Introduction to Welding Technology and Codes Course

Module 1

Overview

- Review the outline of the two-week course
  - Course topics
  - Instructors
- Describe learning objectives – what you will get out of this course
- Provide an overview of the field of welding technology and engineering and how it is applied in welding codes
- Get to know the other participants in the course

Module 1 Learning Objectives

- What you will learn from this course
  - Types of welding processes – advantages and disadvantages
  - How these processes work (or don't work !!)
  - Metallurgy of welding
  - Principles of welding design – weld types and designations, weld properties, and failure modes
  - Weldability – why some welds fail and how to avoid failure of welds in certain materials
  - NDE techniques – advantages and limitations, and how to select
  - Basic codes and standards including weld procedure and welder qualification requirements
- What you won't learn from this course
  - How to weld !!

Expectations

- Periodic Review
  - Discussion and review of modules when time permits
  - No final exam requirement
- Participation – please ask questions !!
- Feedback
  - Surveys on individual topics
  - End of course survey

What is a Weld?

"A localized coalescence of metals or nonmetals produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler material"

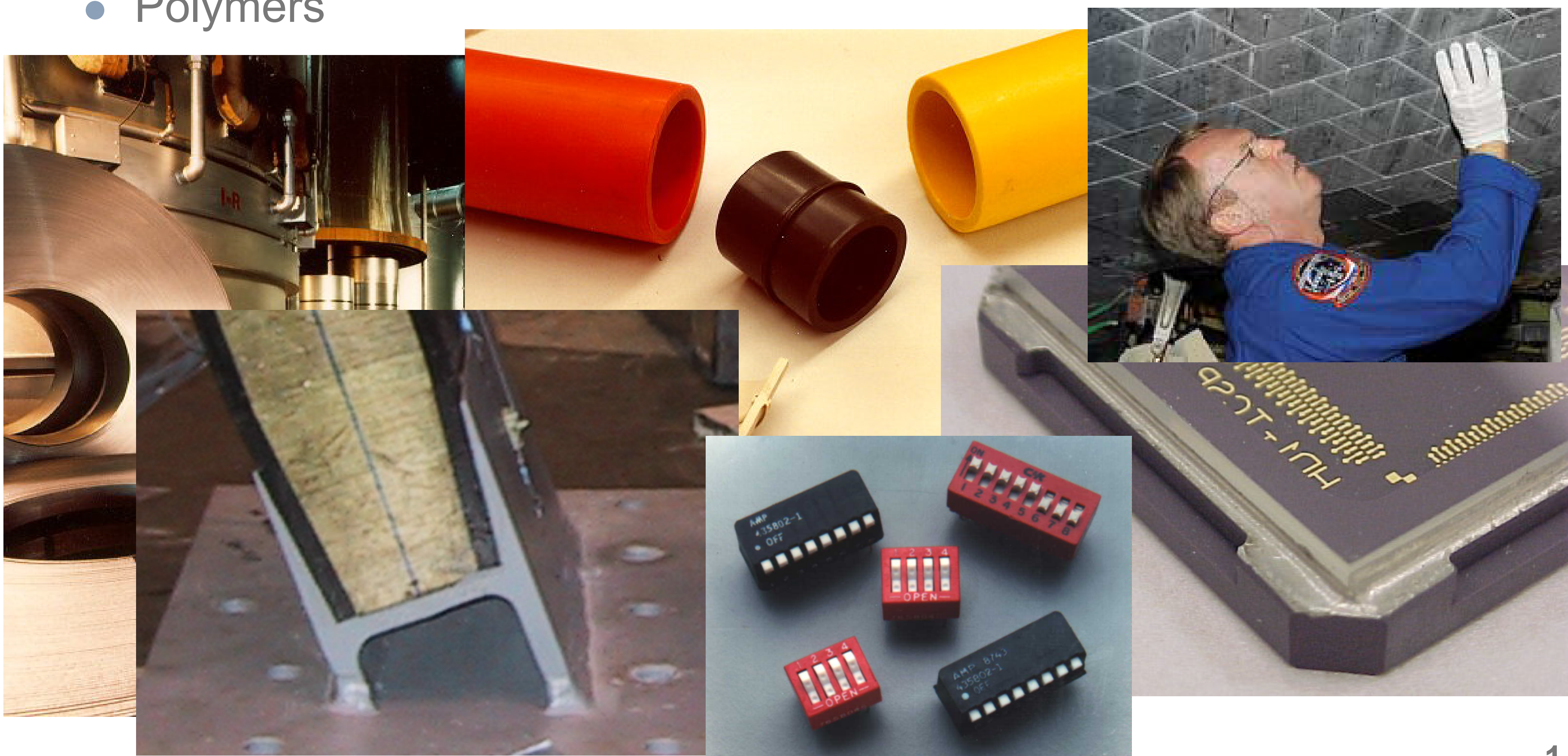
-AWS A3.0 2001

What is Welding?

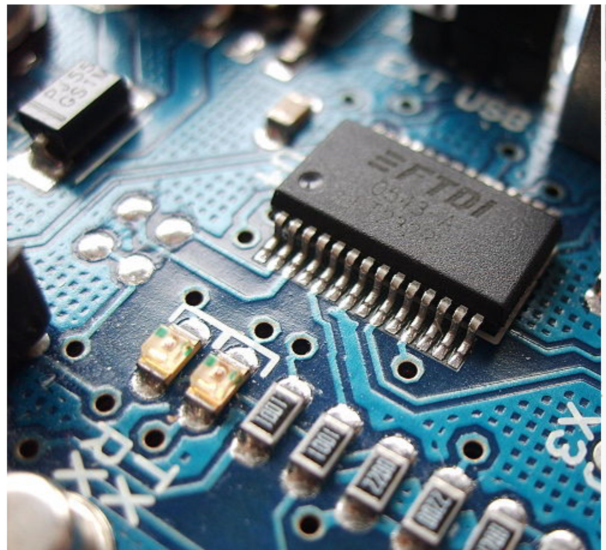
- Welding refers to an extensive group of manufacturing processes
  - Welding
  - Adhesive bonding
  - Brazing and Soldering

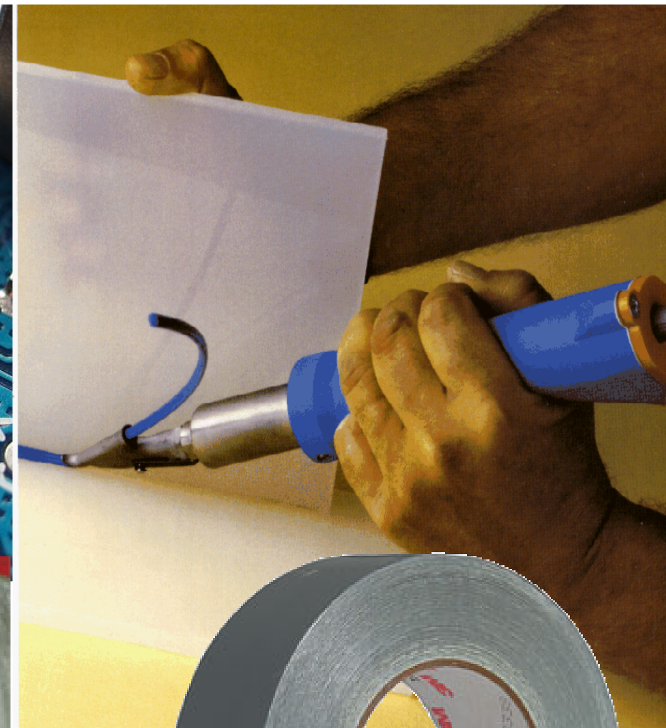
What is Welding?

- These processes join a wide range of materials
  - Metals
  - Ceramics
  - Polymers
  - Composites
  - Electronic materials

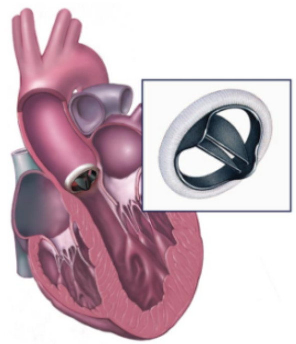


What is Welding?



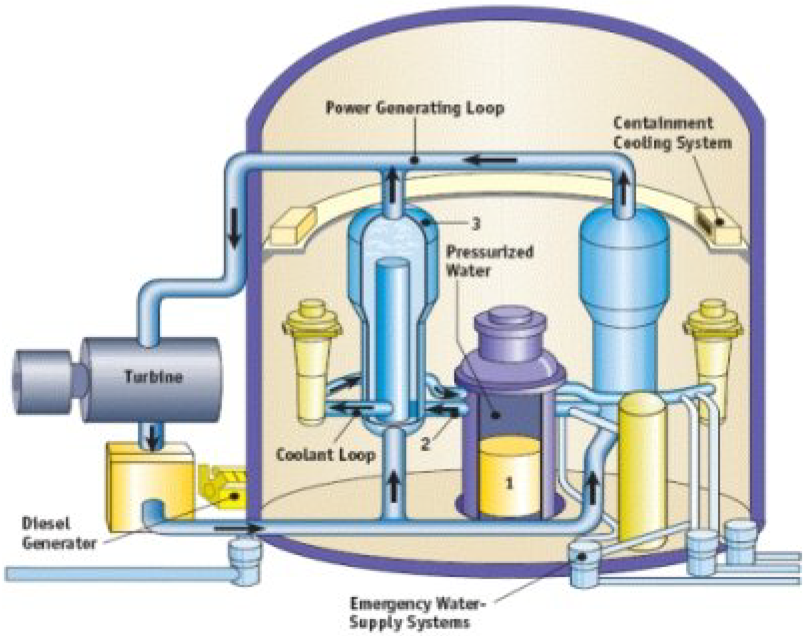


Welding in Our Society



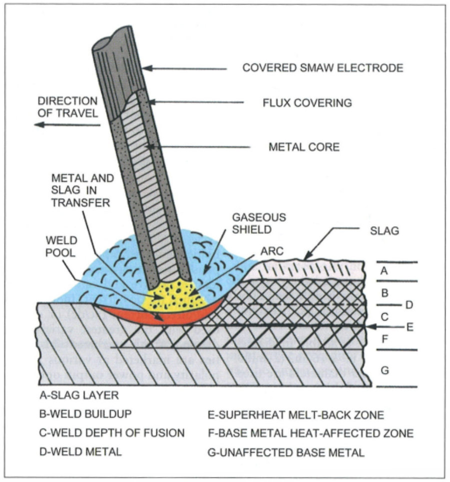
Welding in the Nuclear Industry

- Reactor vessels and internals
- Steam generators
- Pressurizers
- Piping systems
- Nozzles
- Pumps
- Valves
- Construction steel
- Rebar



What is Welding Engineering?

- Several processes capable of performing a job



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.8.

Figure 1.1—Schematic Representation of Shielded Metal Arc Welding

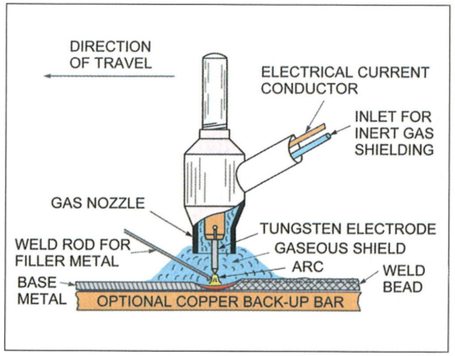
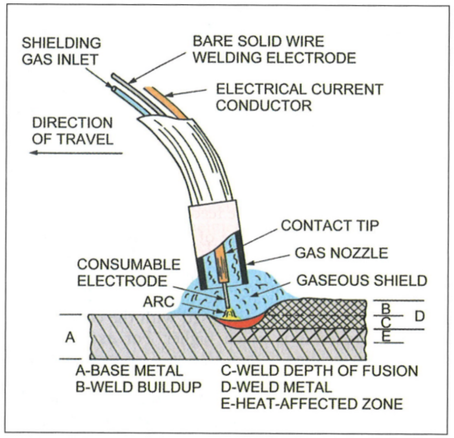


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.12.

Figure 1.6—Schematic Representation of Gas Metal Arc Welding

✓ Cost
✓ Fitness-for-service

Process Technologies

Industrial Engineering

Electrical Engineering

Materials Science

Mechanical Engineering

Nondestructive Evaluation

What Will You Learn ?

Topic	Duration (Days)	Instructor
Introduction	1	Steve Levesque
Welding and Cutting Processes	2.5	David Phillips
Welding Metallurgy	1.5	John Lippold
Welding Design	1	Avi Benetar
Weldability	1	Suresh Babu
Non-Destructive Examination	2	Roger Spencer
Summary	0.5	Matt Boring

Get to Know the Other Course Participants

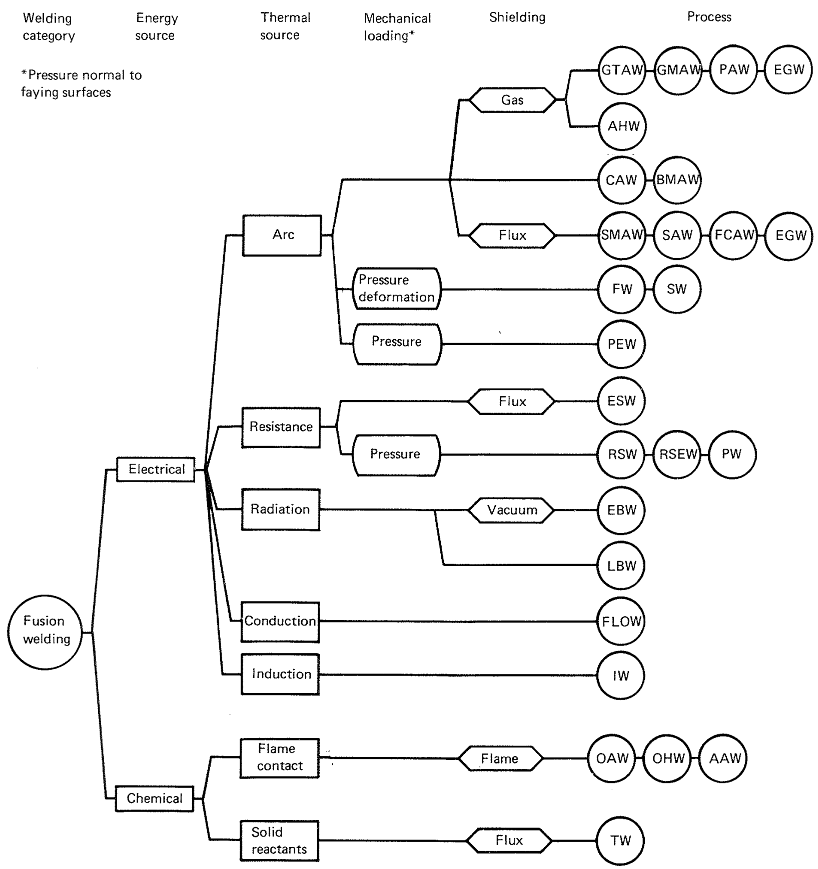
- Name and affiliation
- Why you are here?
- Expectations
- Other relevant background

Welding and Cutting Processes Overview

Module 1A

Fusion Welding

FUSION WELDING CLASSIFICATION CHART

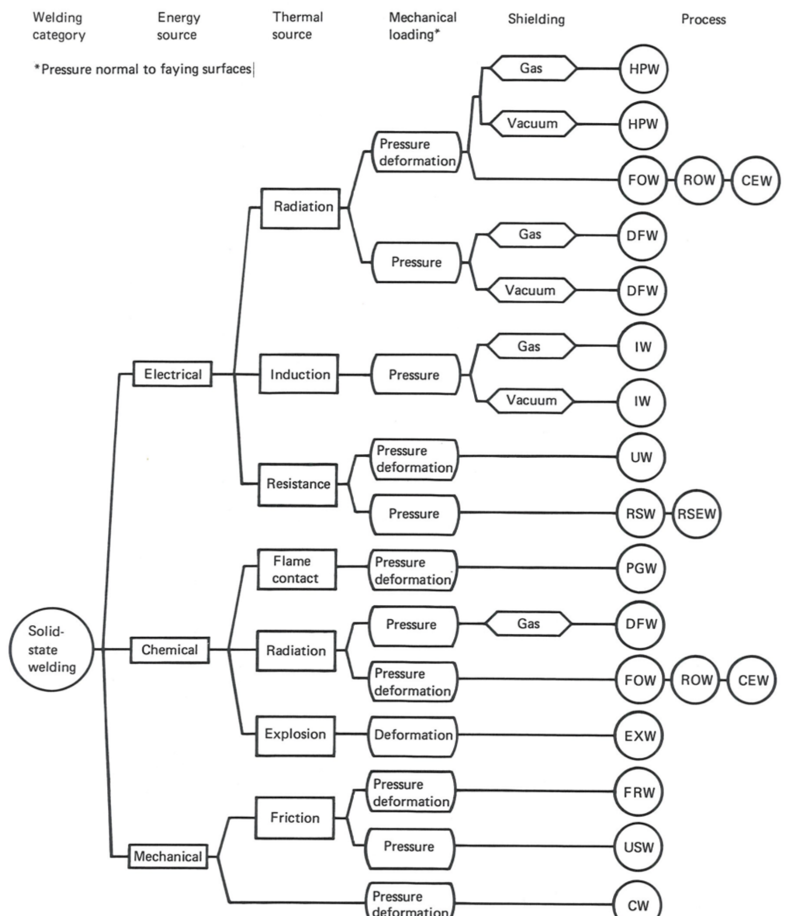


Definitions

Designation	Welding process	Designation	Welding process	Designation	Welding process
AAW	Air acetylene	FW	Flash	PW	Projection
AHW	Atomic hydrogen	GMAW	Gas metal arc	RSEW	Resistance seam
BMAW	Bare metal arc	GTAW	Gas tungsten arc	RSW	Resistance spot
CAW	Carbon arc	IW	Induction	SAW	Submerged arc
EBW	Electron beam	LBW	Laser beam	SMAW	Shielded metal arc
EGW	Electrogas	OAW	Oxyacetylene	SW	Stud arc
ESW	Electroslag	OHW	Oxyhydrogen	TW	Thermit
FLOW	Flow	PAW	Plasma arc		
FCAW	Flux cored arc	PEW	Percussion		

Solid-State Welding

SOLID-STATE WELDING CLASSIFICATION CHART



Definitions

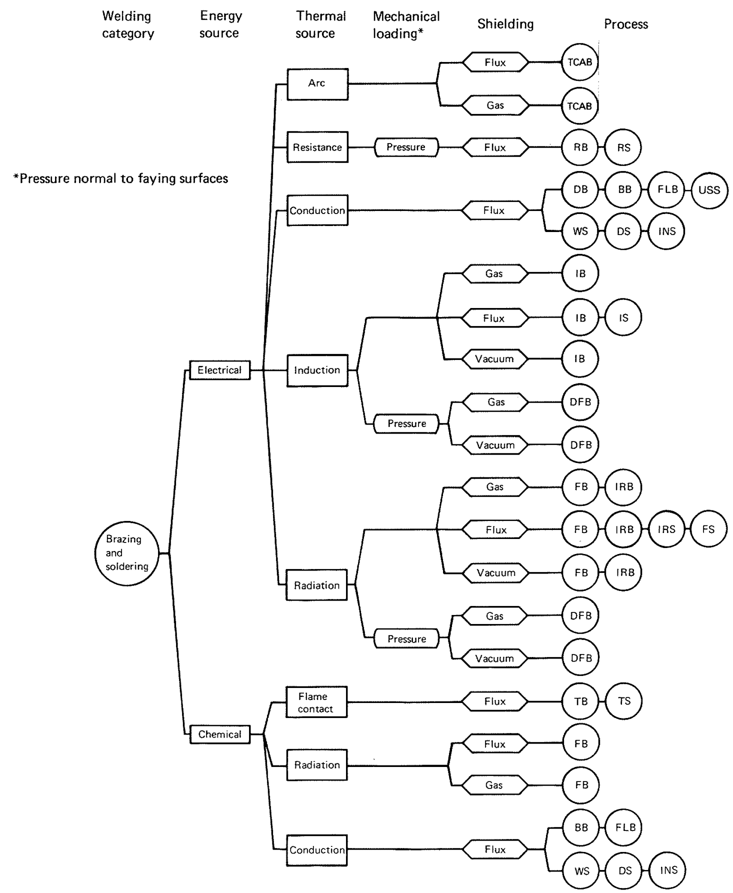
Designation	Welding Process
CEW	Coextrusion
CW	Cold
DFW	Diffusion
EXW	Explosion
FOW	Forge
FRW	Friction
HPW	Hot pressure

Definitions

Designation	Welding process
IW	Induction
PGW	Pressure gas
RSEW	Resistance seam
RSW	Resistance spot
ROW	Roll
USW	Ultrasonic
UW	Upset

Brazing and Soldering

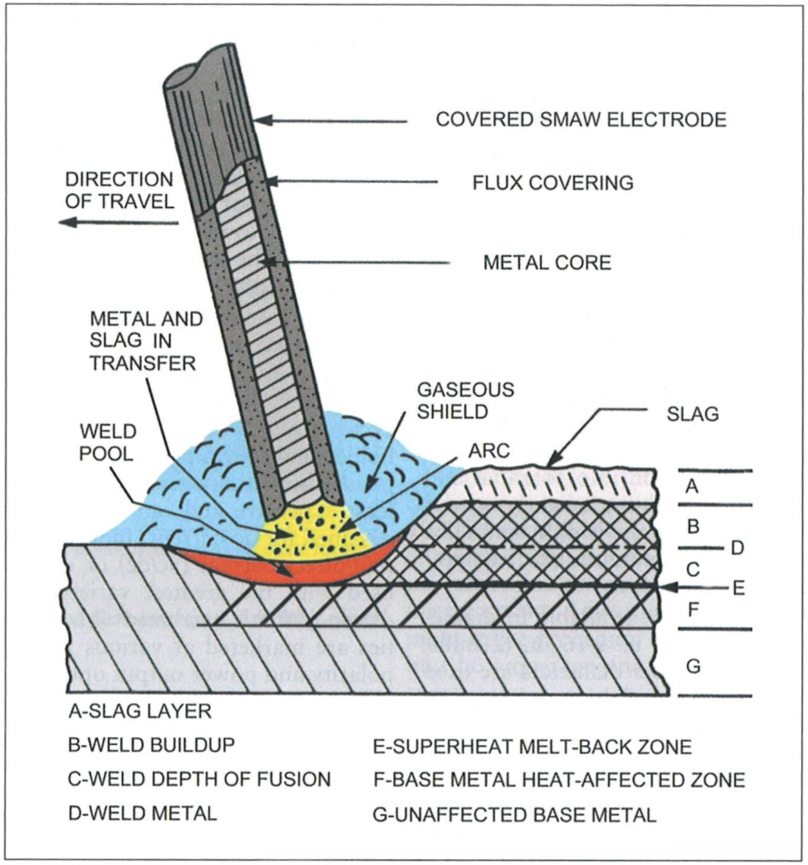
BRAZING AND SOLDERING CLASSIFICATION CHART



Definitions Designation	Process	Definitions Designation	Process
AB	Arc brazing	IS	Induction soldering
BB	Block brazing	IRB	Infrared brazing
TCAB	Twin carbon arc brazing	IRS	Infrared soldering
DB	Dip brazing	INS	Iron soldering
DS	Dip soldering	RB	Resistance brazing
DFB	Diffusion brazing	RS	Resistance soldering
FB	Furnace brazing	TB	Torch brazing
FS	Furnace soldering	TS	Torch soldering
FLB	Flow brazing	USS	Ultrasonic soldering
IB	Induction brazing	WS	Wave soldering

Shielded Metal Arc Welding (SMAW)

- A.K.A. stick welding
- Consumable metal electrode with flux coating
  - Flux forms a shielding atmosphere and slag
  - Simple and portable equipment
- Most widely used process in the world
  - Applicable to several nuclear applications especially repair



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.8.

Figure 1.1—Schematic Representation of Shielded Metal Arc Welding

Source: AWS Handbook 9th ed. Vol. 1

Gas Tungsten Arc Welding (GTAW)

- A.K.A. tig welding
- Non-consumable tungsten electrode
  - Can be performed with or without filler material
  - Gas shielding
  - Manual, semi-automatic, automatic
- Applicable to several nuclear applications, widely used in orbital welding and overlays

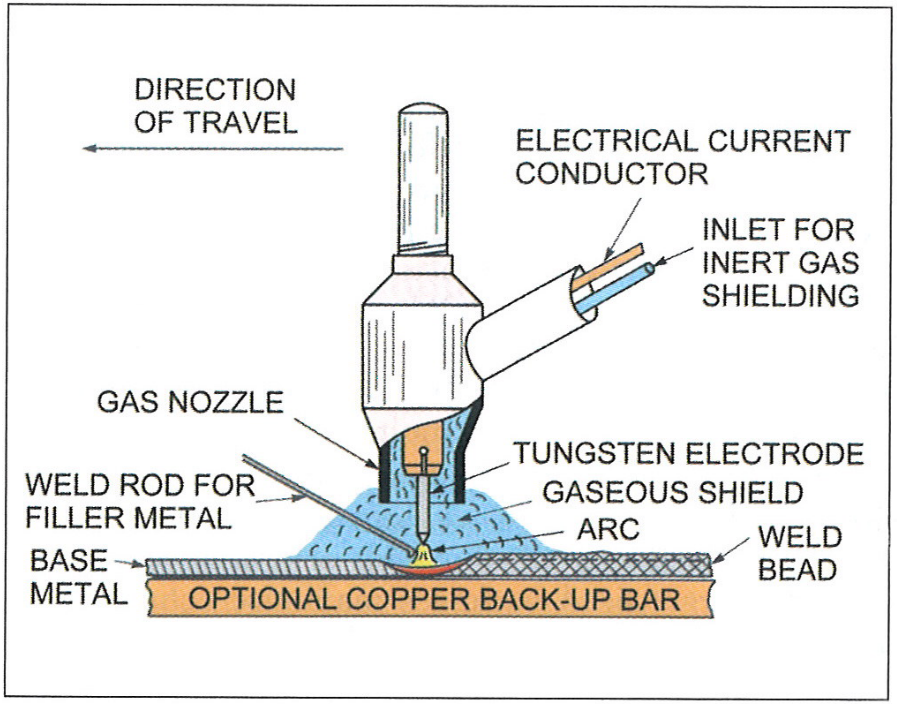


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding

Source: AWS Handbook 9th ed. Vol. 1

Plasma Arc Welding (PAW) & Cutting

- Non-consumable electrode is used to create a plasma heat source
    - Can be used with or without filler metal
- Applicable to many metals and competes with GTAW in many applications
- Widely used for cutting thinner metals

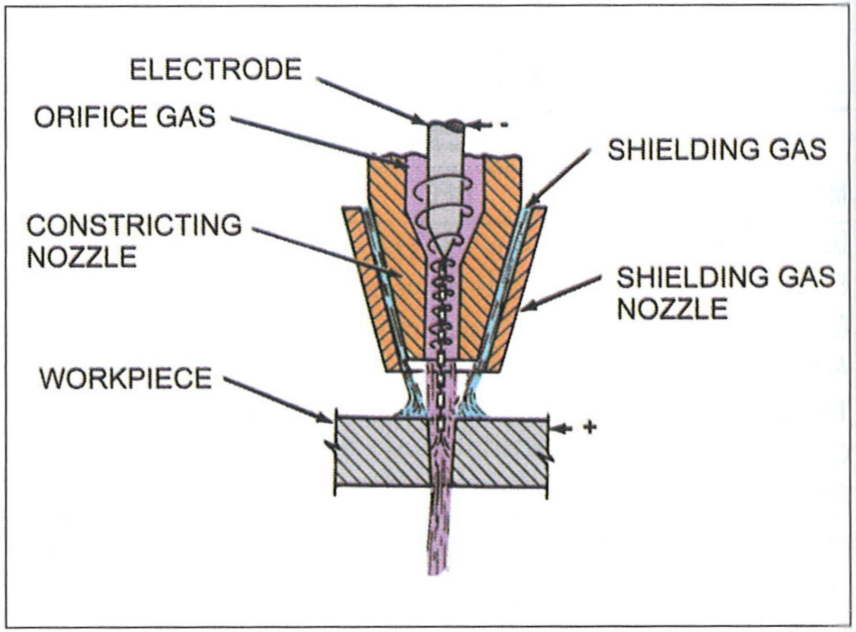
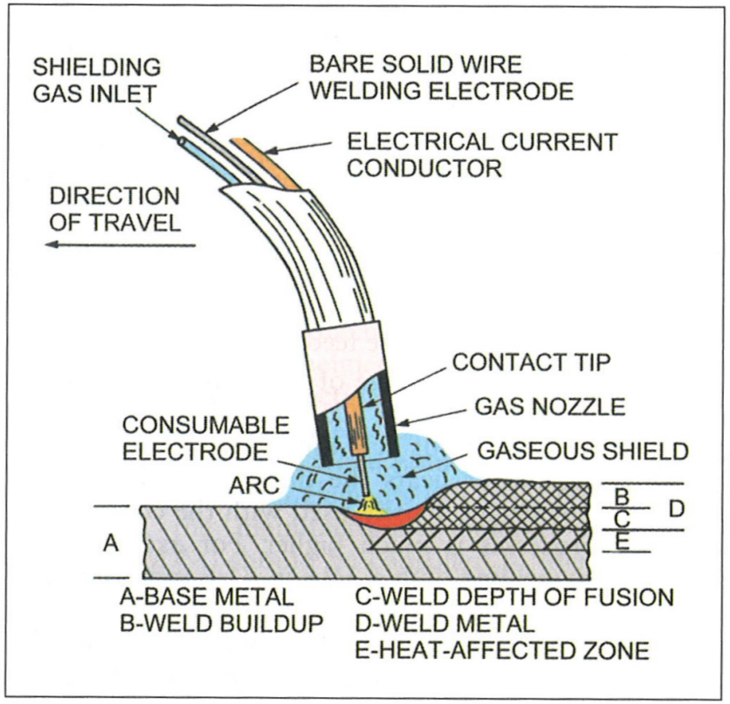


Figure 1.54—Schematic Representation of Plasma Arc Cutting

Source: AWS Handbook 9th ed. Vol. 1

Gas Metal Arc Welding (GMAW) & Flux Cored Arc Welding (FCAW)

- A.K.A. mig welding
- Continuously fed electrode
  - Semi-automatic or automated
  - Shielding through gas, flux or both
  - Several transfer modes
- Applicable to several components, although it is not used as widely as SMAW and GTAW



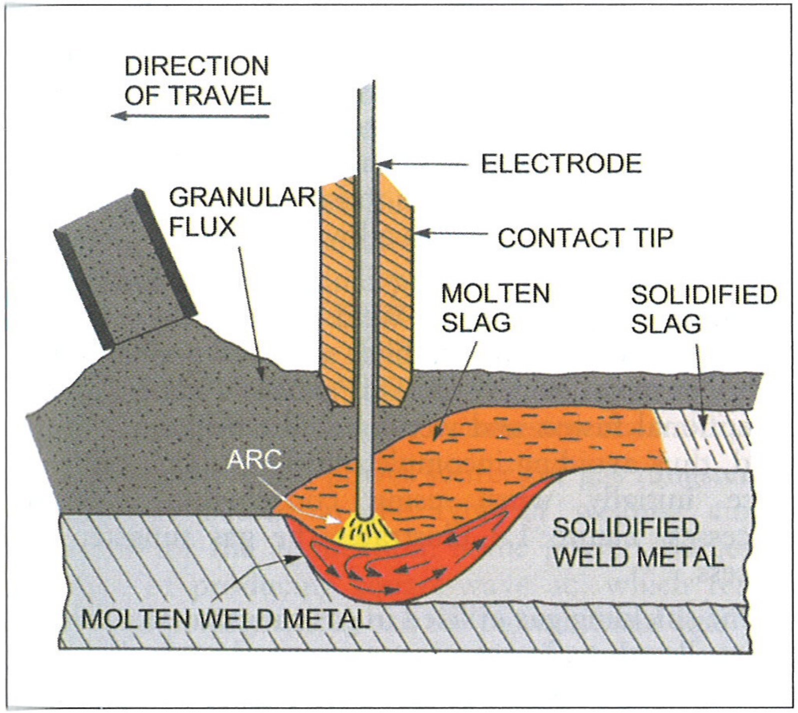
Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.12.

Figure 1.6—Schematic Representation of Gas Metal Arc Welding

Source: AWS Handbook 9th ed. Vol. 1

Submerged Arc Welding (SAW)

- Continuously fed metal electrode with a granular flux shielding
  - Arc is “submerged” and not visible to the user
- High deposition rates make this technology attractive to large component fabricators



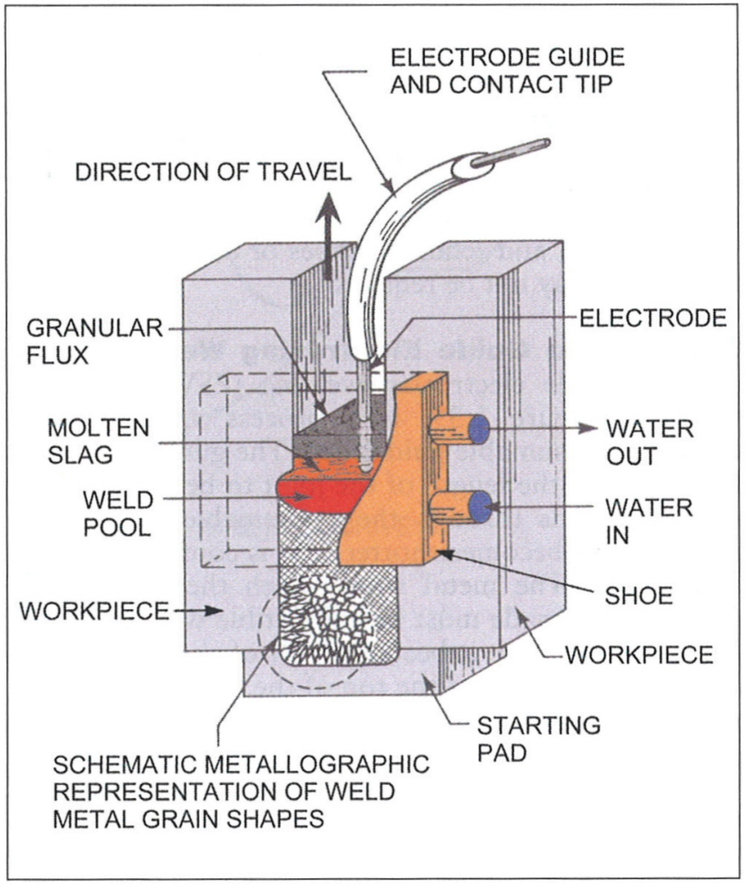
Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.18.

Figure 1.2—Schematic of Submerged Arc Welding

Source: AWS Handbook 9th ed. Vol. 1

Electroslag Welding (ESW)

- Pieces welded by molten slag that melts the filler metal and the surfaces of both workpieces to be welded
  - ESW is not a true arc process
- Applicable to carbon and low alloy steels and some stainless steels
  - Used on large single pass welds
  - Can be used in cladding applications



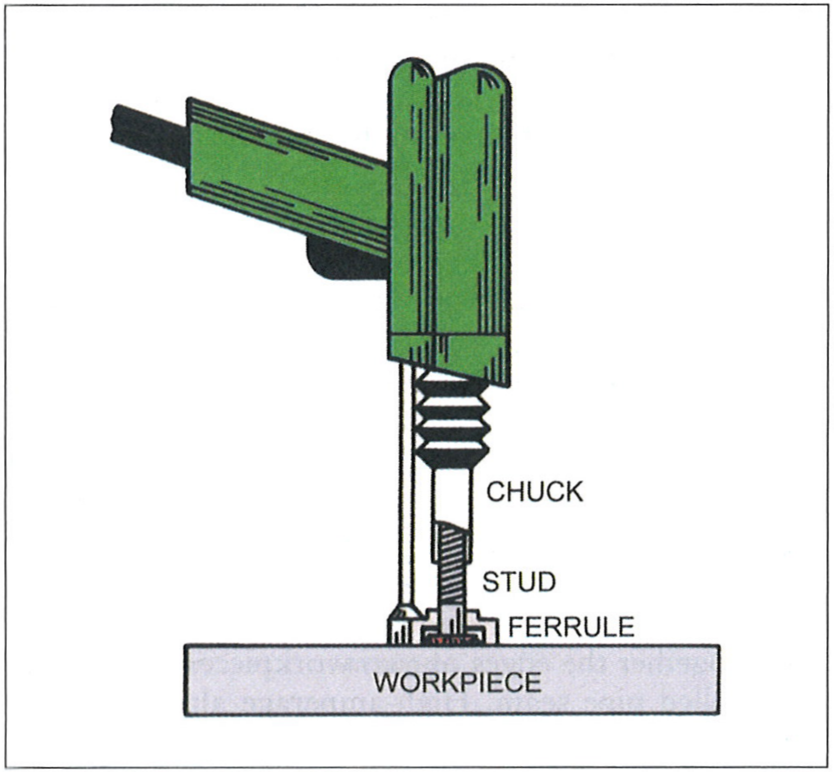
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.51.

Figure 1.38—Schematic Representation of Electroslag Welding

Source: AWS Handbook 9th ed. Vol. 1

Stud Welding

- Metal stud welded to the workpiece through a rapid discharge of electrical energy
  - Small heat affected zone
- Applications include construction supports and also temporary attachment of heat treatment blankets



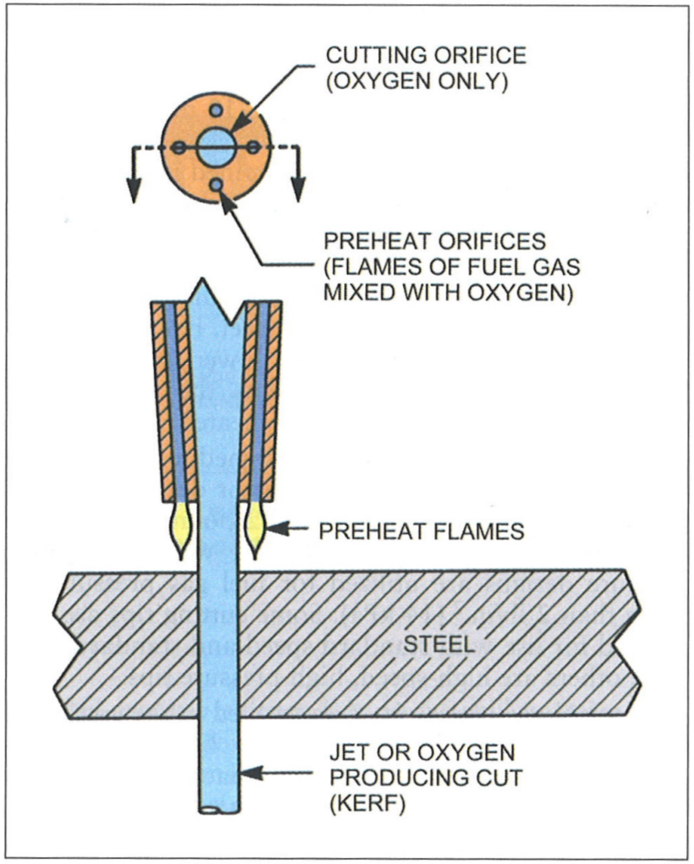
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.63.

Figure 1.15—Schematic Representation of Stud Welding

Source: AWS Handbook 9th ed. Vol. 1

Oxyfuel Welding, Heating & Cutting

- Oxygen used with a fuel (Acetylene, MAPP, Propane) to create a heat source
  - Welding, heating, cutting applications
- Widely used to preheat and post weld heat treatment
- As a cutting process it can be used to cut through very thick section steel



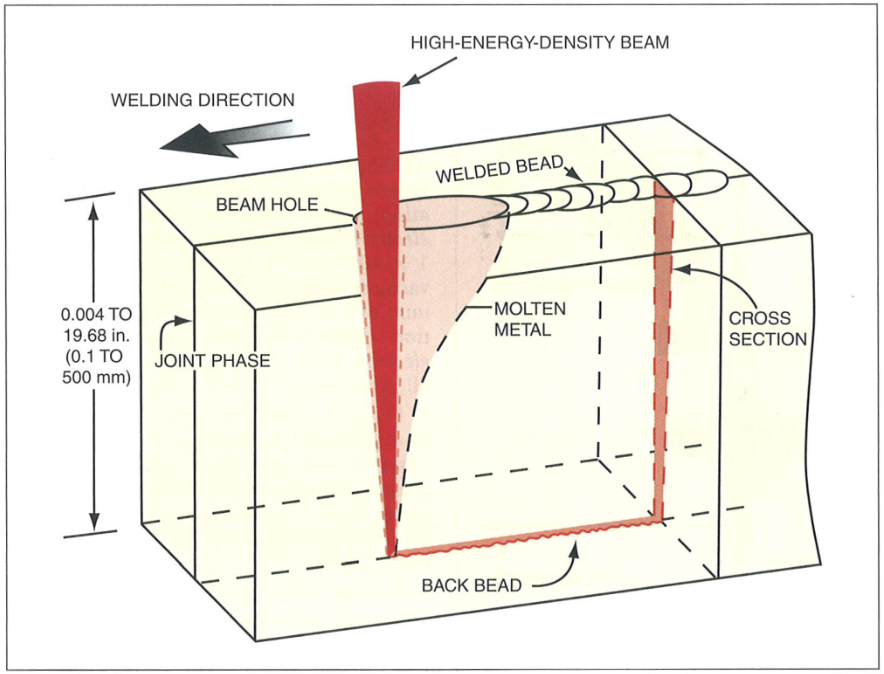
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.82.

Figure 1.53—Schematic Representation of Oxyfuel Gas Cutting

Source: AWS Handbook 9th ed. Vol. 1

High Energy Density Welding

- Power density (power / area) is significantly higher than that achieved by the common arc welding processes
  - Low heat input
  - High production rates
  - Accurate positioning required
  - High capital costs
- Can be used on a wide variety of metals
  - Laser cutting is widely used



Source: Adapted from Powers, D. E., and G. R. LaFlamme, 1988, EBW vs. LBW—A Comparative Look at the Cost and Performance Traits of Both Processes, *Welding Journal* 67(3): 25–31, Figure 1.

Figure 1.33—Schematic Representation of a Keyhole Weld

Source: AWS Handbook 9th ed. Vol. 1

Friction Welding

- Rotational Friction Welding Processes
  - Inertia and Continuous Drive Friction Welding
    - Ideal for round bars and shapes
    - One part is rotated at high speed relative to other part
    - Parts are brought together, axial force is applied creating frictional heating
    - Softened material is upset into the “flash”, which is later removed

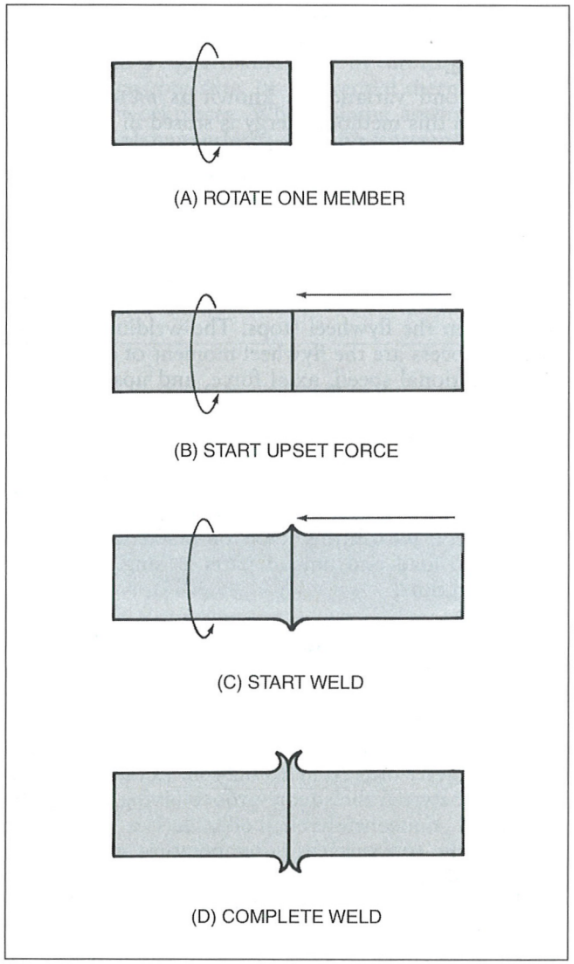


Figure 1.26—Schematic Illustration of Friction Welding

Source: AWS Handbook 9th ed. Vol. 1

Ultrasonic Welding

- A welding process that produces a solid-state weld through the application of high frequency vibrations combined with low pressure
  - Negligible heating of parts
  - Minimal deformation

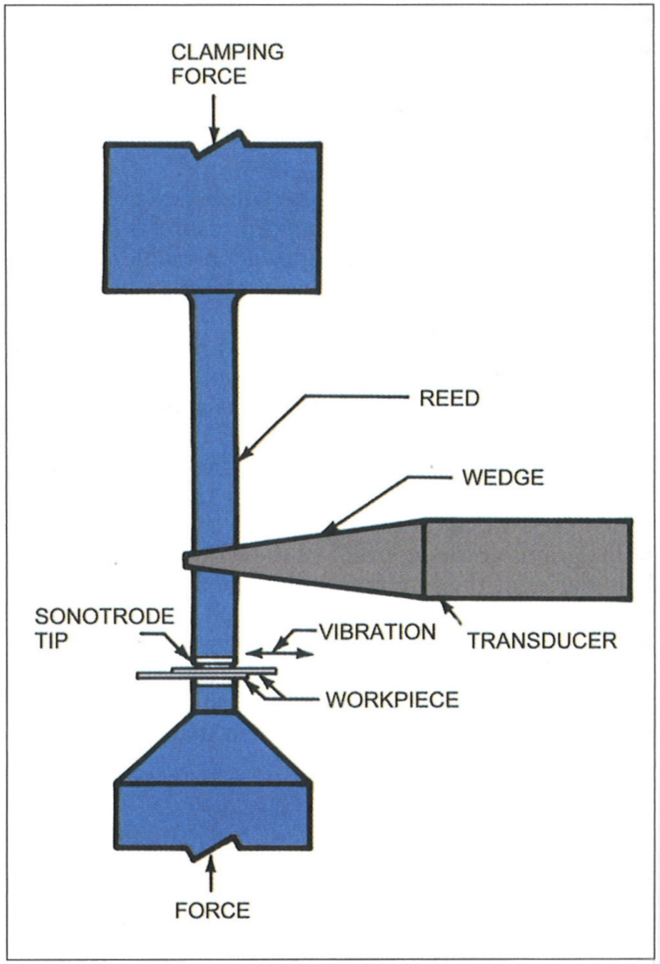
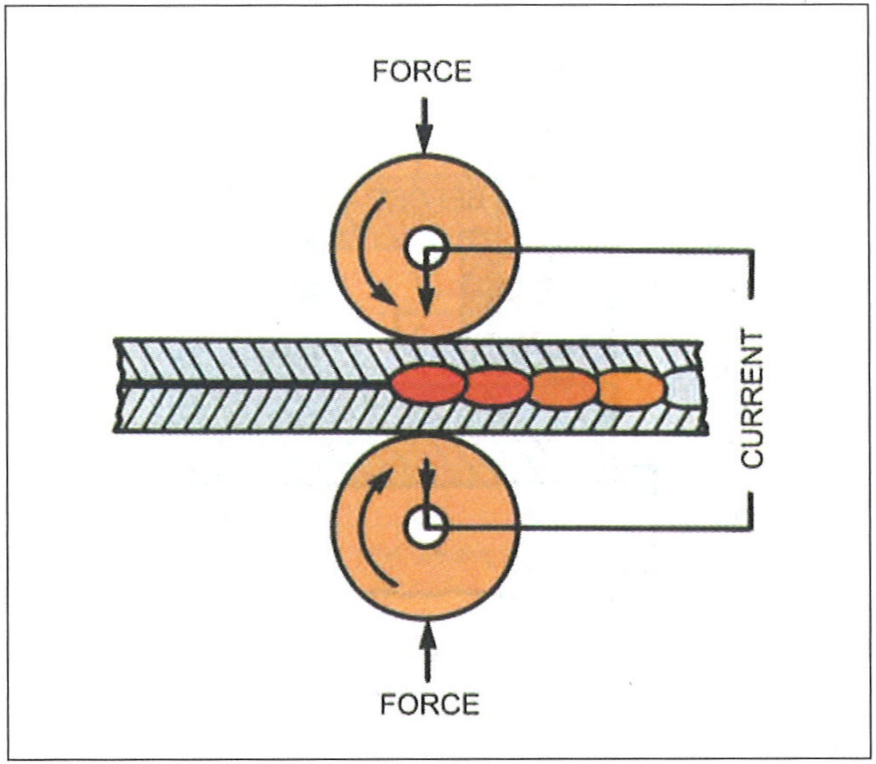


Figure 1.29—Schematic Representation of Ultrasonic Welding

Source: AWS Handbook 9th ed. Vol. 1

Resistance Welding

- Resistive heating through the workpiece
  - With or without melting
  - Various amounts of pressure
- Applications
  - Cladding
  - Seam welds



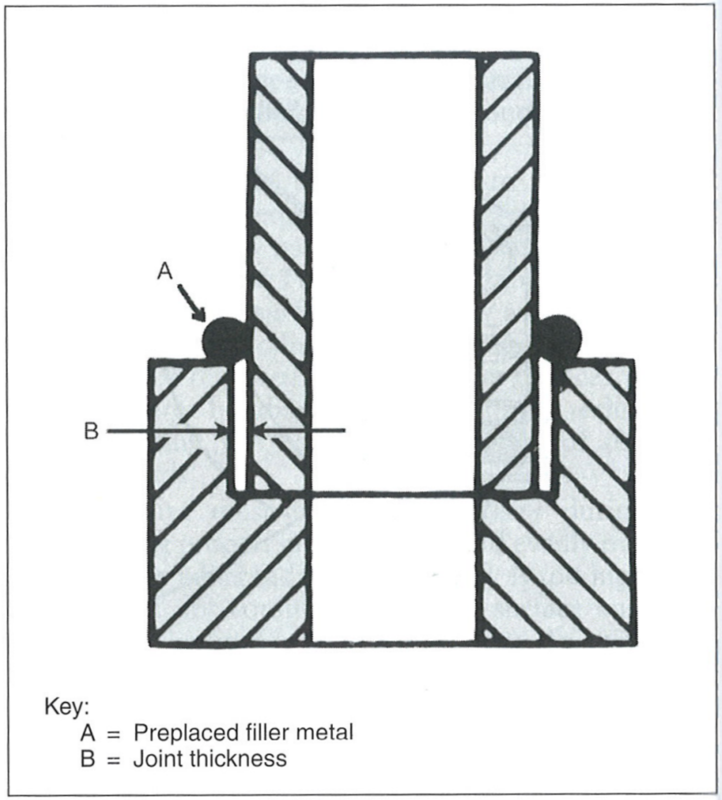
Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(B).

Figure 1.18—Schematic Illustration of Resistance Seam Welding

Source: AWS Handbook 9th ed. Vol. 1

Brazing and Soldering

- Joining processes which utilize a filler metal which melts below the melting temperature of the base metal
  - Brazing: filler metal liquidus > 450ºC
  - Soldering: filler metal liquidus < 450ºC
- Joint formation
  - Filler metal melting
  - Joint gap filled by capillary action
  - Filler metal solidifies



Source: American Welding Society (AWS) Committee on Brazing and Soldering, 1991, *Brazing Handbook*, Miami: American Welding Society, Figure 12.24A.

Figure 1.42—Typical Joint for Brazing and Soldering

Source: AWS Handbook 9th ed. Vol. 1

Welding Automation

Semi-automatic

Machine
(Mechanized)

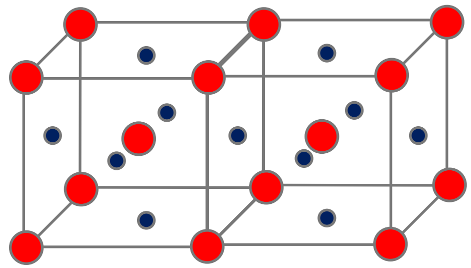
Automatic

Welding Metallurgy Overview

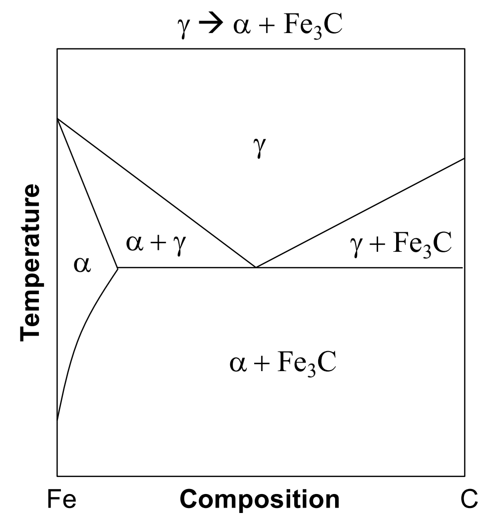
Module 1B

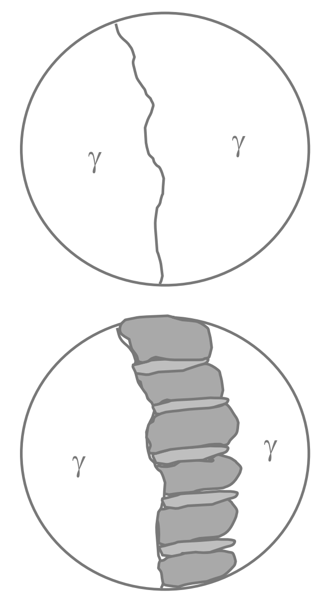
Physical Metallurgy Concepts

- Atomic Bonds
  - Metallic Bonding
    - Elastic modulus
- Crystal Structures
  - Defects
  - Solid Solutions
- Phase Diagrams
- Diffusion
- Strengthening Mechanisms
  - Grain Size
  - Solid Solutions
  - Cold Work (Strain Hardening)
  - Precipitation



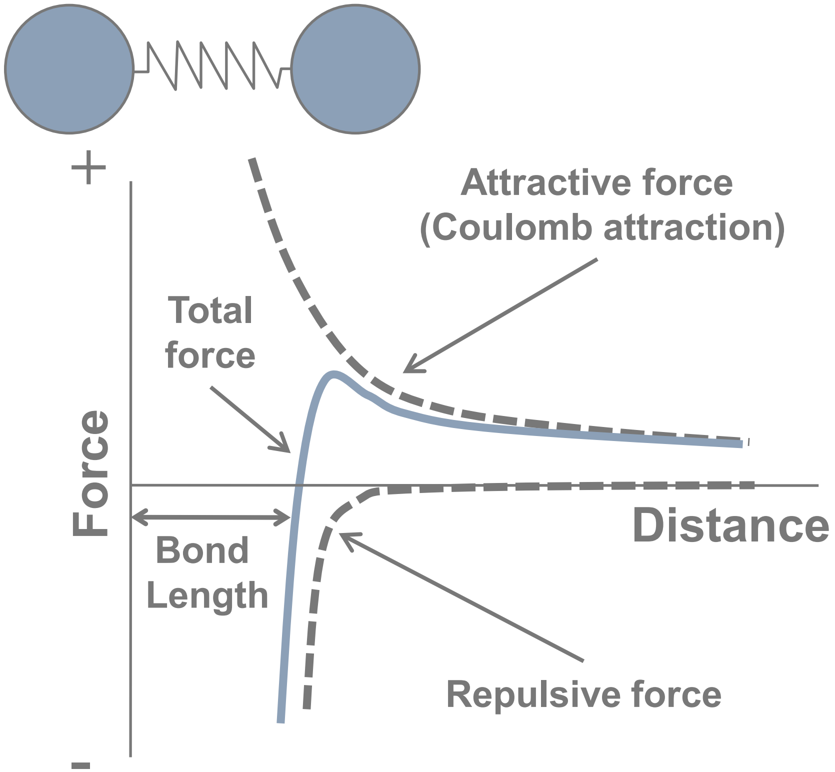
- Fe is the solvent
- C is the solute

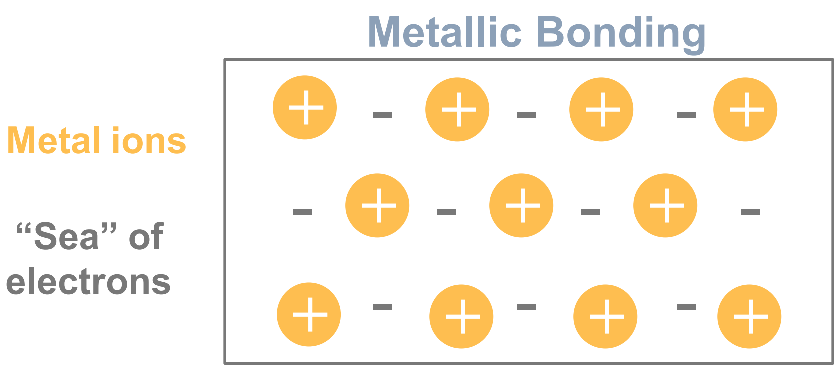




Physical Metallurgy Concepts

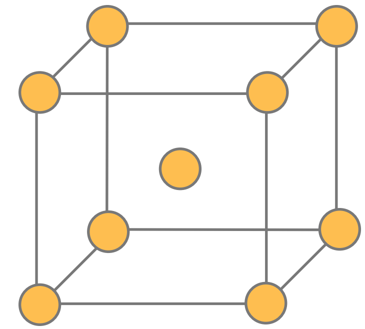
- Atomic bonds
  - Ionic, covalent, metallic
  - Metallic bonding
    - Free electrons
    - Elastic behavior





Physical Metallurgy Concepts

- Crystal structures
  - BCC
    - Iron & ferritic steels
  - FCC
    - Ni alloys & Al alloys
  - HCP
    - Ti (alpha alloys) & Zr



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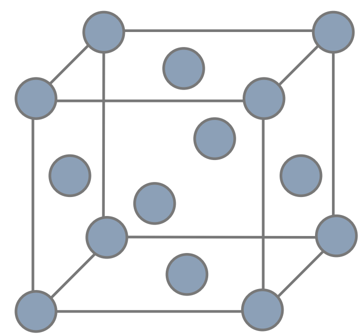

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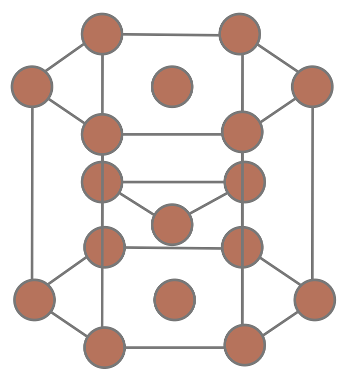
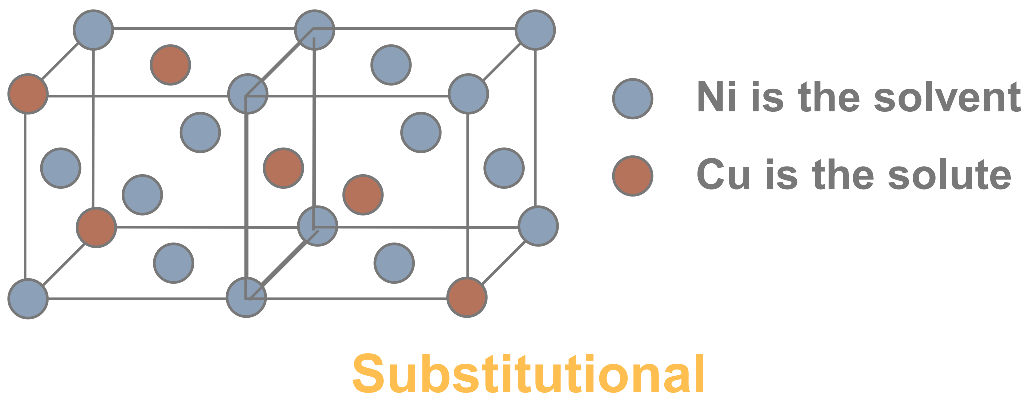
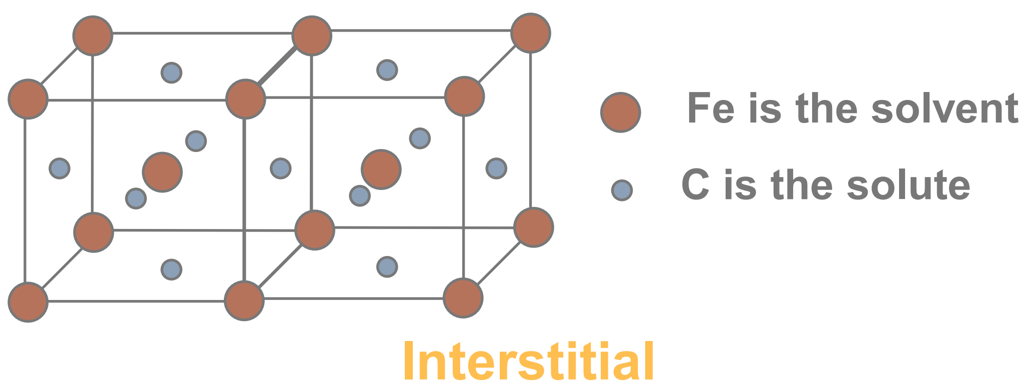


HCP

Physical Metallurgy Concepts

- Solid solutions
  - Substitutional
    - Ni-Cu alloys
  - Interstitial
    - Steels

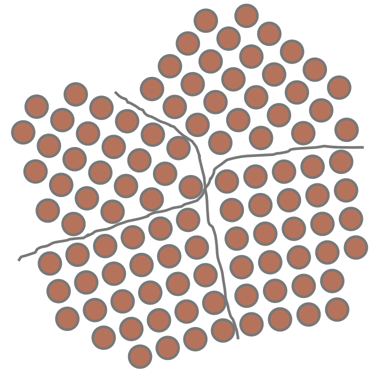




Physical Metallurgy Concepts

- Defects
  - Dislocations & grain boundaries
- Diffusion
  - Vacancy, interstitial, interdiffusion
- Strengthening mechanisms
  - Grain size reduction
  - Solid solutions
  - Strain hardening (cold work)
  - Precipitation hardening

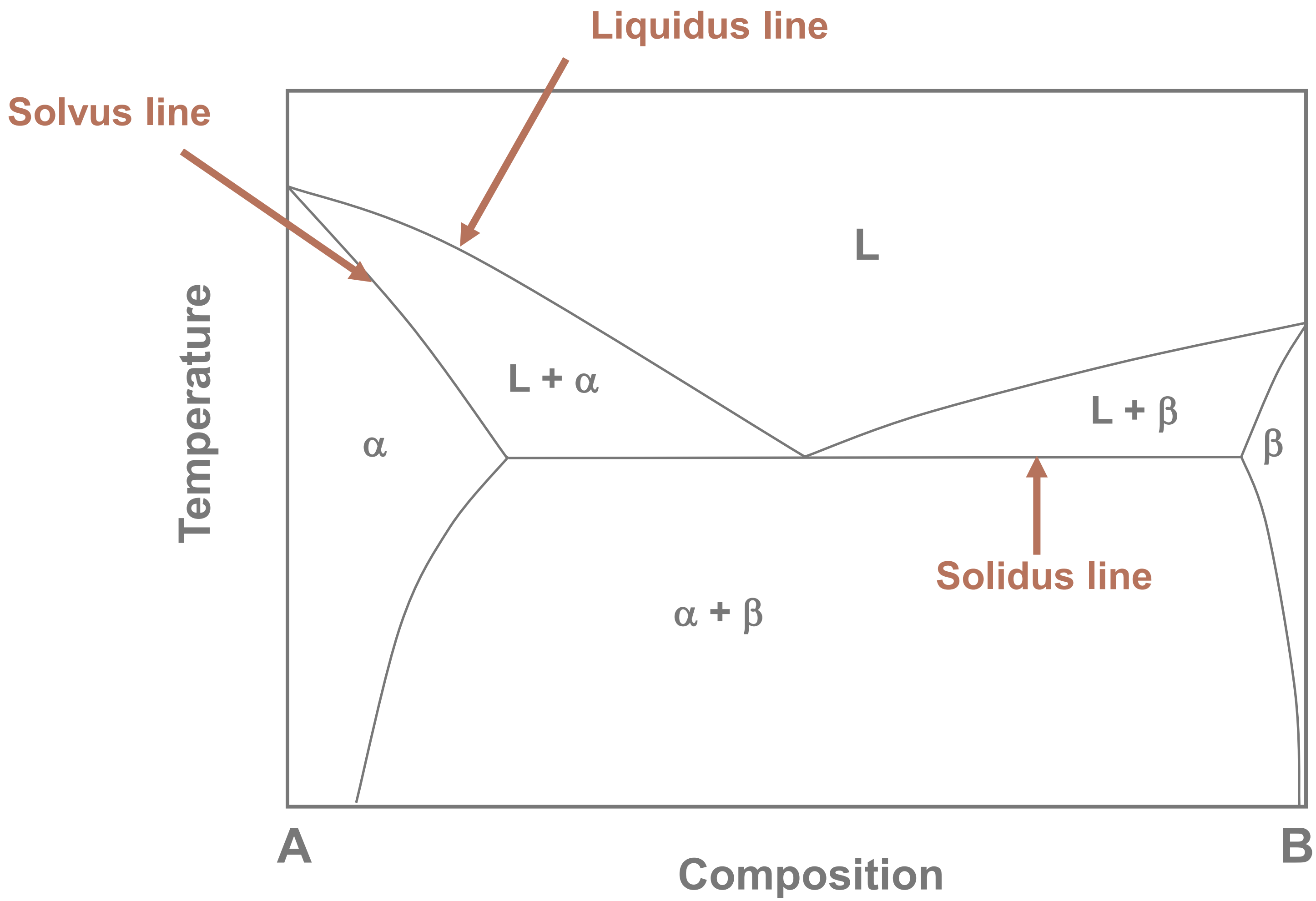
Grain boundaries



Cold work expressed in terms of area reduction:

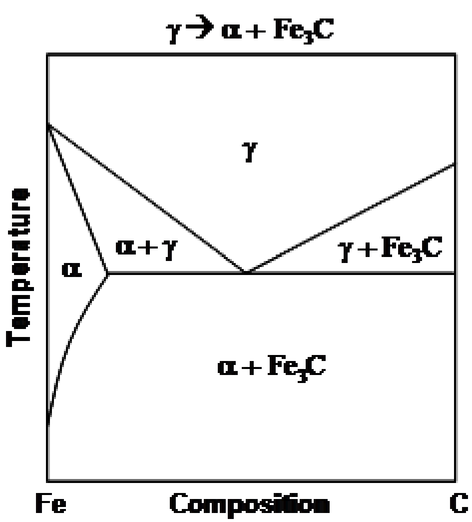
$$\%CW = \left(\frac{A_{initial} - A_{final}}{A_{initial}} \right) * 100$$

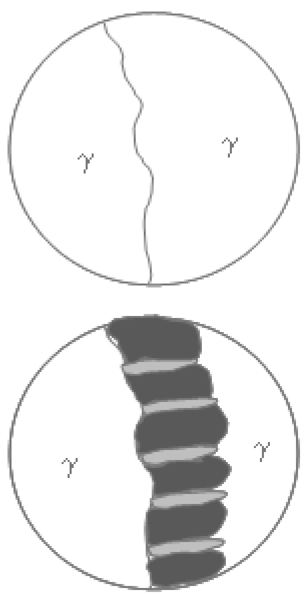
Phase Diagrams

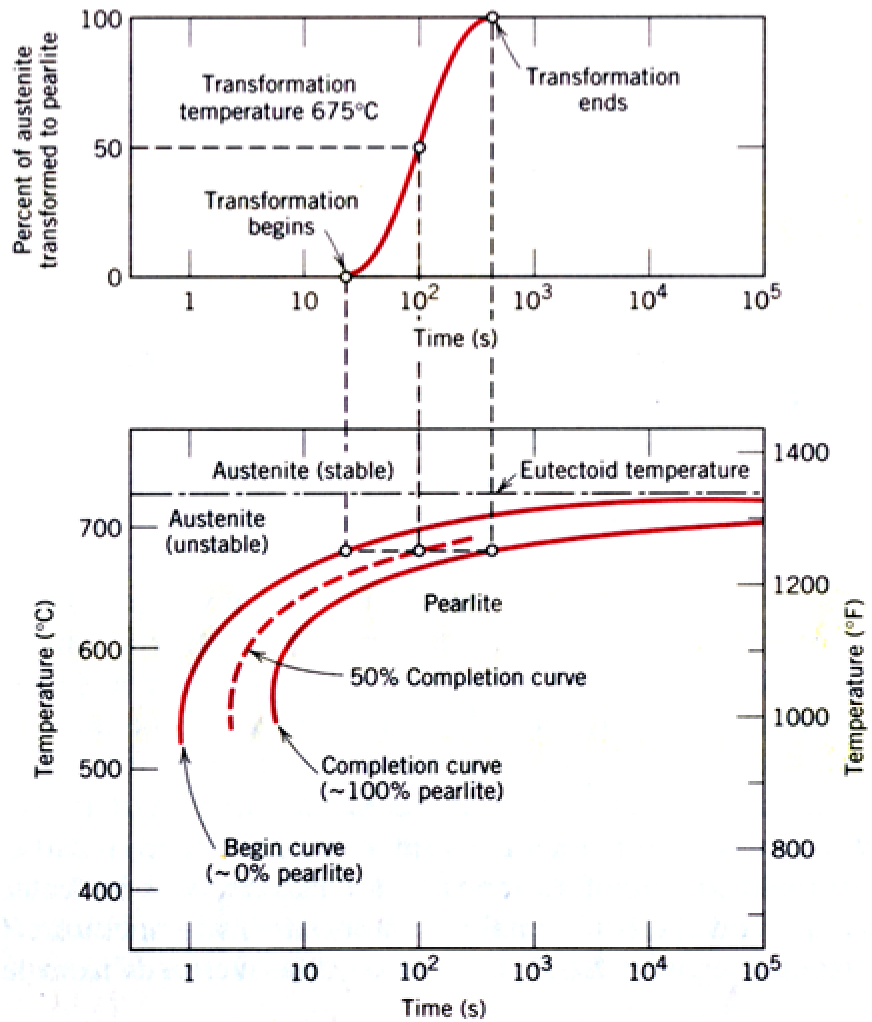


Phase Transformations

- TTT diagrams describe the nucleation and growth behavior at a hold temperature



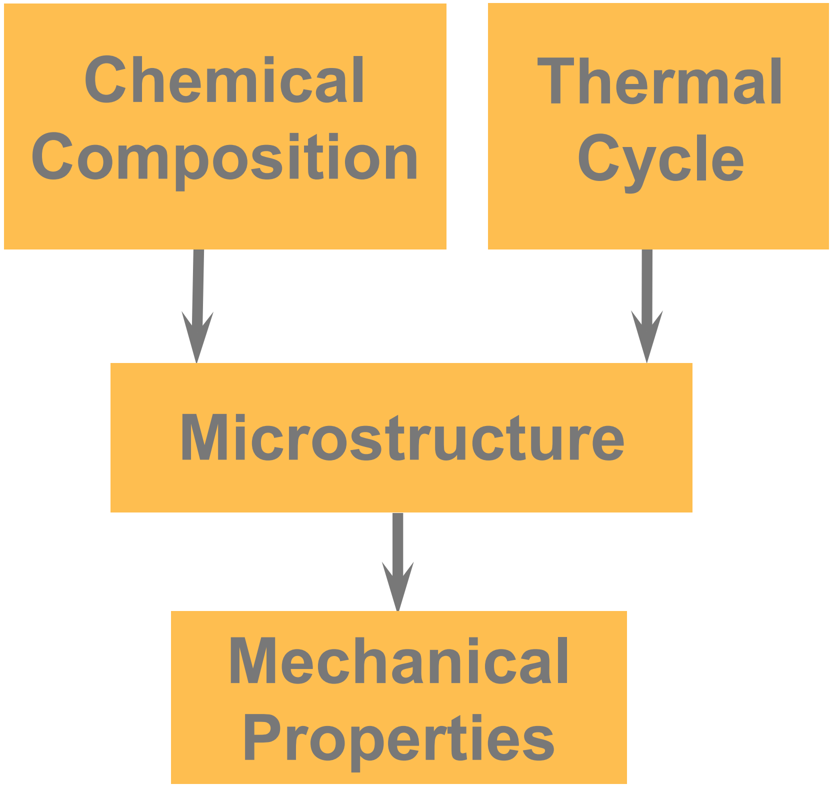




Reference: Callister, W.D. (2000)

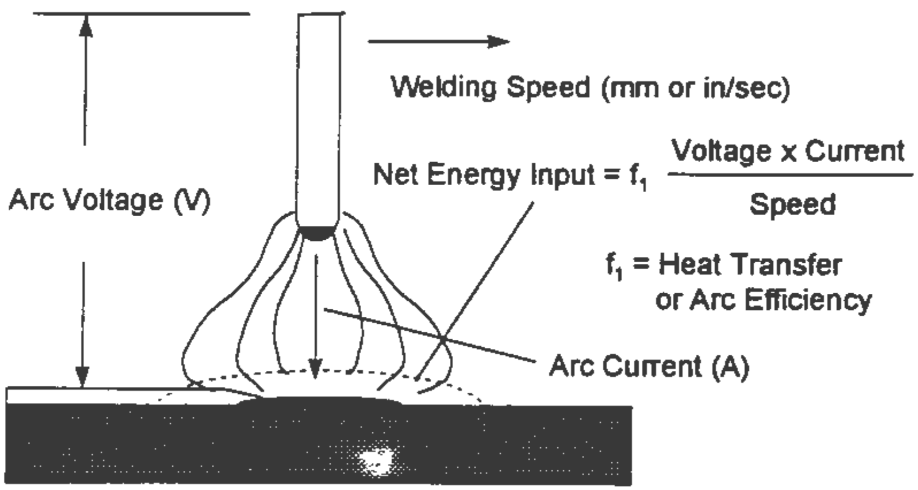
Welding Metallurgy

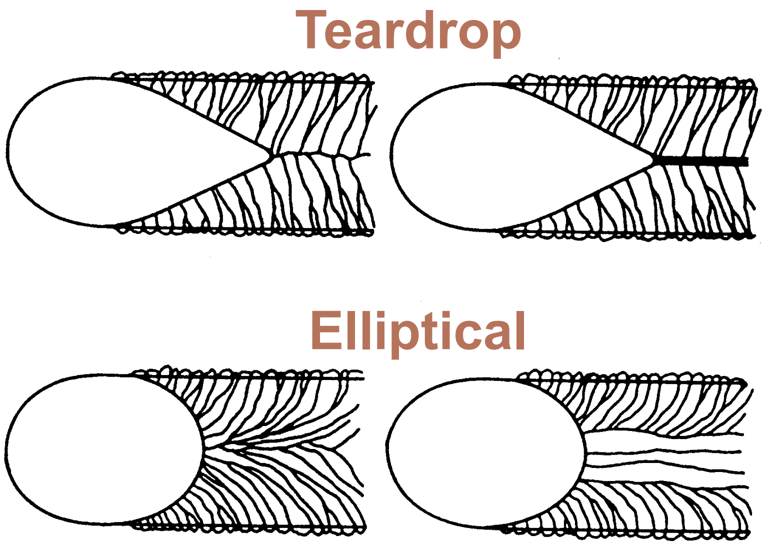
- The cooling rate and chemical composition affect the microstructure of the welded joint
- The mechanical properties of a welded joint depend on the microstructure produced by welding



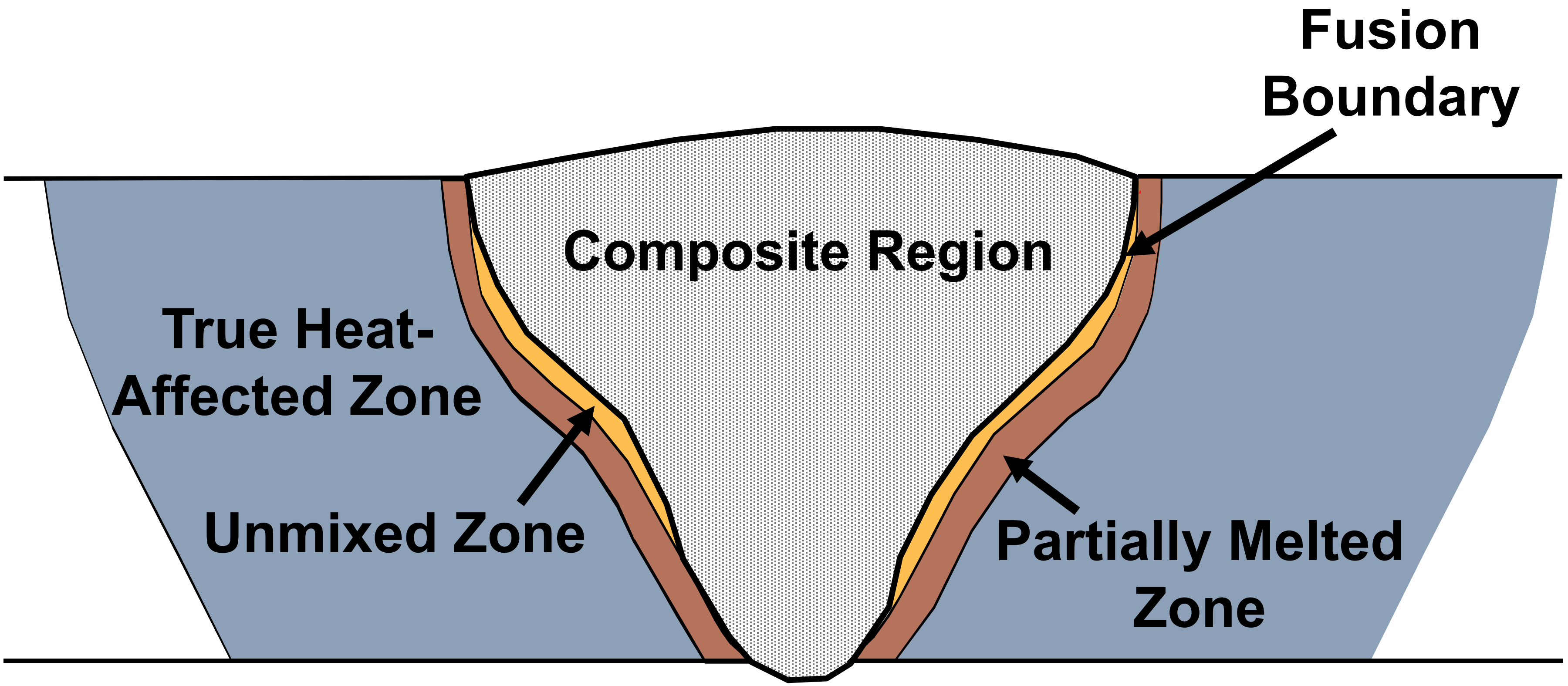
Solidification

- Nucleation
  - Heterogeneous nucleation is dominate in welding
    - Occurs from a foreign particle (oxide, nitride, sulfide, etc.)
- Weld pool shape
  - Teardrop vs. elliptical



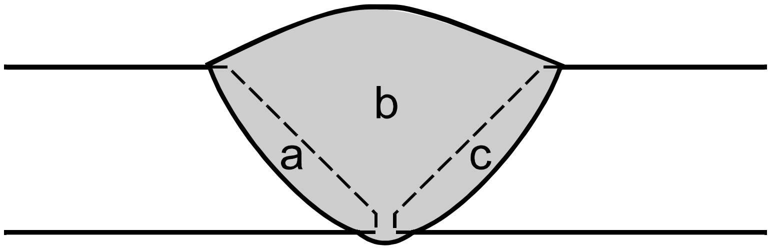


Regions of a Fusion Weld



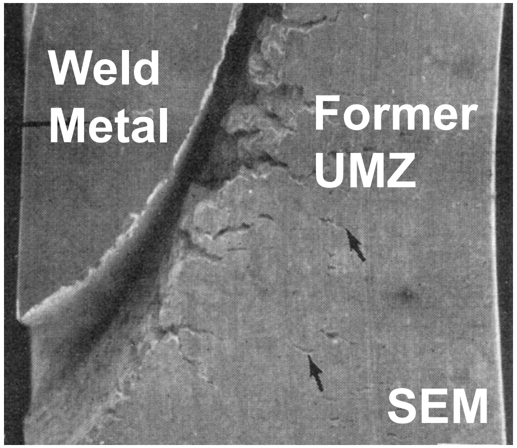
Fusion Zone Principles

- Dilution
  - Amount of melted base metal mixed with the filler metal
  - Significant effect on microstructure and properties
- May exhibit three regions
  - Composite zone
  - Transition zone
  - Unmixed zone



$$\text{Dilution (\%)} = \frac{a + c}{a + b + c} \times 100$$

Austenitic Stainless Steel

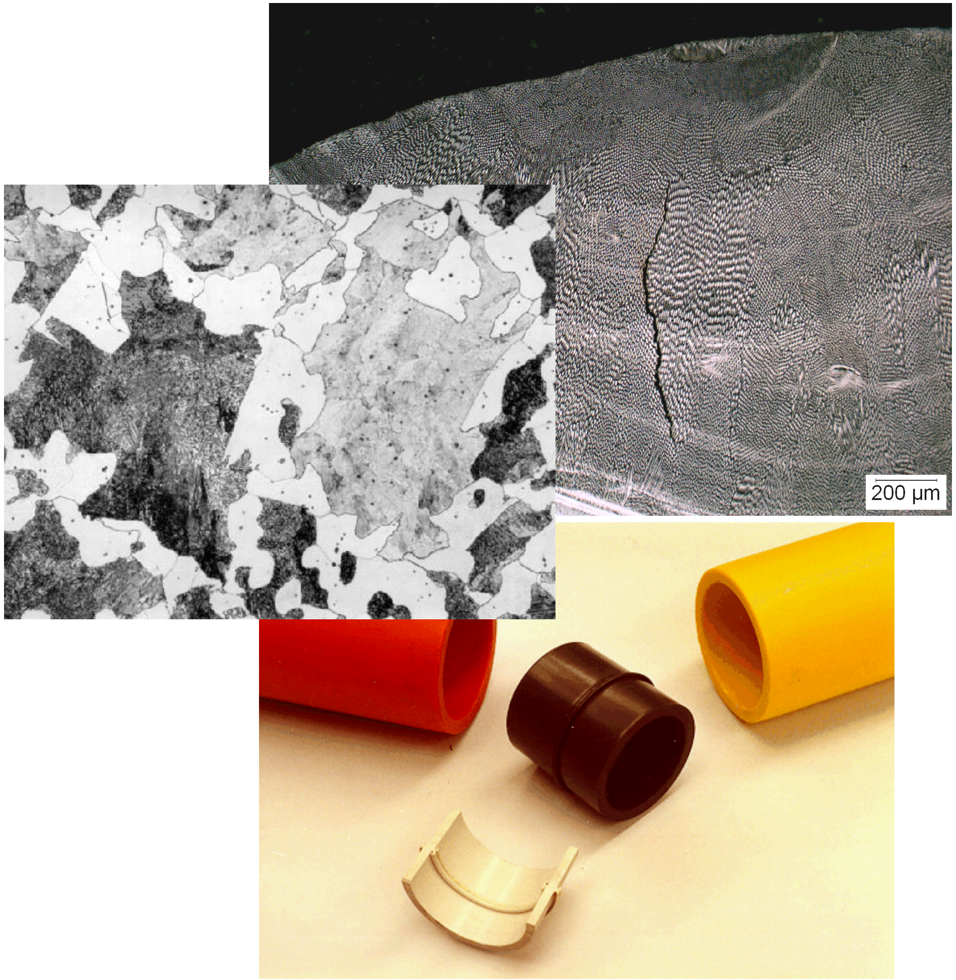


True Heat-Affected Zone

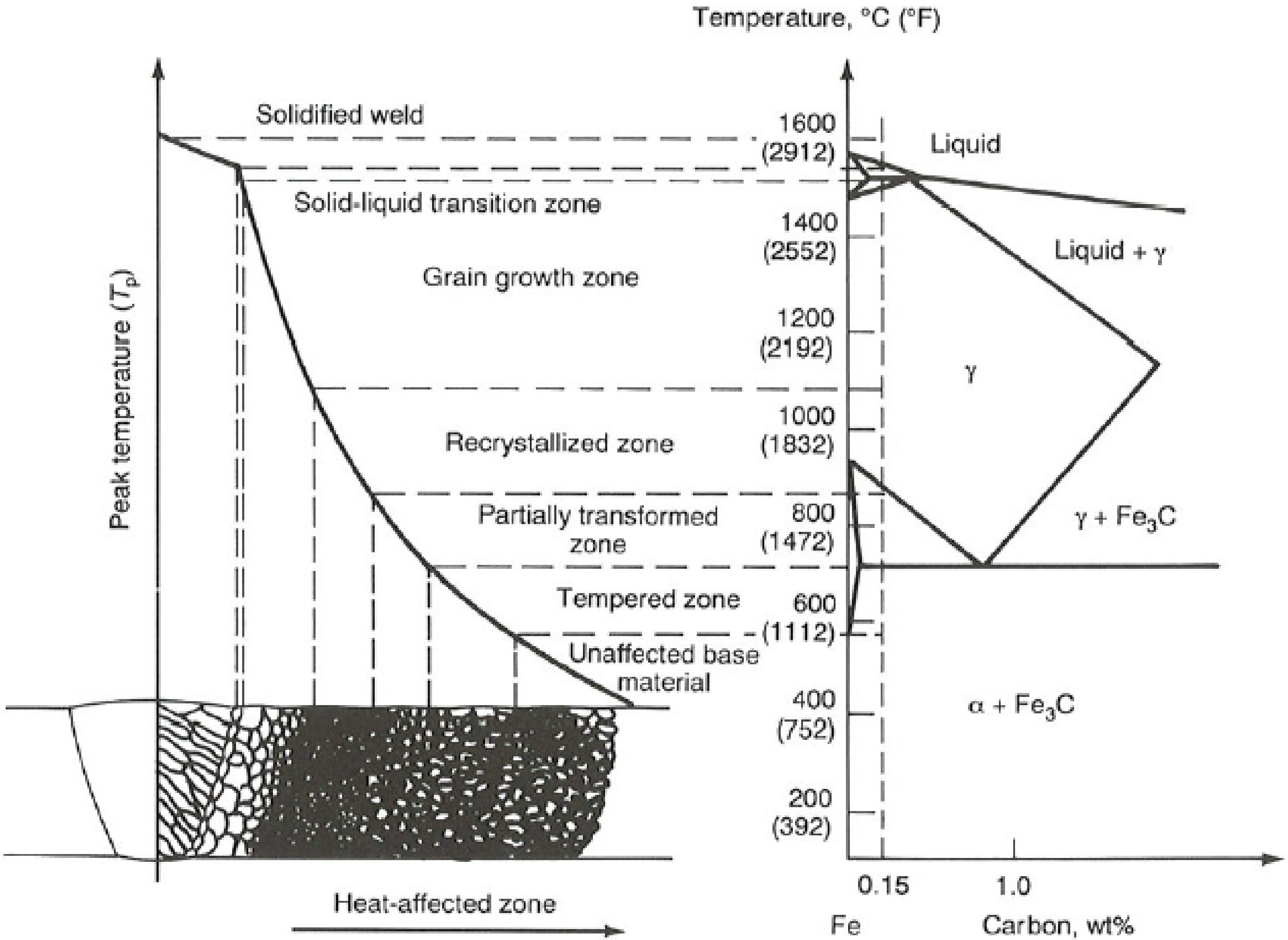
- All metallurgical reactions occur in the solid-state
- Strongly dependent on weld thermal cycle and heat flow conditions
- Solid-state metallurgical reactions
  - Recrystallization
  - Grain growth
  - Allotropic/phase transformations
  - Dissolution/overaging of precipitates
  - Formation of precipitates
  - Formation of residual stresses
- Degradation often associated with HAZ

Alloys

- Carbon steels
- Stainless steels
- Ni-alloys
- Al-alloys
- Ti-alloys
- Cu-alloys
- Polymers

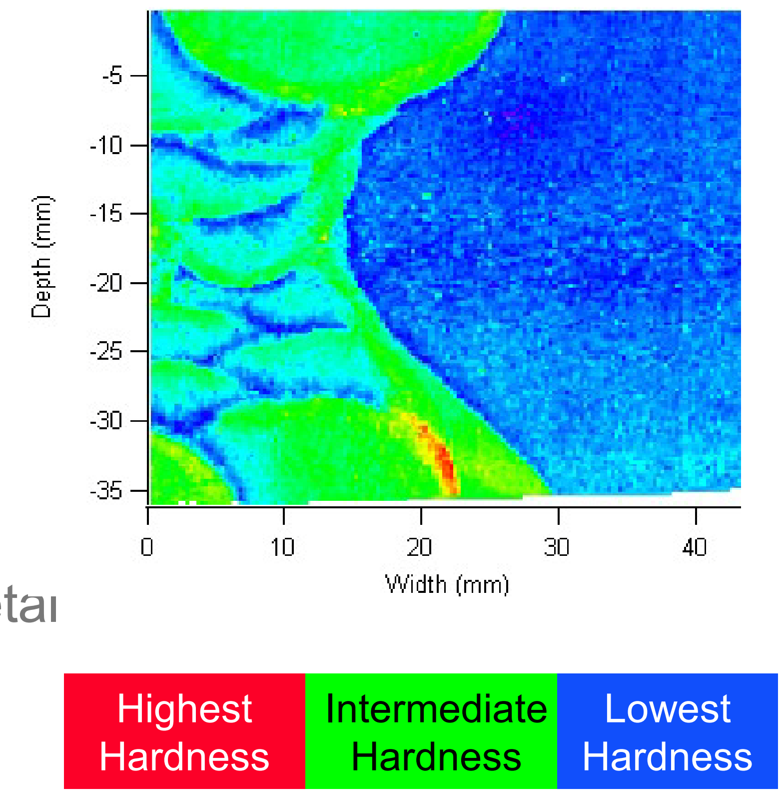


Welding Metallurgy of Carbon Steels

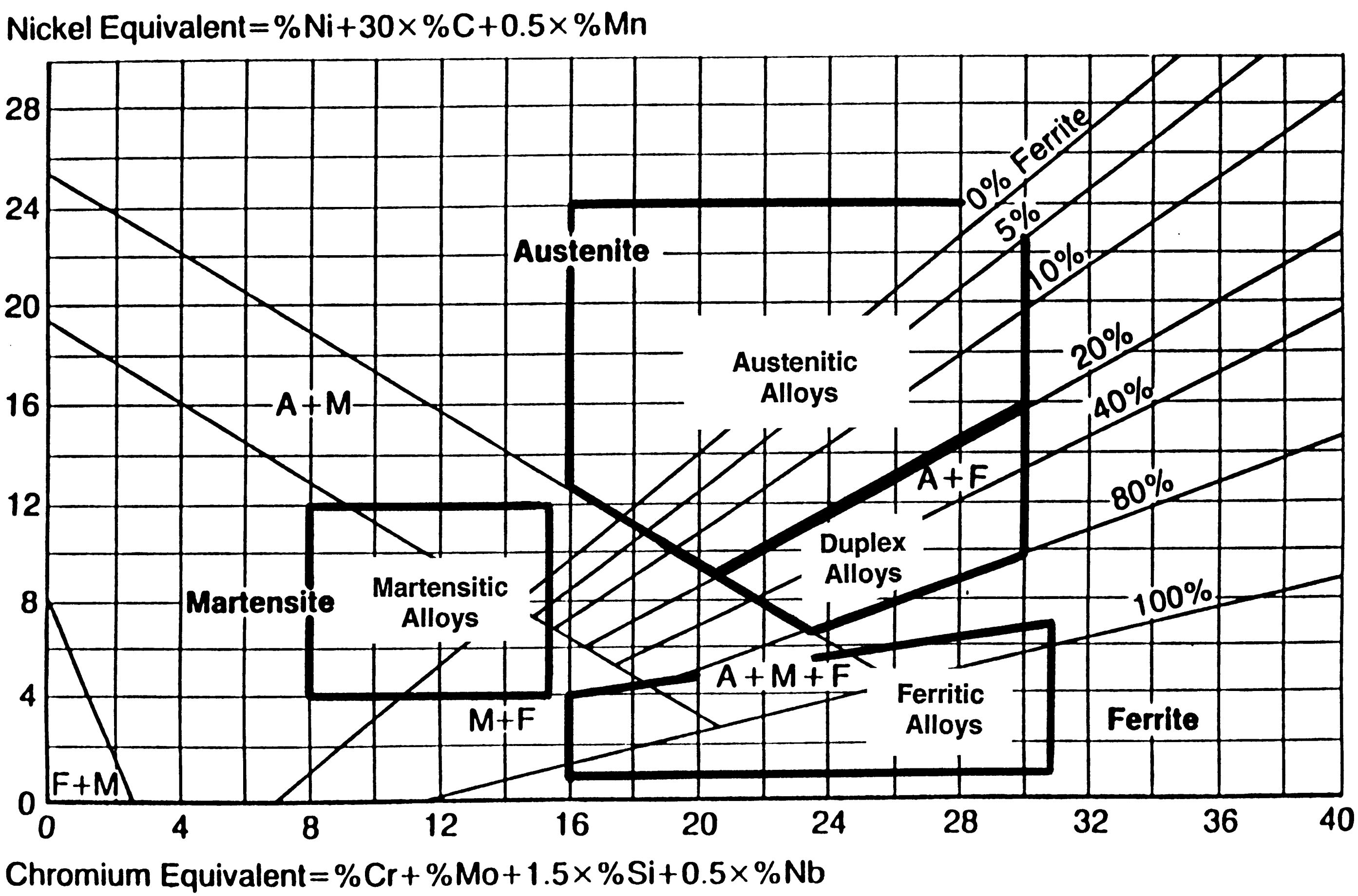


Local Hardening/Softening

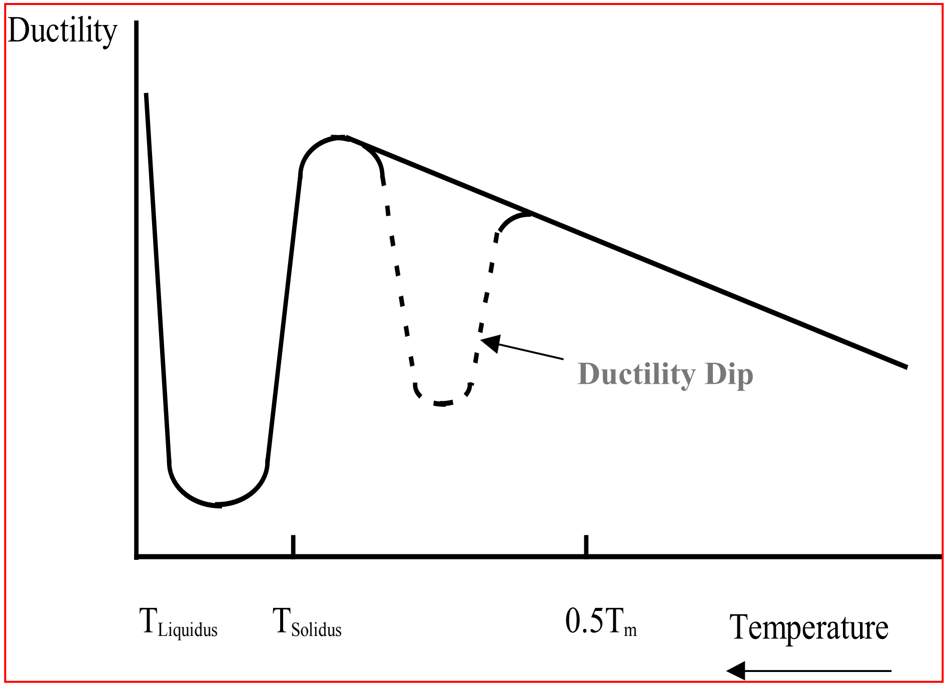
- Thermal cycles and material composition may change the mechanical properties locally
  - The extent of softening and hardening will depend on the alloy and the welding conditions
- Preheat
  - Reduce cooling rate of weld
  - Reduces hydrogen cracking susceptibility
- Post-weld Heat Treatment (PWHT)
  - Reduce risk of brittle fracture
  - Match weld and HAZ closer to base metal
  - Avoid stress corrosion cracking
  - Limit some types of local corrosion
- Temper Bead Welding
  - Alternative to PWHT

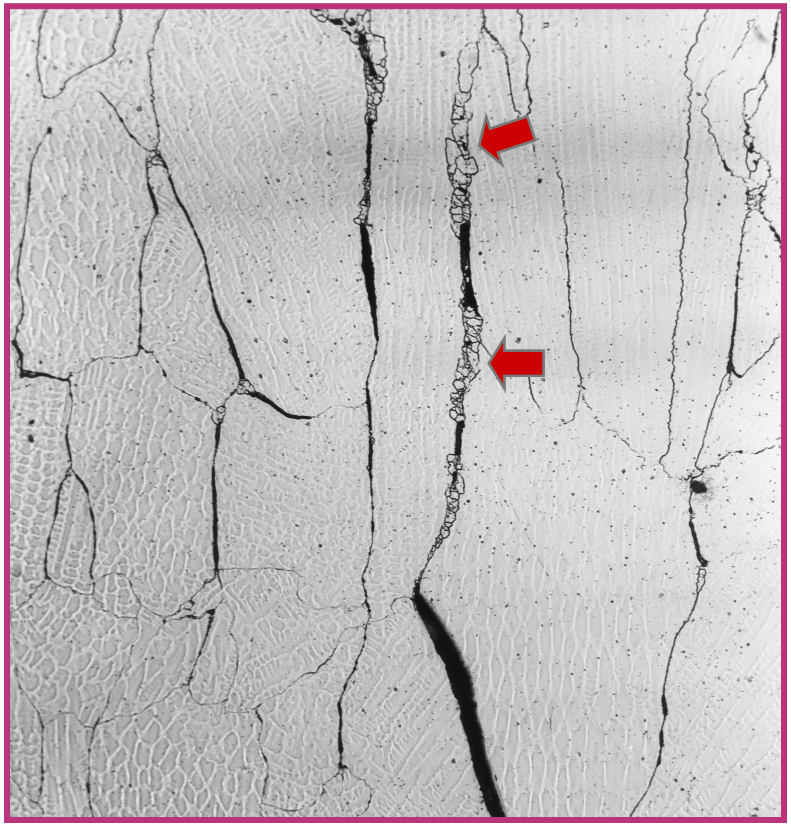


Welding Metallurgy of Stainless Steels

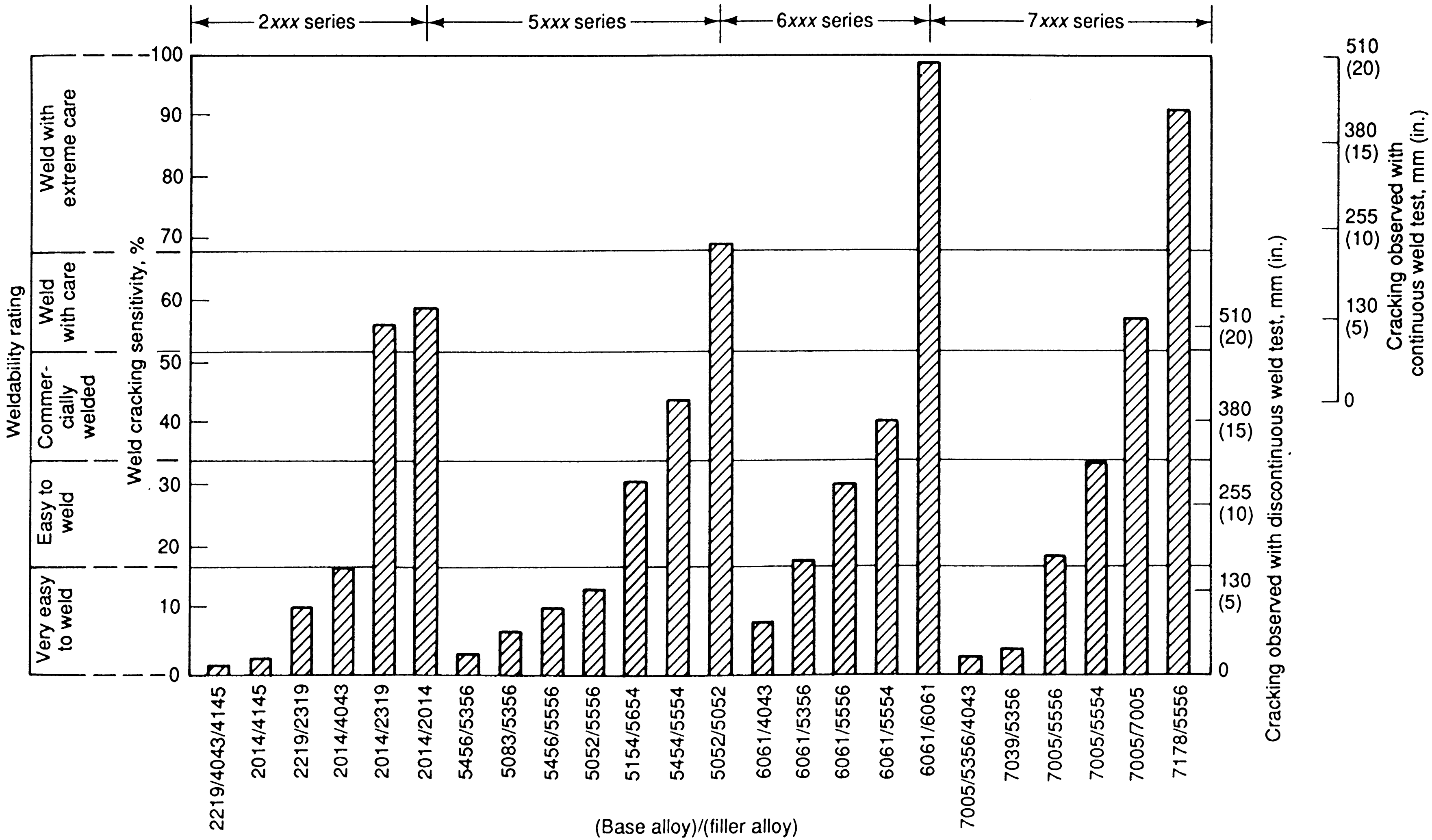


Welding Metallurgy of Nickel-based Alloys

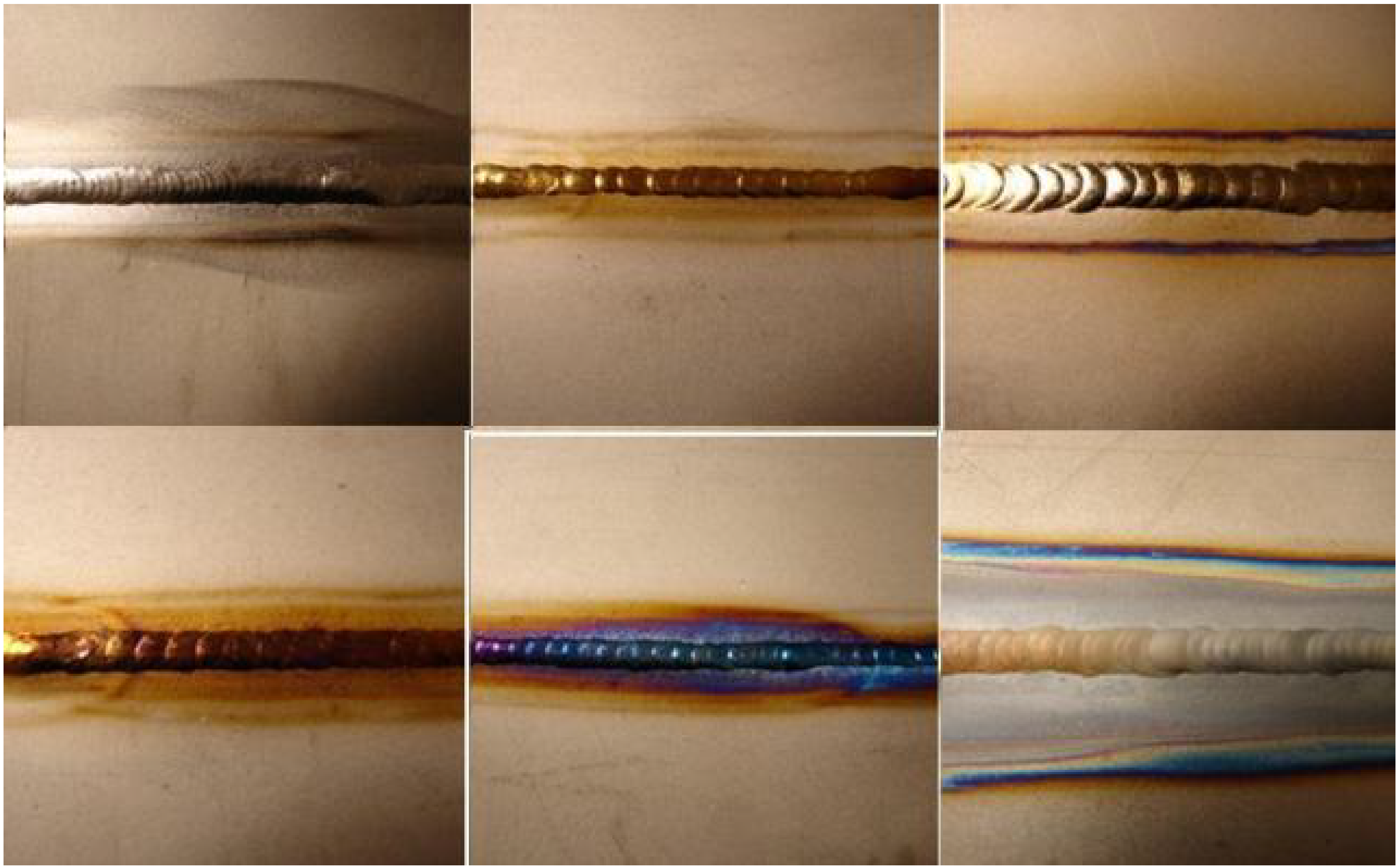




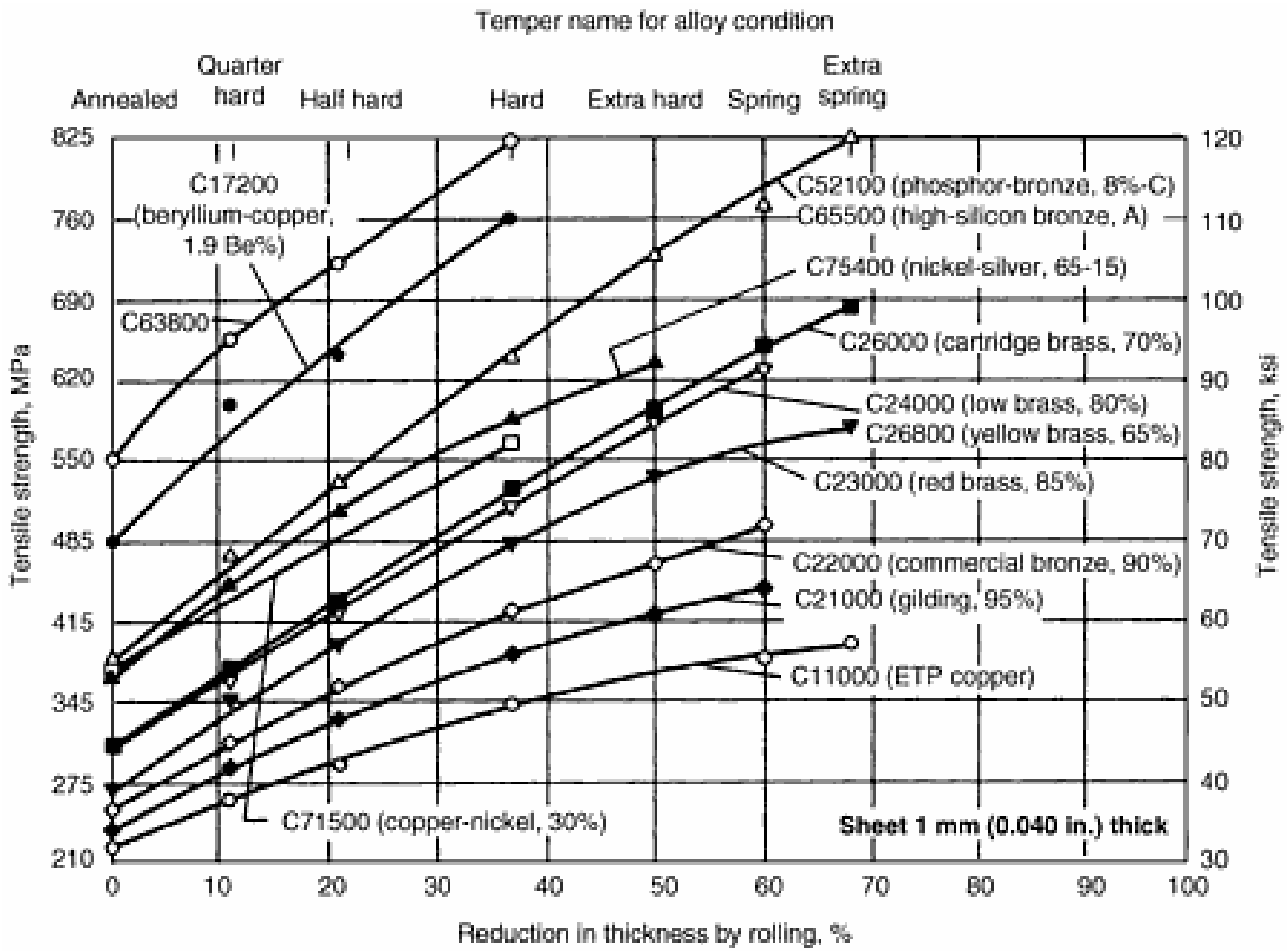
Welding Metallurgy of Aluminum Alloys



Welding Metallurgy of Titanium Alloys



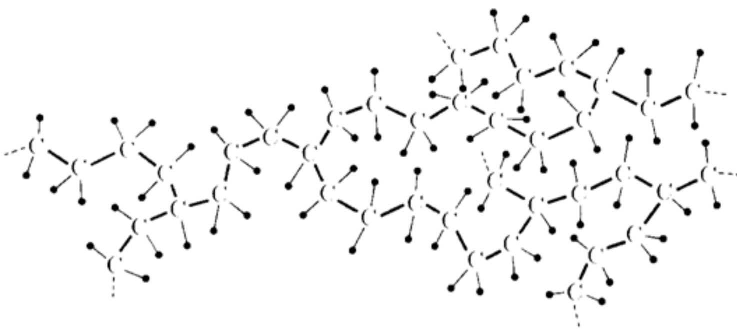
Welding Metallurgy of Copper Alloys



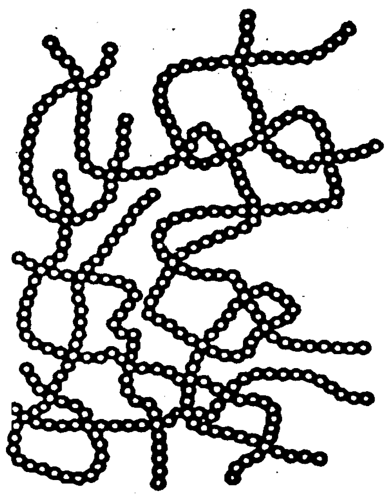
Welding Metallurgy of Polymers

POLYMER

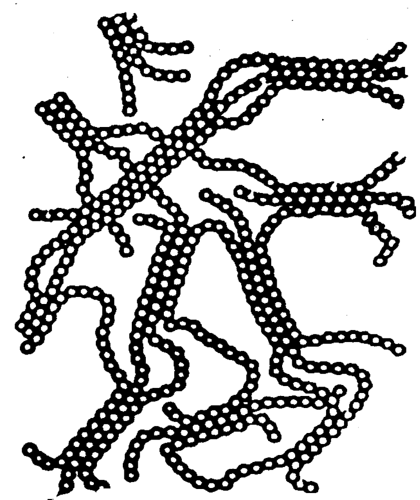
- **THERMOSET**
- **THERMOPLASTIC**
  - **AMORPHOUS**
  - **SEMI-CRYSTALLINE**



Thermoset



Amorphous



Semi-crystalline