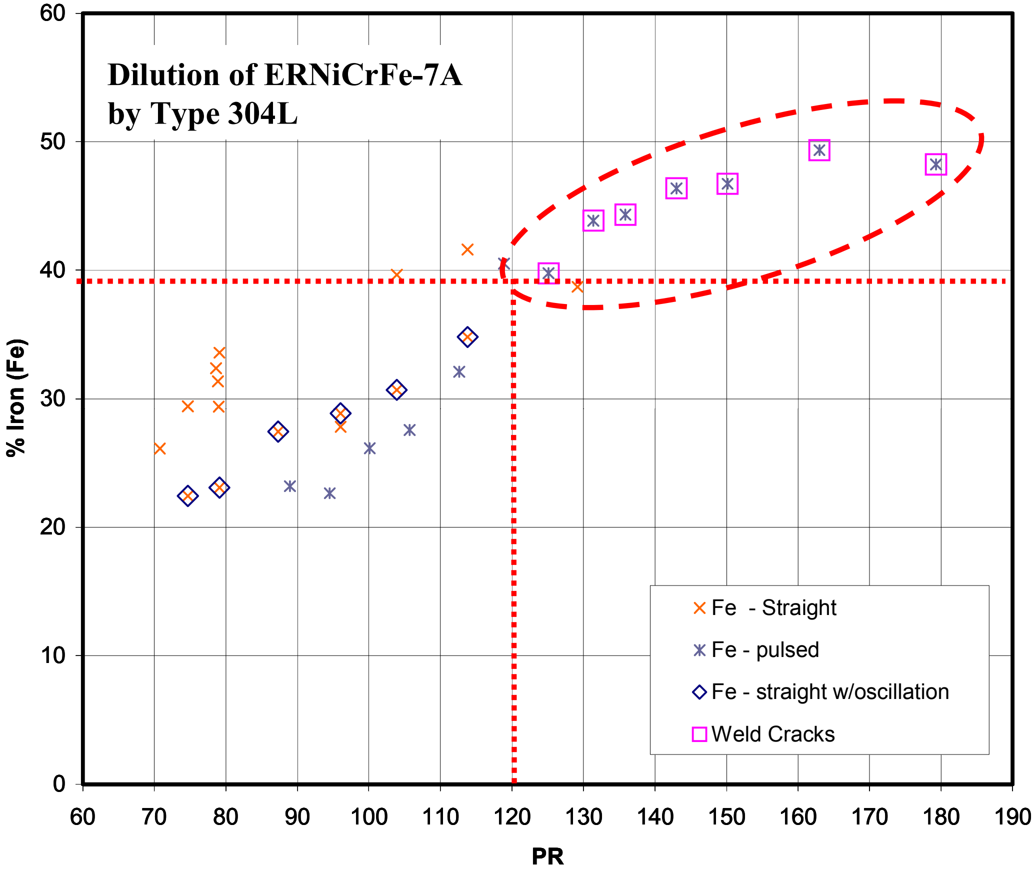
Case Study: Ni-Base Overlays on Stainless Steel



Ferrite is generated even with high dilution providing resistance to solidification cracking

But – There May Still be a Problem





$$\text{Power Ratio} = \frac{I \times V}{(\text{WFS/TS}) \times A_{\text{wire}}}$$

Other Nonferrous Alloys

Module 3F

Nonferrous Alloys

- Selection of nonferrous alloys based on performance advantages over steel
    - Strength/weight or “specific” strength
    - Corrosion resistance
    - Conductivity
- More expensive than steel on per pound basis
- Greater concern for fabricability
- Alloy specific weldability issues

Classes of Nonferrous Alloys

- Aluminum alloys
- Cobalt alloys
- Copper alloys
- Lead alloys
- Magnesium alloys
- Molybdenum alloys
- Nickel alloys
- Silicon alloys
- Tin alloys
- Titanium alloys
- Tungsten alloys
- Zinc alloys
- Precious metals

Alloy Selection

- Aluminum alloys
  - Low density
  - Moderate strength
  - Corrosion resistance
  - Conductivity
- Titanium alloys
  - Specific strength
  - Corrosion resistance
  - Damage tolerance
- Nickel alloys
  - Corrosion resistance
  - Moderate to high strength
  - Elevated temperature properties
- Copper alloys
  - Electrical/thermal conductivity
  - Corrosion resistance

Weldability Issues

- Solidification and liquation cracking
- Porosity
- Postweld heat treatment cracking
- Joint efficiency (strength)
- Weldment properties

Aluminum Alloys

- Low density
- Electrical conductivity (2 times Cu on weight basis)
- Thermal conductivity (50-60% of Cu)
- Strengthened by cold work and/or precipitation
- Good fabricability
  - Machinability
  - Formability
  - Weldability

Classes of Aluminum Alloys

Series	Type of alloy composition	Strengthening method	Tensile strength range	
			MPa	ksi
1*xxx*	Al	Cold work	70-175	10-25
2*xxx*	Al-Cu-Mg (1-2.5% Cu)	Heat treat	170-310	25-45
2*xxx*	Al-Cu-Mg-Si (3-6% Cu)	Heat treat	380-520	55-75
3*xxx*	Al-Mn-Mg	Cold work	140-280	20-40
4*xxx*	Al-Si	Cold work (some HT)	105-350	15-50
5*xxx*	Al-Mg (1-2.5% Mg)	Cold work	140-280	20-40
5*xxx*	Al-Mg-Mn (3-6% Mg)	Cold work	280-380	40-55
6*xxx*	Al-Mg-Si	Heat treat	150-380	22-55
7*xxx*	Al-Zn-Mg	Heat treat	380-520	55-75
7*xxx*	Al-Zn-Mg-Cu	Heat treat	520-620	75-90
8*xxx*	Al-Li-Cu-Mg	Heat treat	280-560	40-80

Commercial Uses

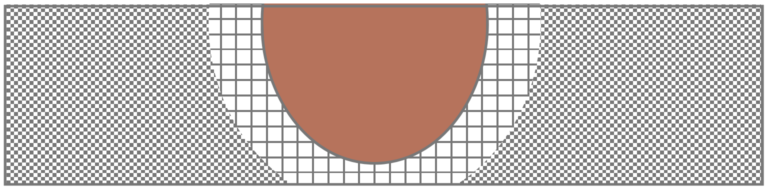
1XXX	Foil, electrical applications
2XXX	Structural aerospace and marine applications
3XXX	Can stock, cooking utensils, siding, sheet metal
4XXX	Welding filler metals
5XXX	Tanks, pressure vessels, automotive
6XXX	General structural, automotive
7XXX	Commercial aircraft skin and support structure
8XXX	Aerospace

Weldability Issues

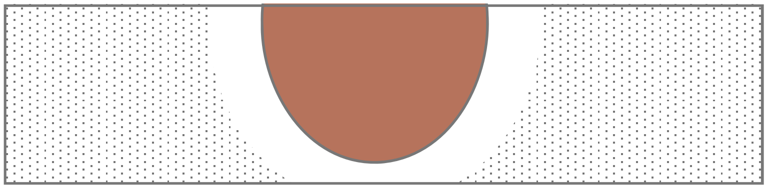
- Weld solidification cracking
- Liquation cracking
- Porosity
- Weld metal and HAZ property degradation
- Stress corrosion cracking and pitting

Softening in the Heat-Affected Zone

- Welding eliminates work hardened structure

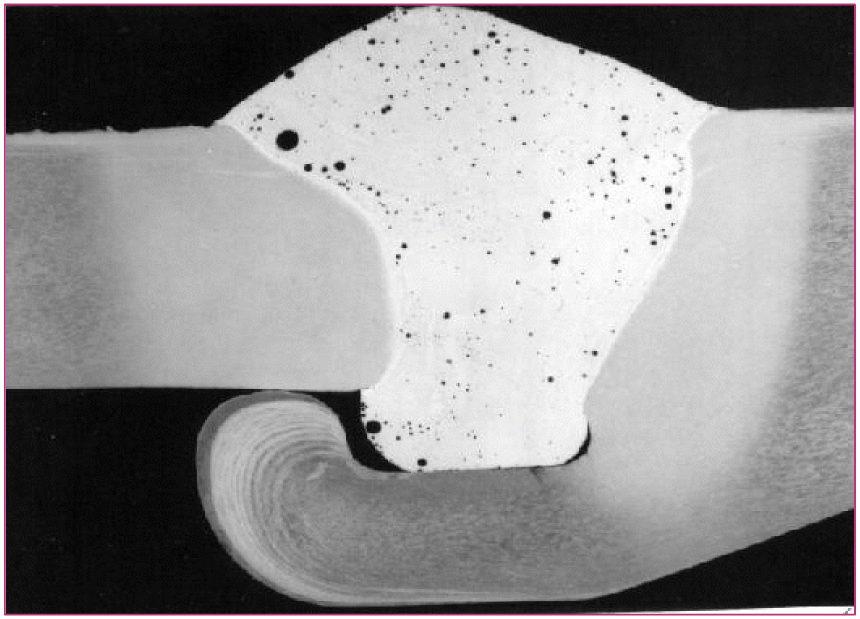


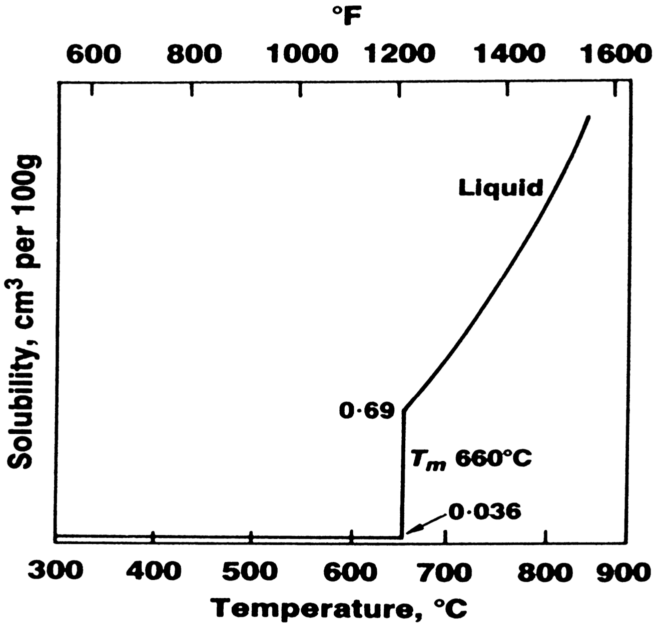
- Welding dissolves or overages precipitates in HAZ



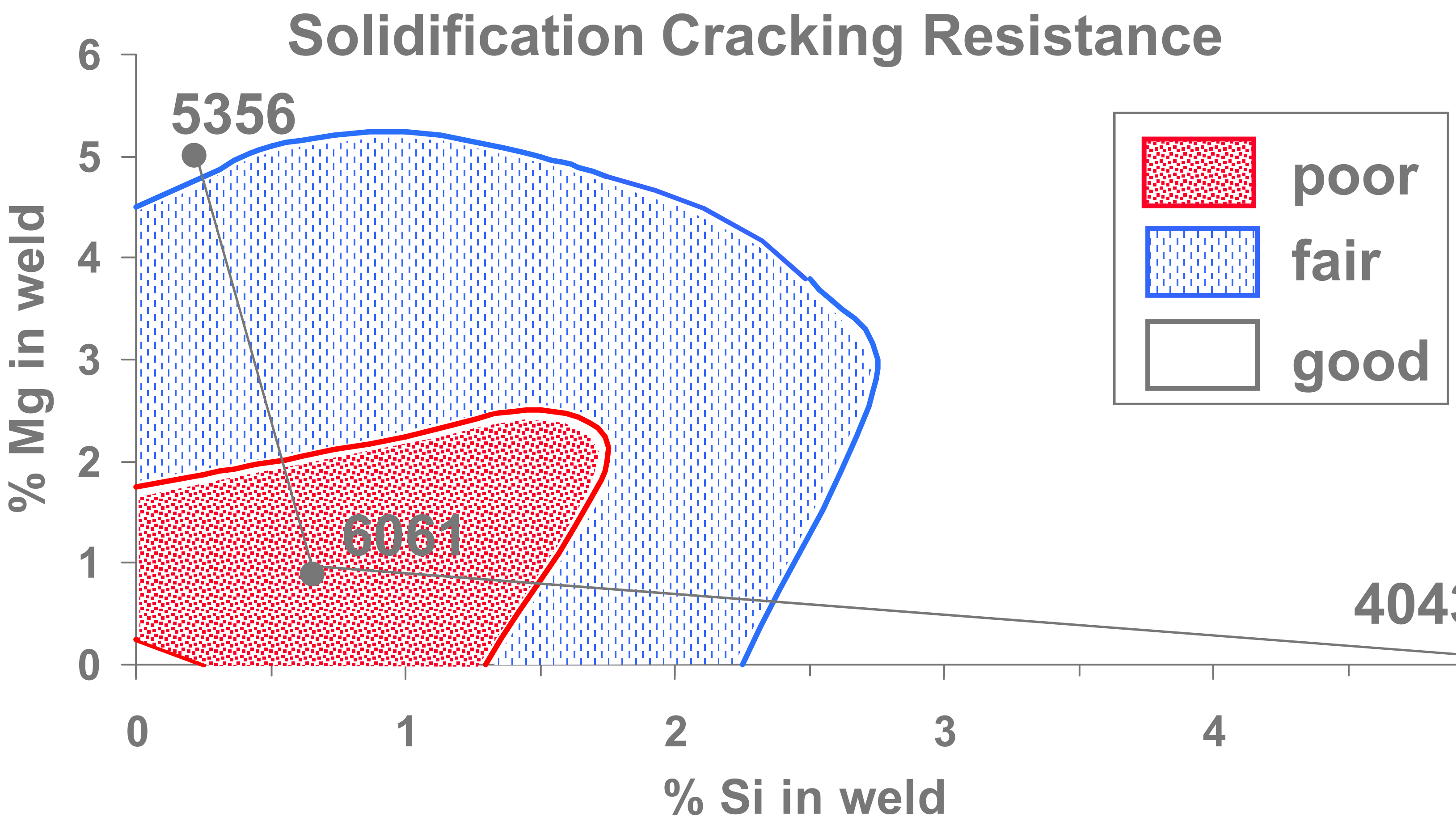
Reducing Hydrogen Porosity

- Most aluminum welds contain some level of porosity
  - Hydrogen is less soluble in solid aluminum than in liquid
- Reducing porosity
  - Plate surface should be properly cleaned and dried
  - Electromagnetic stirring

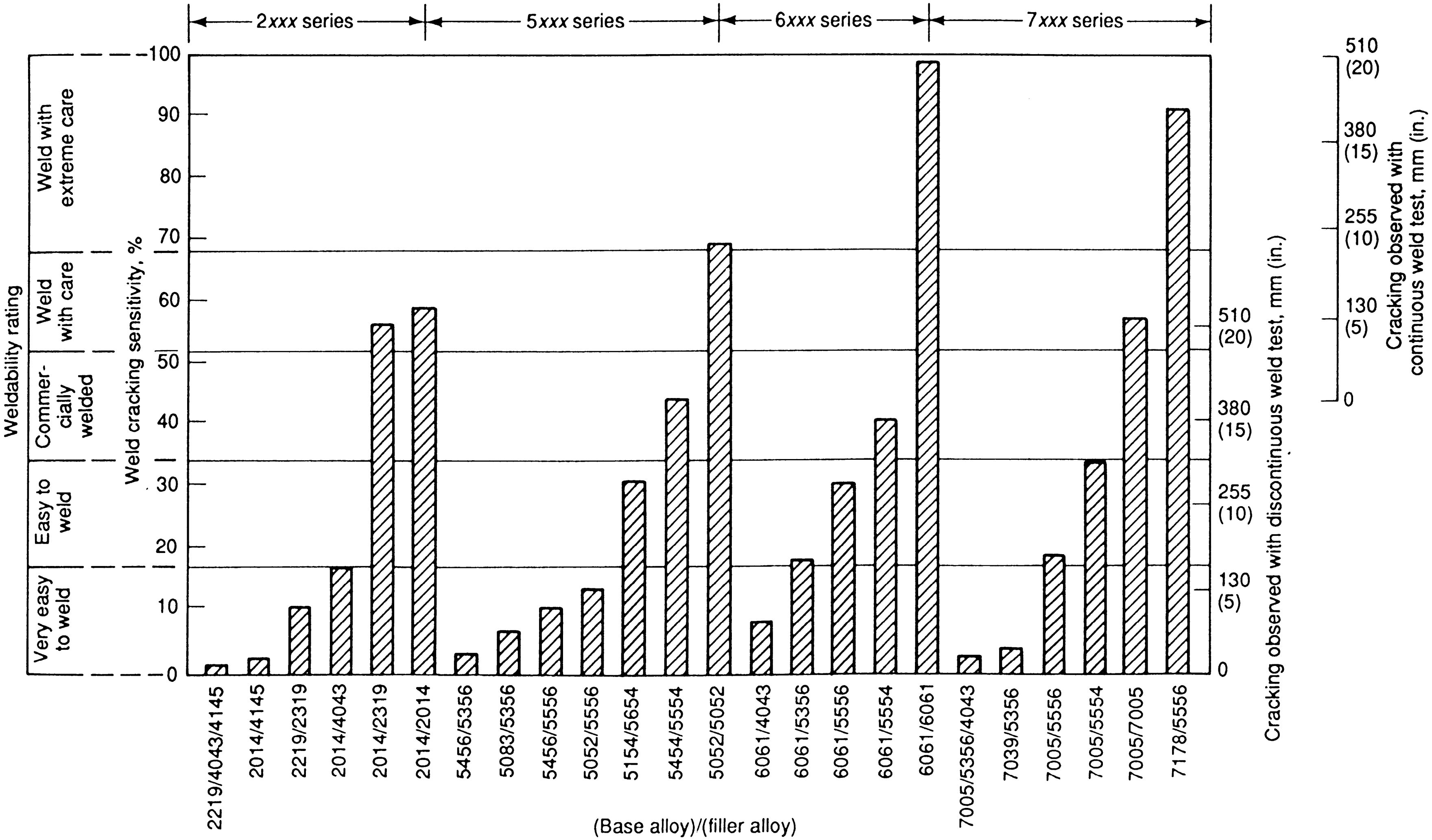




Why Not Weld 6061 with 6061?



Filler Metal Selection Chart



from ASM Handbook, 10th Edition, Volume 6

Titanium Alloys

- Low density
- High strength-to-weight ratio
- Low coefficient of thermal expansion
- Good corrosion resistance
- Use range up to 1000ºF (540ºC)
- Biocompatible
- Relatively high cost

Classes of Titanium Alloys

- Titanium alloys are classified by their microstructure
  - Commecially pure (CP) grades
  - Alpha and Near-Alpha Alloys
  - Alpha-Beta Alloys
  - Metastable Beta Alloys

Commercial Uses

- Corrosion Applications
  - Piping and tubing
  - Heat exchangers
  - Tanks and pressure vessels
  - Waste storage
  - Medical - joint replacement and implants
- Specific Strength Applications
  - Aerospace
    - Airplane “skin”
    - Structural support
    - Engines
  - Sporting goods (golf clubs, bicycle frames)

Weldability Issues

- Solidification segregation
- Beta grain size
- Weld solidification cracking
- Contamination cracking
- Ductility-dip cracking
- Hydrogen embrittlement
- Porosity

Characteristics

- High thermal and electrical conductivity
- Low to moderate strength
- High ductility and toughness
- Good corrosion resistance
- Good fabricability
- Architectural distinction

Classes of Alloys

Pure coppers	Oxygen Free, Electrolytic
Deoxidized	Contain P (reduces porosity)
Beryllium copper	1.5-2.0 wt% BE, age hardenable
Low-Zn brass	Red brass (15% Zn)
High-Zn brass	Cartridge brass (30% Zn)
Tin brass	Naval brass (39Zn-1Sn)
Nickel silver	20Zn-15Ni (silver luster)
Phosphor bronzes	1-10Zn, 0.2P
Al-bronzes	6-10 Al, Ni, Fe
Si-bronzes	1.5-3 Si
Copper-nickel	70Cu-30Ni (cupronickel)

Alloying Additions

Aluminum	Up to 15%, improves oxidation resistance
Nickel	Provides solid solution strength
Silicon	Deoxidation and solid-solution strength
Tin	Strength and corrosion resistance
Zinc	Strength, corrosion resistance and luster
Beryllium	Precipitation strengthener

- Pb, Se, S, and Te may be added to improve machinability

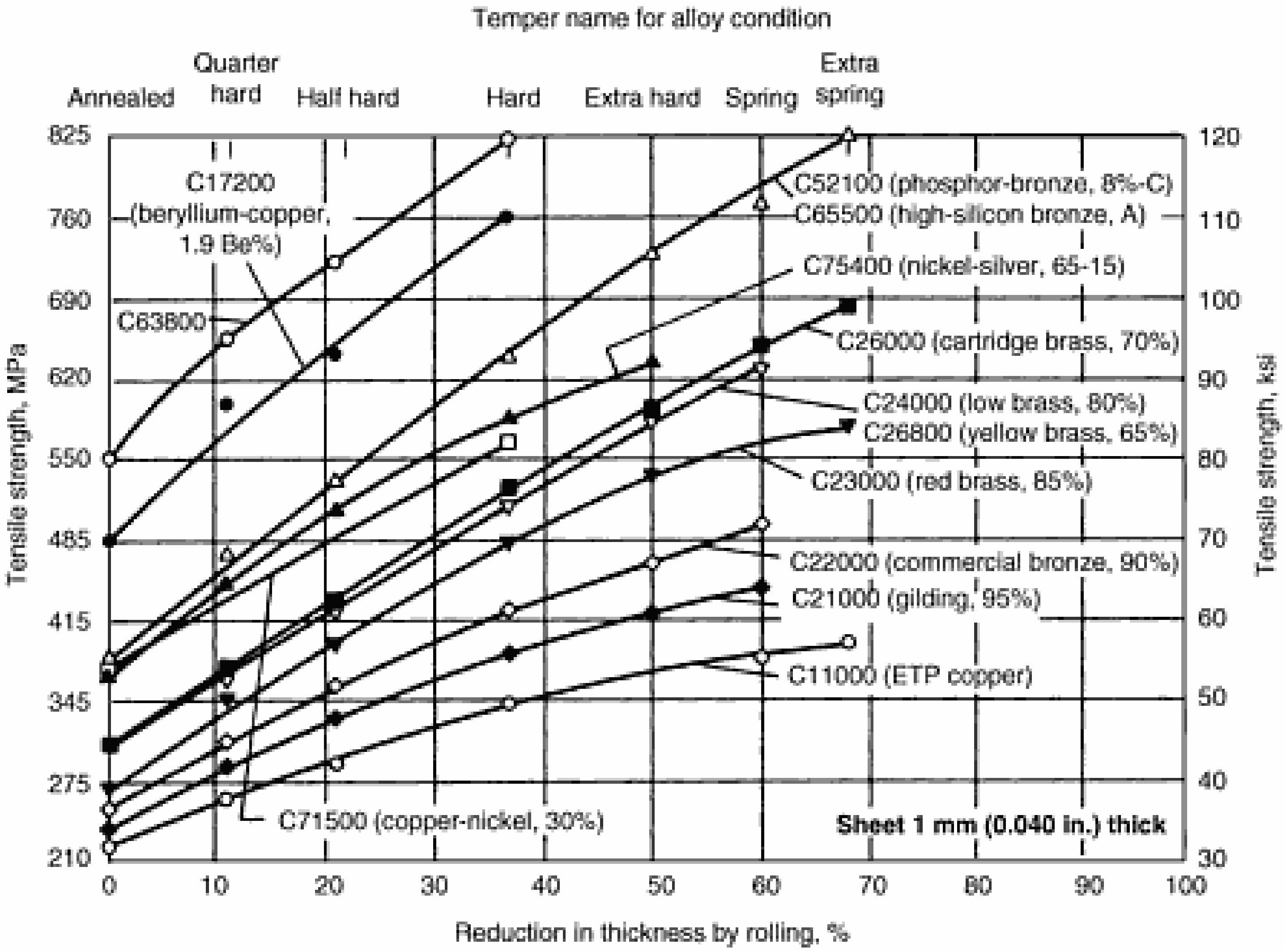
Applications

- Piping and tubing
  - Good resistance to pitting and stress corrosion cracking in marine environments
  - Easily fabricated by welding or brazing
- Heat exchangers
- Storage casks - nuclear fuel
- Architectural - roofing
- Other - caskets, golf clubs

Physical Metallurgy

- Single phase (FCC) or dual phase (FCC + BCC)
- Most alloying elements have high solubility in FCC phase
- Strengthened by
    - Solid-solution
    - Cold work
    - Precipitation (Be-bearing alloys)

Cold Work Hardening



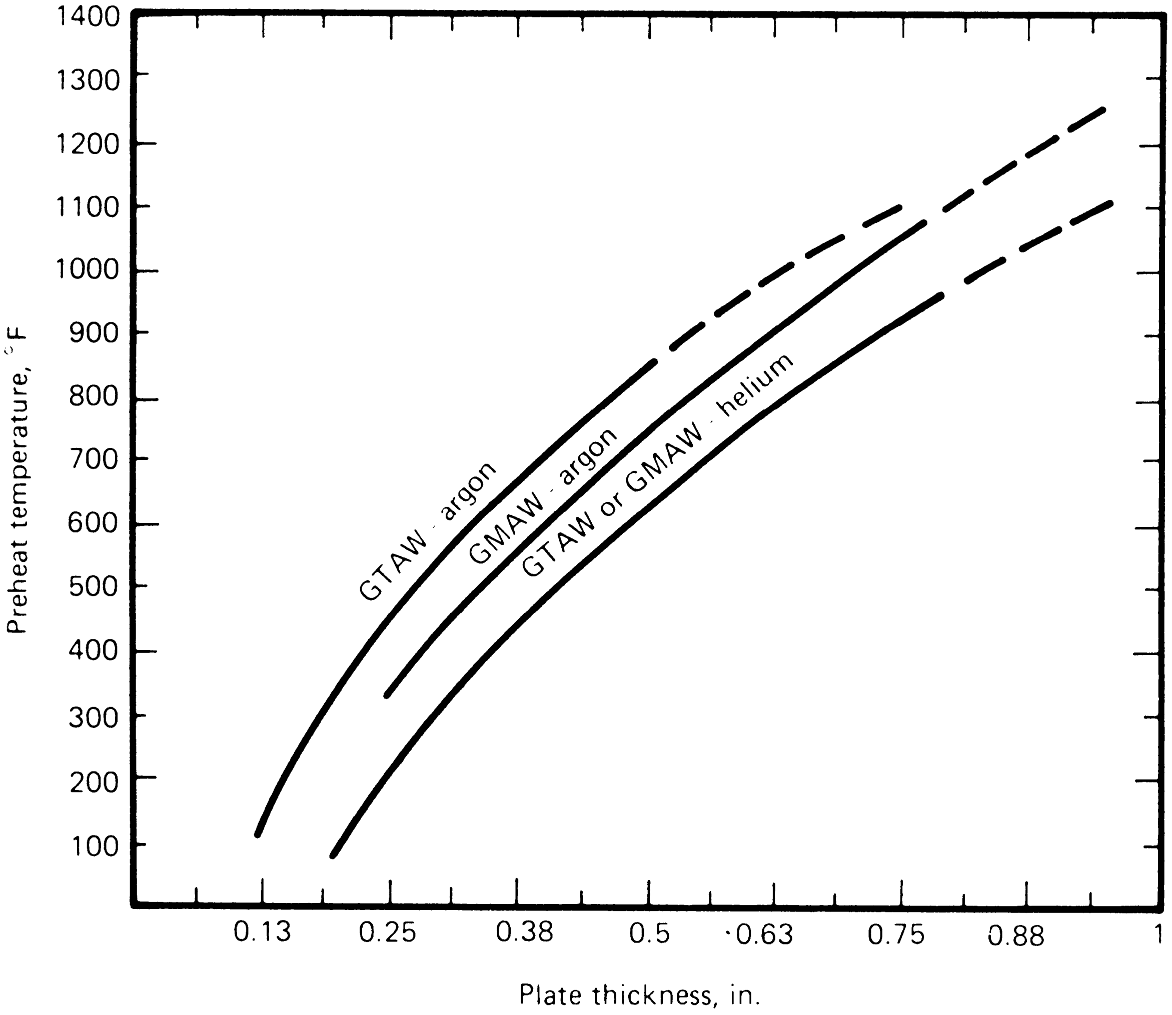
Weldability Issues

- Joint efficiency
  - Most alloys strengthened by cold work
  - Recrystallization and grain growth in HAZ
- Porosity
  - Alloys containing Zn, Cd, and (P can induce and control)
  - Selection of appropriate filler metal (P and Si)
- Solidification cracking
  - Alloys containing Sn and Ni
  - Wider solidification temperature range
  - Beware of free-machining grades
- Ductility dip cracking - 70Cu-30Ni
- Toxic Fumes
  - Alloys containing Be and Zn

Welding Considerations

- Mechanical or chemical cleaning if porosity is a problem
- Filler metals
  - Matching grades available for most alloys
  - Color match for architectural use
- Weld penetration
  - Most alloys have high thermal conductivity
  - Preheat required if thickness > 0.25 in. (~ 6 mm)

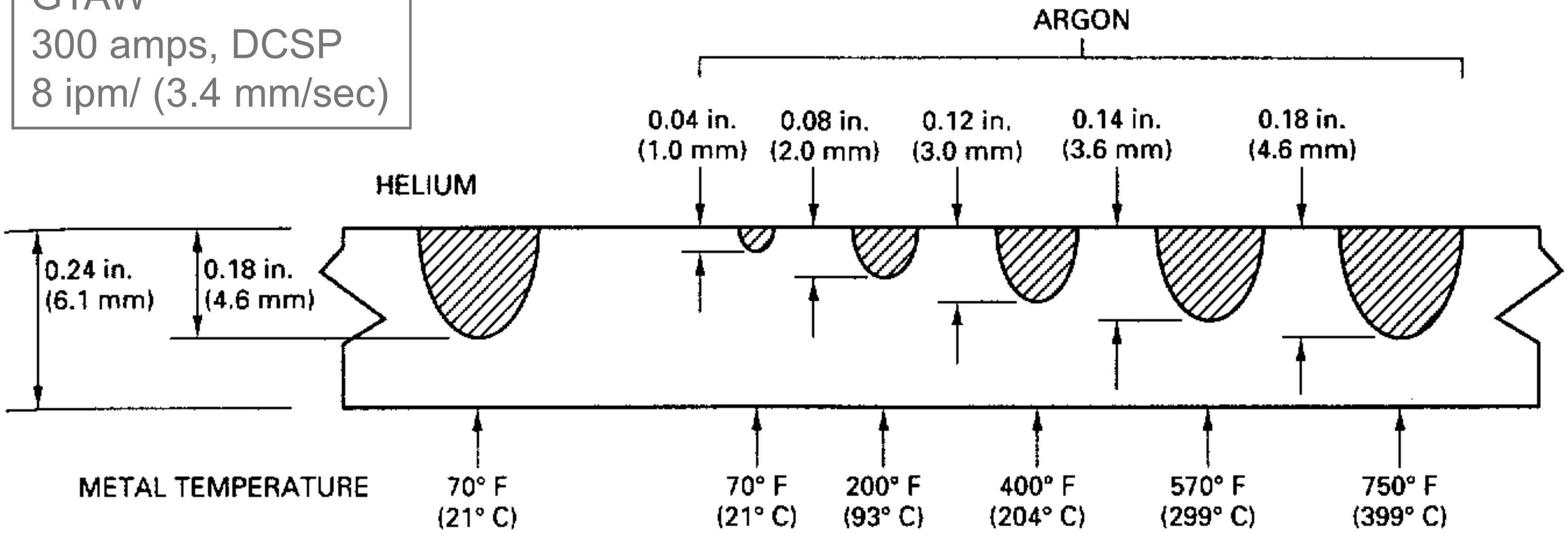
Preheat Requirements



AWS Welding Handbook, 8th Edition, Vol. 3

Effect of Shielding Gas and Preheat

GTAW
300 amps, DCSP
8 ipm/ (3.4 mm/sec)



AWS Welding Handbook, 8th Edition, Vol. 3

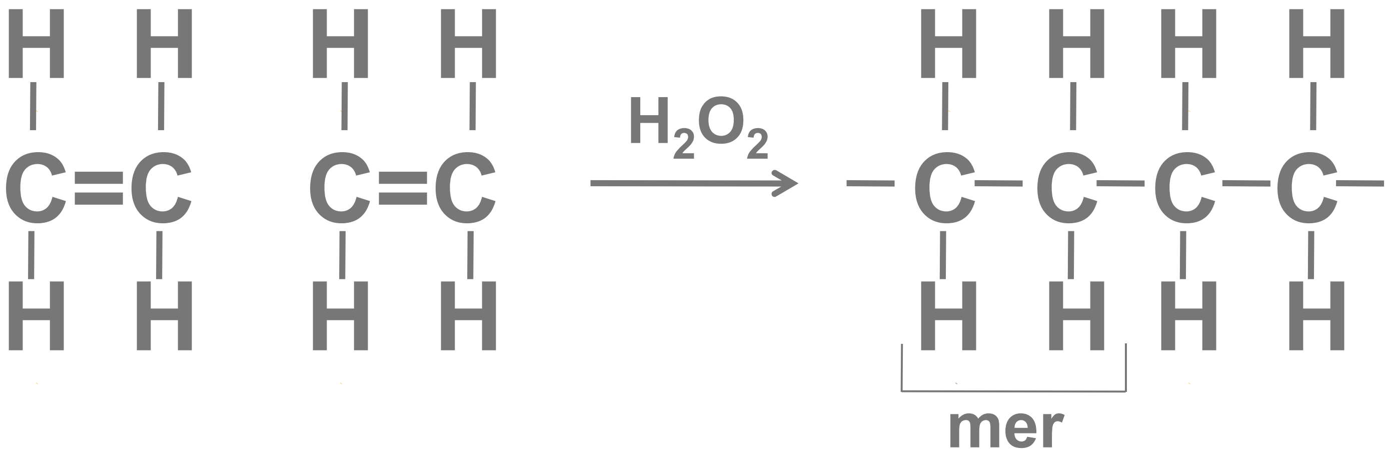
Polymers

Module 3G

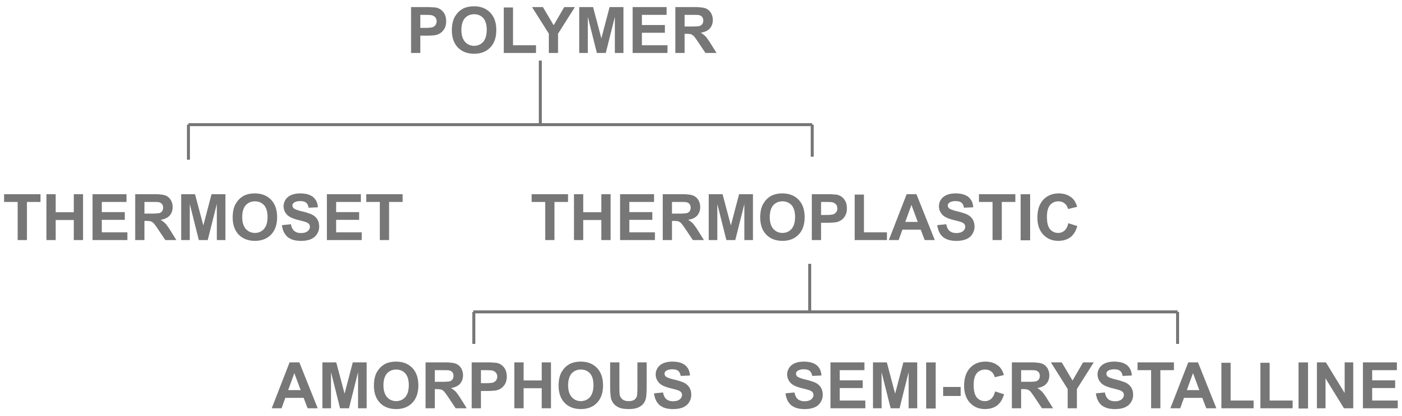
What is a Polymer?

- From Greek, Poly = many, Meros = parts
  Polymers are large molecules made up of many (poly) repeating units (meros or mers)
- Plastics – commercial synthetic polymers

(Poly)ethylene



Classification of Polymers



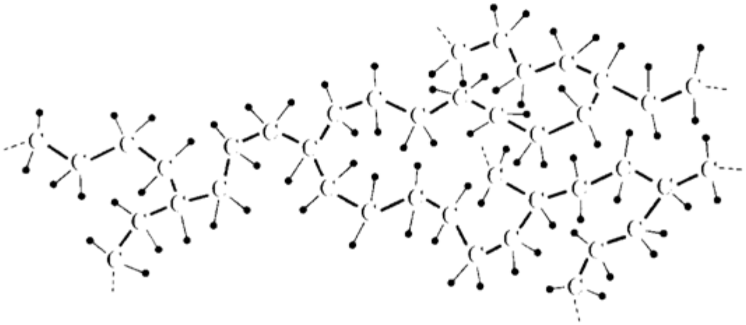
POLYMER

THERMOSET

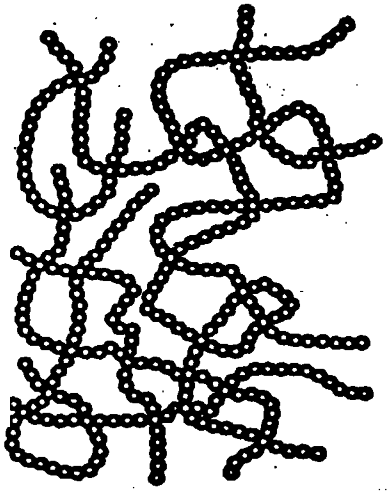
THERMOPLASTIC

AMORPHOUS

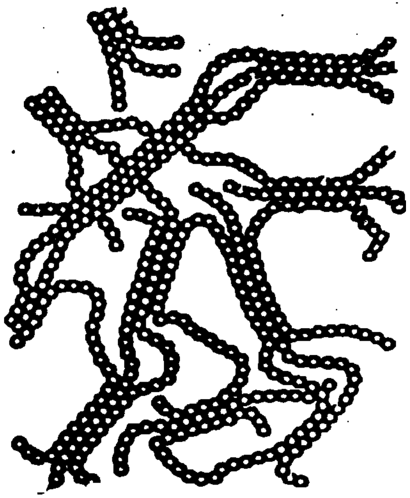
SEMI-CRYSTALLINE



Thermoset



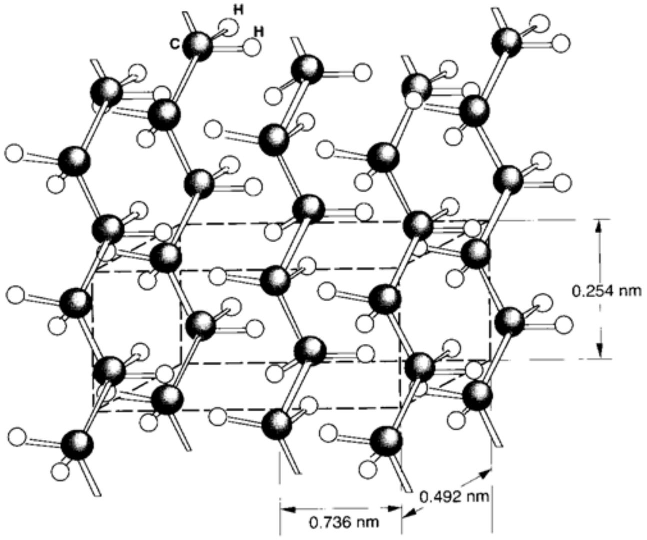
Amorphous



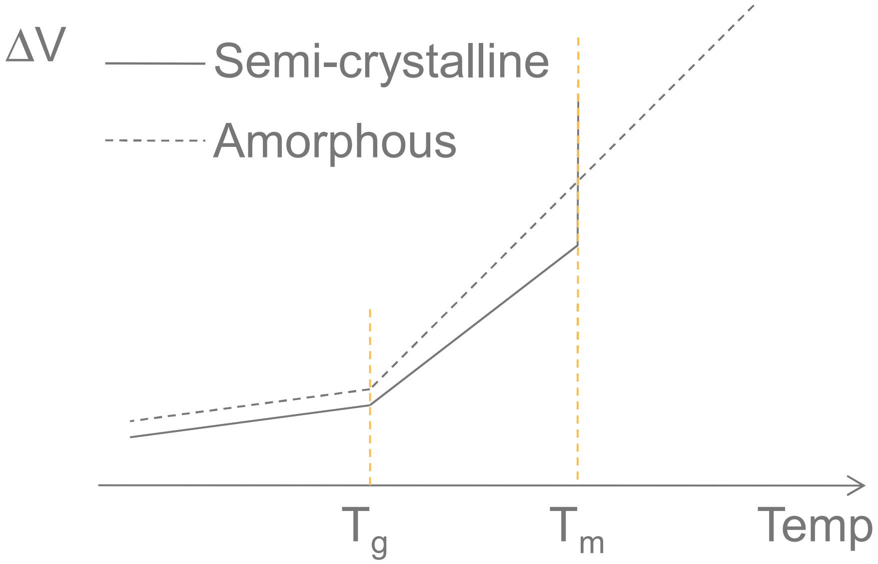
Semi-crystalline

Thermoplastics

- Amorphous polymers have no crystalline regions, chains are randomly oriented – like wet spaghetti
- Semi-crystalline polymers have crystalline regions where molecules fold on themselves forming orderly structure



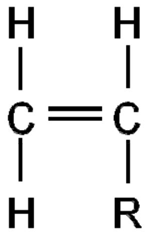
Crystalline Structure HDPE



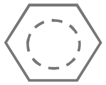
Polymer Types

- A variety of groups are attached to polymer backbones (e.g. Vinyl, Vinylidene compounds)

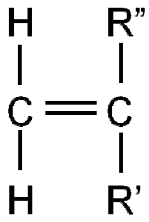
VINYL COMPOUNDS



$\underset{H}{\overset{H}{C}}=\underset{R}{\overset{H}{C}}$

- R	COMP.
- H	ETHYLENE
- Cl	VINYL CHLORIDE
- OH	VINYL ALCOHOL
- $CONH_2$	ACRYLAMIDE
- $COOCH_3$	METHYL ACRYLATE
- 	STYRENE

VINYLIDENE COMPOUNDS

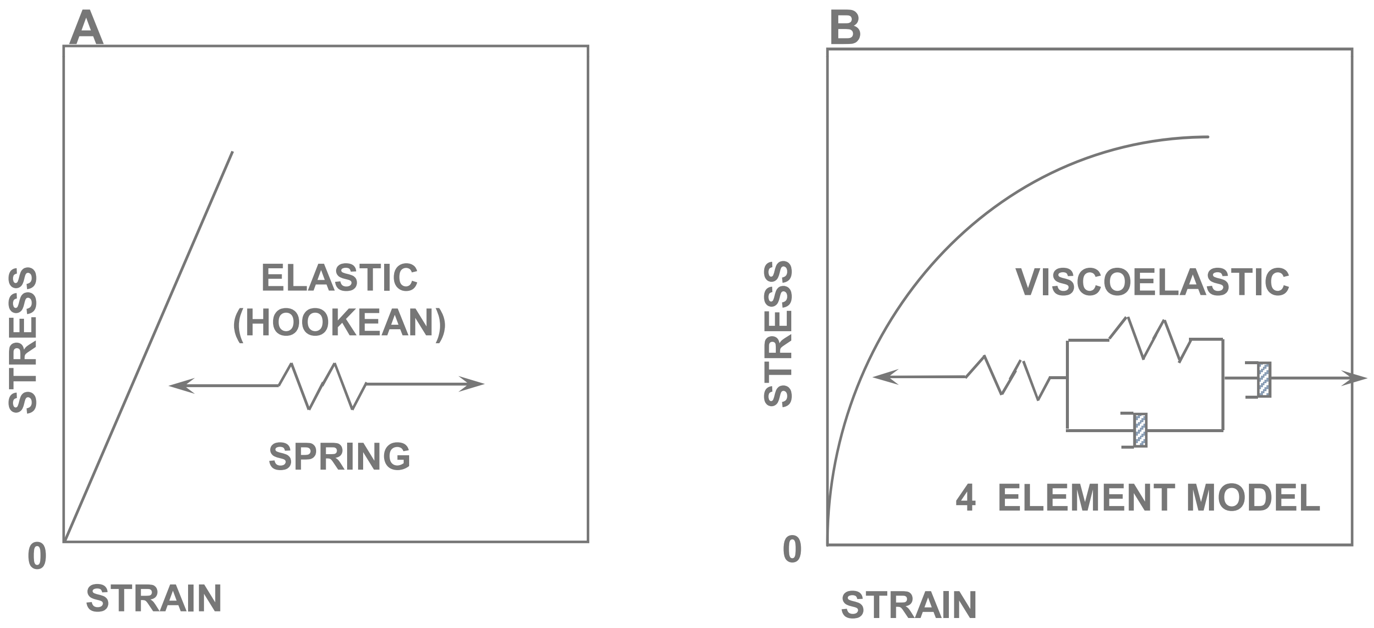


$\underset{H}{\overset{H}{C}}=\underset{R'}{\overset{R''}{C}}$

R'	R"	COMP.
$-CH_3$	$-CH_3$	ISOBUTYLENE
-Cl	- Cl	VINYLIDENE CHLORIDE
$-CH_3$	$-COOCH_3$	METHYL METHACRYLATE
-F	-F	VINYLIDENE FLUORIDE

Viscoelasticity

- When stressed, thermoplastics exhibit both elastic and viscous behavior
  - Elastic – Spring-like
  - Viscous - Dashpot



Joining of Polymers

- Mechanical connections
  - Press fits
  - Snap fits
  - Rivets, bolts
  - Staking
  - Swaging
- Adhesive bonding
- Joining
  - Currently there is no requirements incorporated into ASME Section IX that covers joining of polymers
  - ASME B31.1, Nonmandatory Appendix III covers joining qualifications

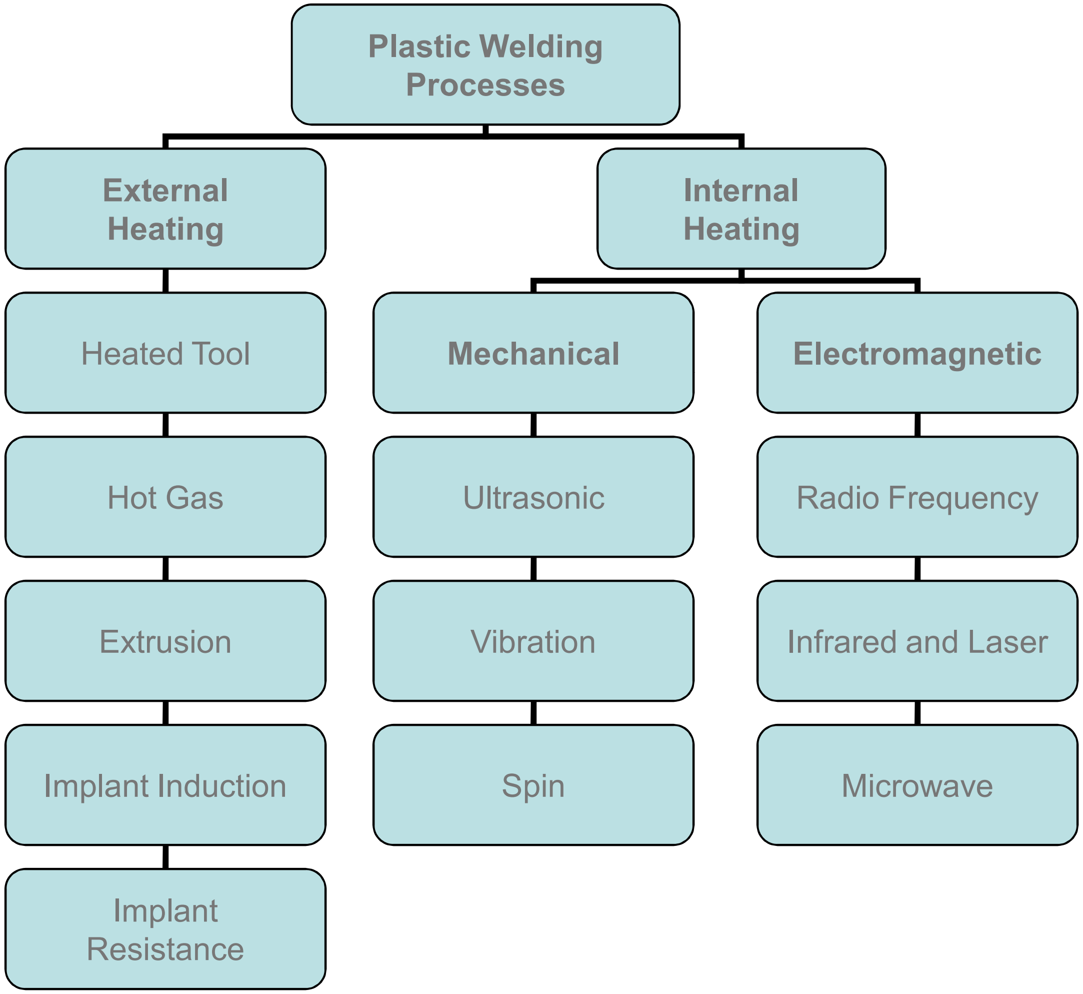
Staking

Snap-fit

Welding Steps

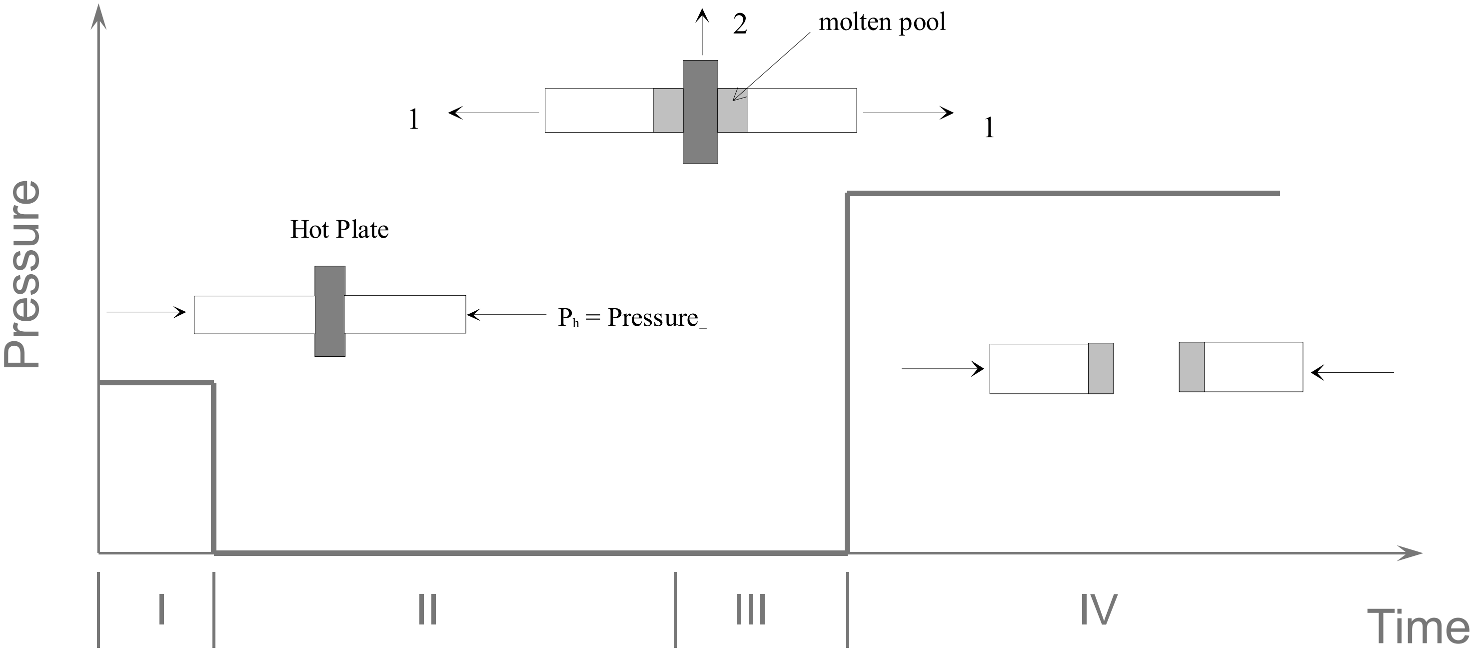
- Surface Preparation
  - Clean and/or square the surfaces for welding
- Surface Heating
  - Heat to soften or melt the polymer at the weld interface
- Pressing
  - Apply pressure to deform surface asperities and to achieve intimate contact
- Intermolecular Diffusion
  - Diffusion of polymer chains across interface and chain entanglement provides strength to the joint
- Cooling

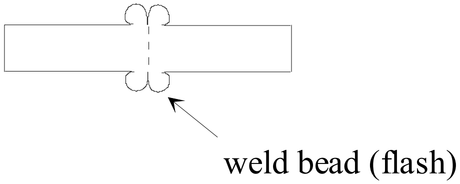
Plastic Welding Methods



- **Plastic Welding Processes**
  - **External Heating**
    - Heated Tool
    - Hot Gas
    - Extrusion
    - Implant Induction
    - Implant Resistance
  - **Internal Heating**
    - **Mechanical**
      - Ultrasonic
      - Vibration
      - Spin
    - **Electromagnetic**
      - Radio Frequency
      - Infrared and Laser
      - Microwave

Hot Tool (Plate) Welding

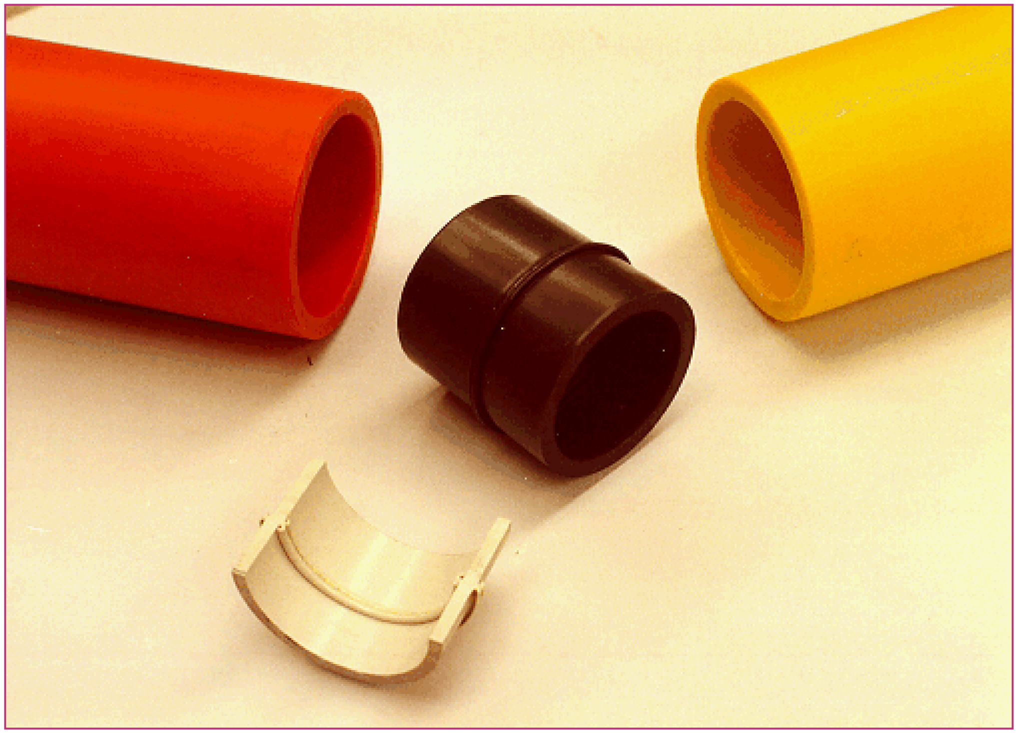




I. Heating with Pressure
II. Heating without Pressure
III. Change-Over
IV. Welding/Forging

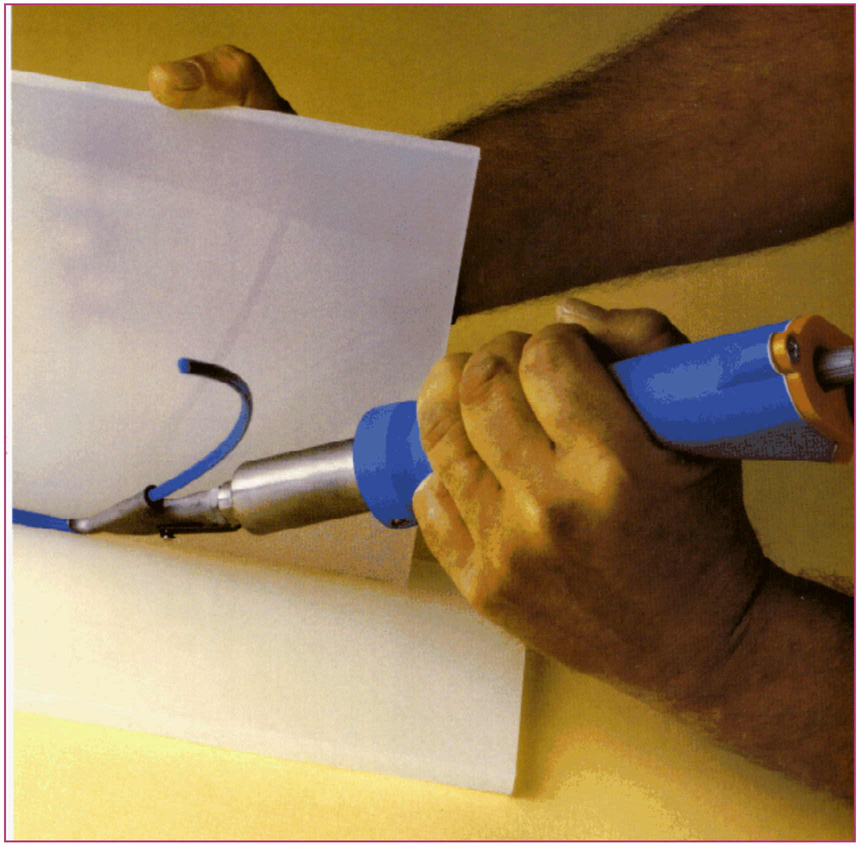
Hot Tool (Plate) Welding

- Advantages
  - Provide strong joints
  - Reliable
  - Used on difficult to join plastics
- Limitations
  - Slow
  - Limited temperature range



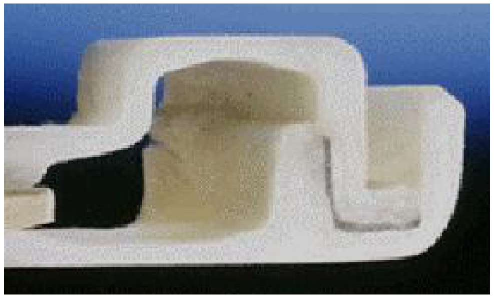
Hot Gas Welding

- Hot gas softens/melts filler rod and base material
- Filler rod is fed and pushed into the joint
- Different welding tips can be used for tacking and welding
- Well suited for large parts and for prototyping



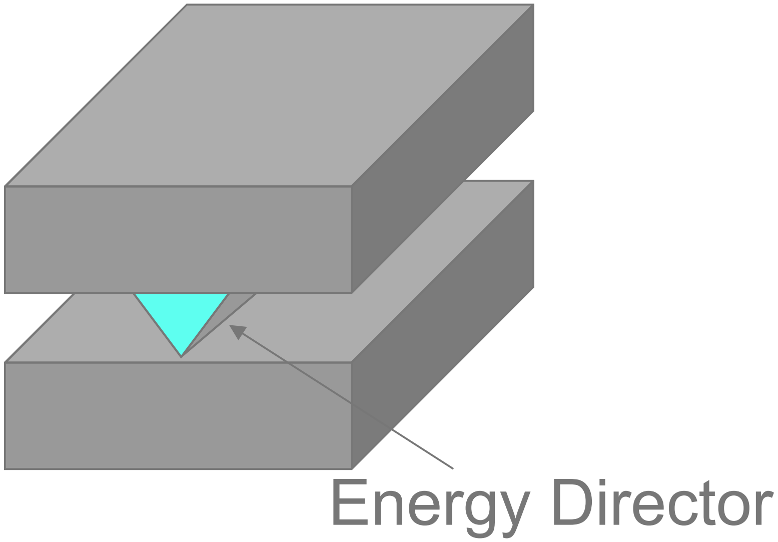
Implant Induction Welding

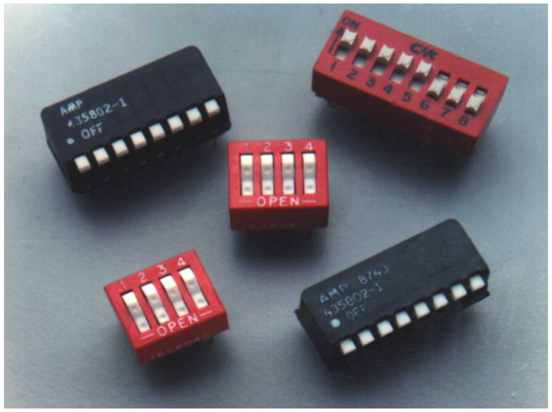
- Gasket - composite of ferromagnetic material and polymer
- Induction heating of gasket to melt polymer in gasket and parts
- Gasket remains embedded at the weld



Ultrasonic Welding

- Use low amplitude high frequency vibration.
- Energy director heats due to intermolecular friction
- Molten energy director flows sideways melting the part surfaces and welding the parts
- Ultrasonic energy can also be used for staking, swaging, insertion, etc.

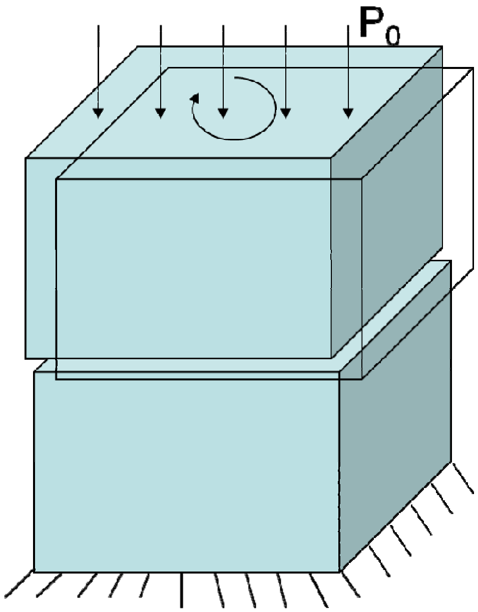




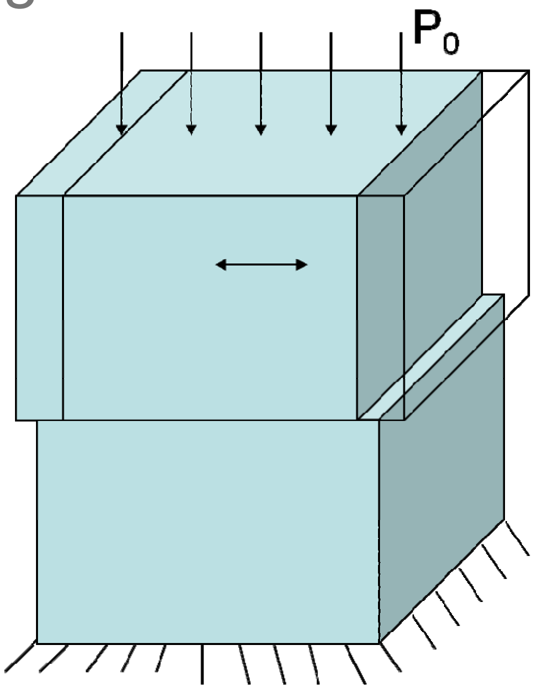
Vibration Welding

- Frictional heating followed by viscous heating once melt forms
- Linear or orbital motion can be used

Instrument Panel Assembly



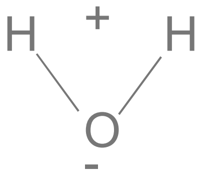
Orbital

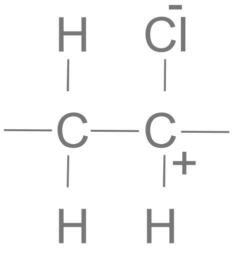


Linear

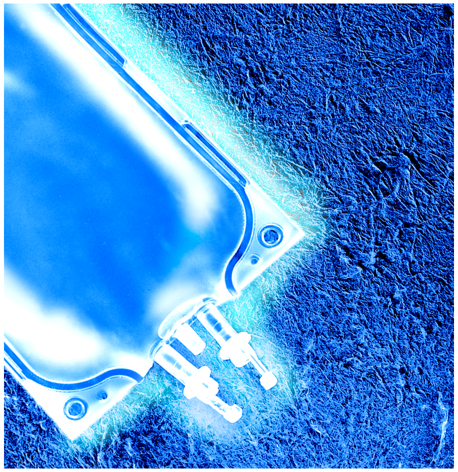
Radio Frequency (Dielectric) Welding/Sealing

- Dipolar (dielectric) heating - polar molecules
- Works very well with PVC as well as other polymers with polar groups
- Very rapid heating with typical cycle times of a few seconds





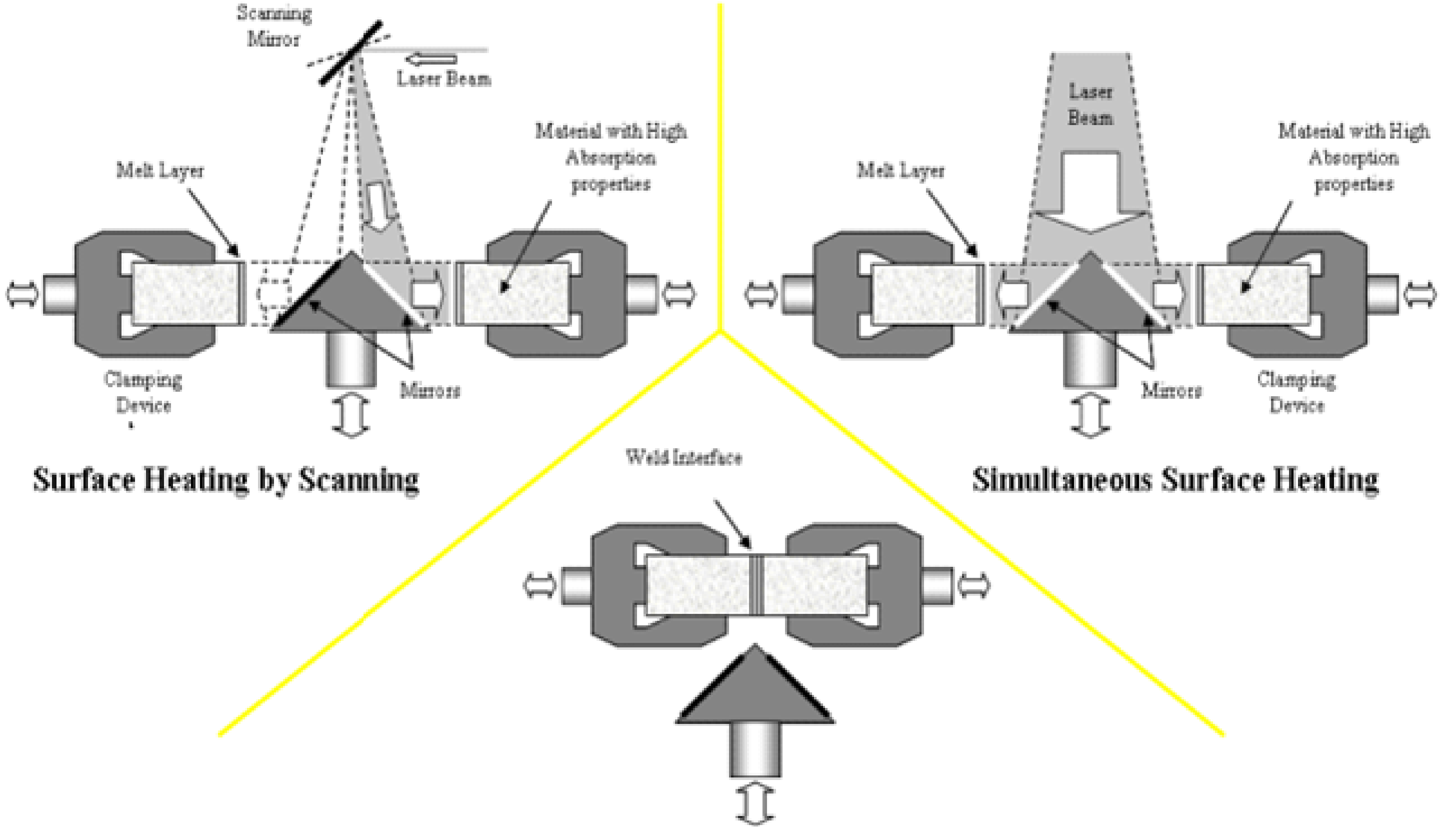
Blister Pack



Medical Bag

Infrared/Laser Welding

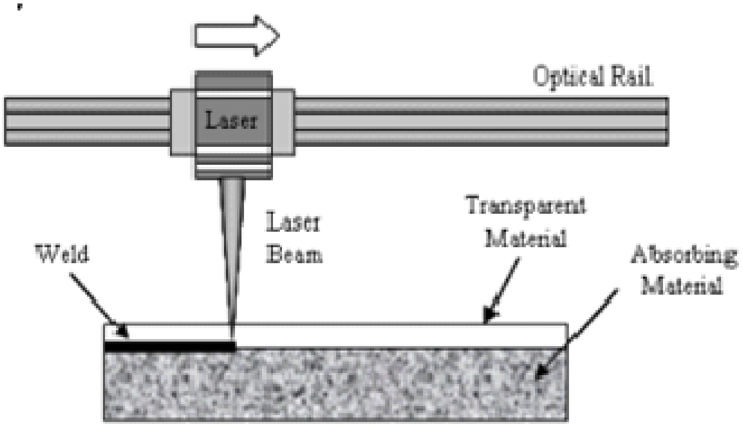
- Surface Heating



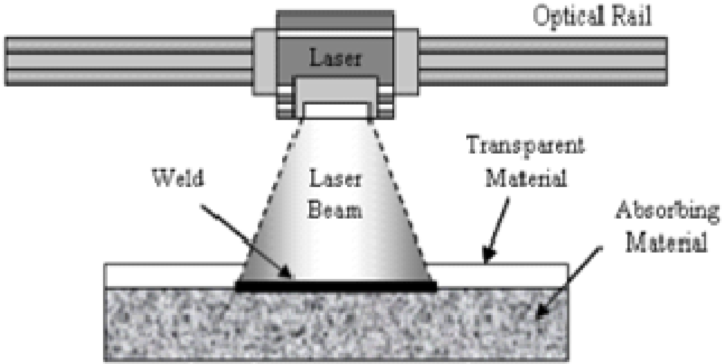
Surface Heating by Scanning

Simultaneous Surface Heating

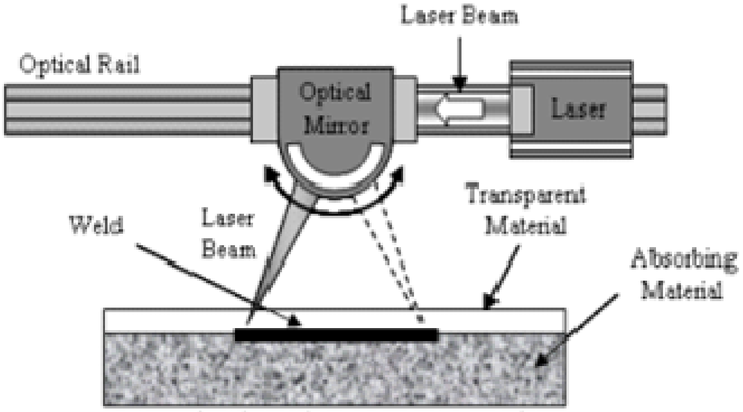
Through Transmission IR/Laser Welding



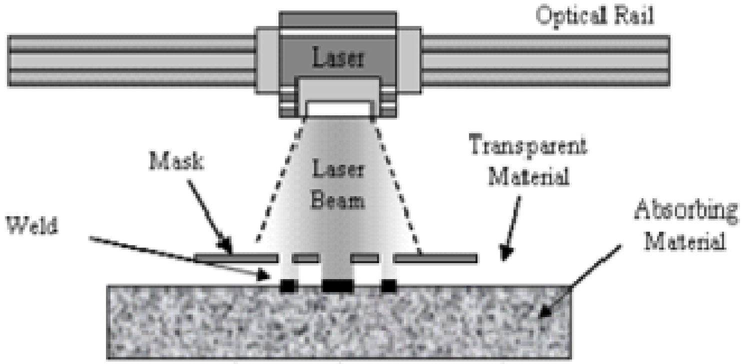
Heating by Scanning/Tracing



Simultaneous Heating



Quasi-Simultaneous Heating



Heating Using a Mask