

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 !!

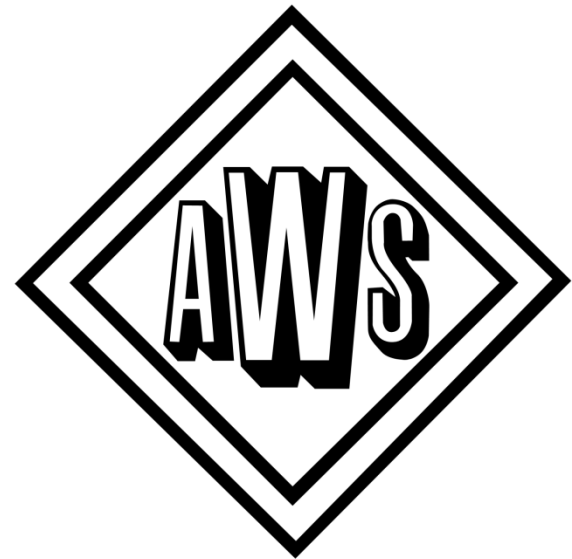
Expectations

- 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

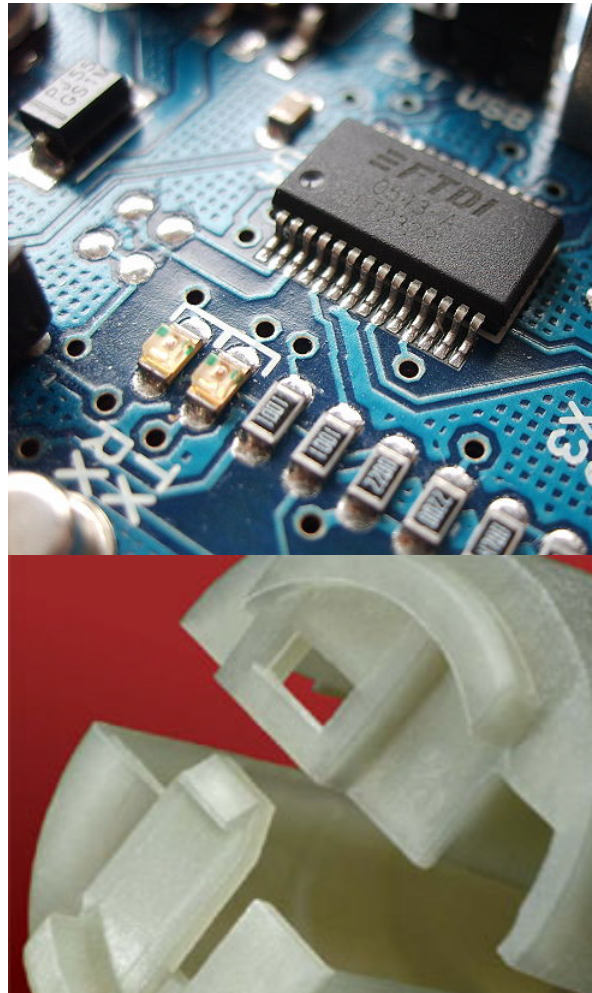


What is Welding?

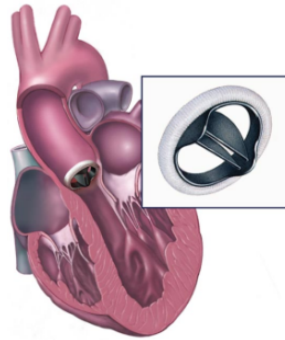
- These processes join a wide range of materials
 - Metals
 - Composites
 - Ceramics
 - Electronic materials
 - Polymers



What is Welding?

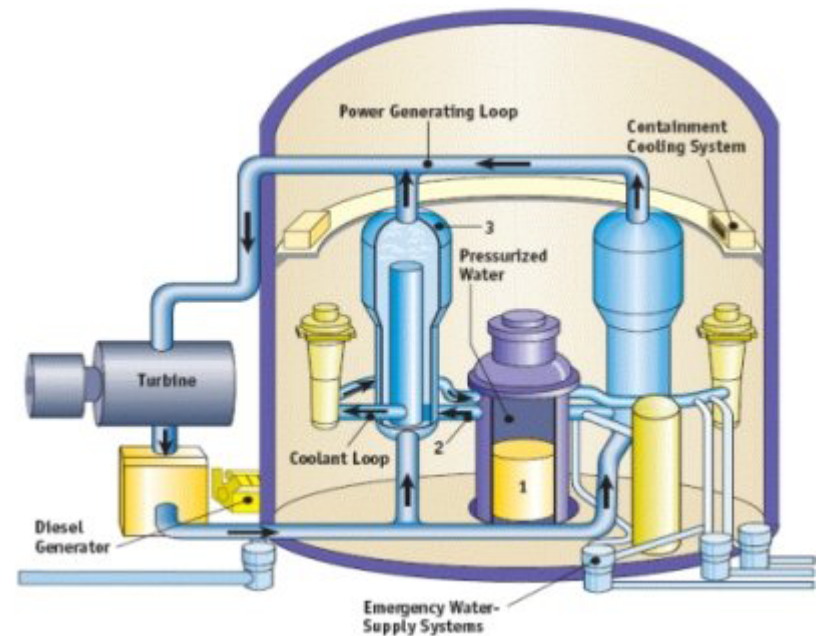


Welding in Our Society



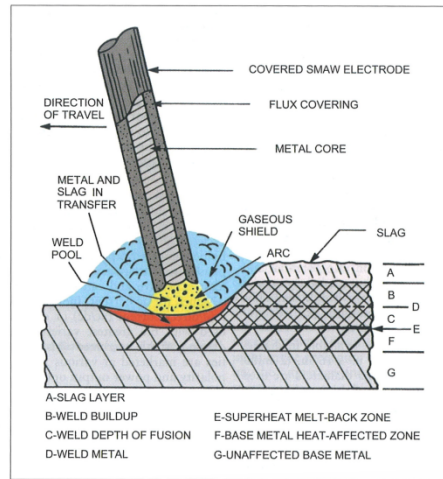
Welding in the Nuclear Industry

- 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

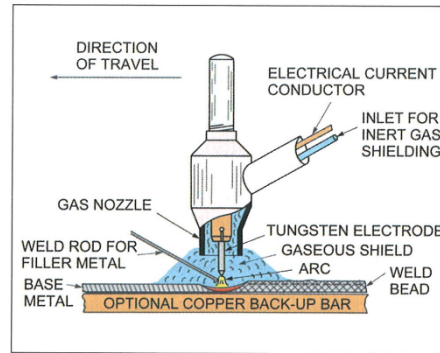
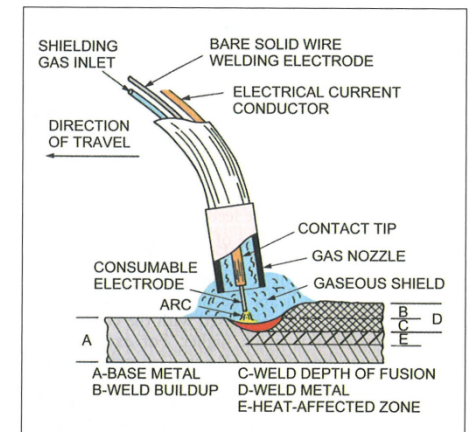


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding



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

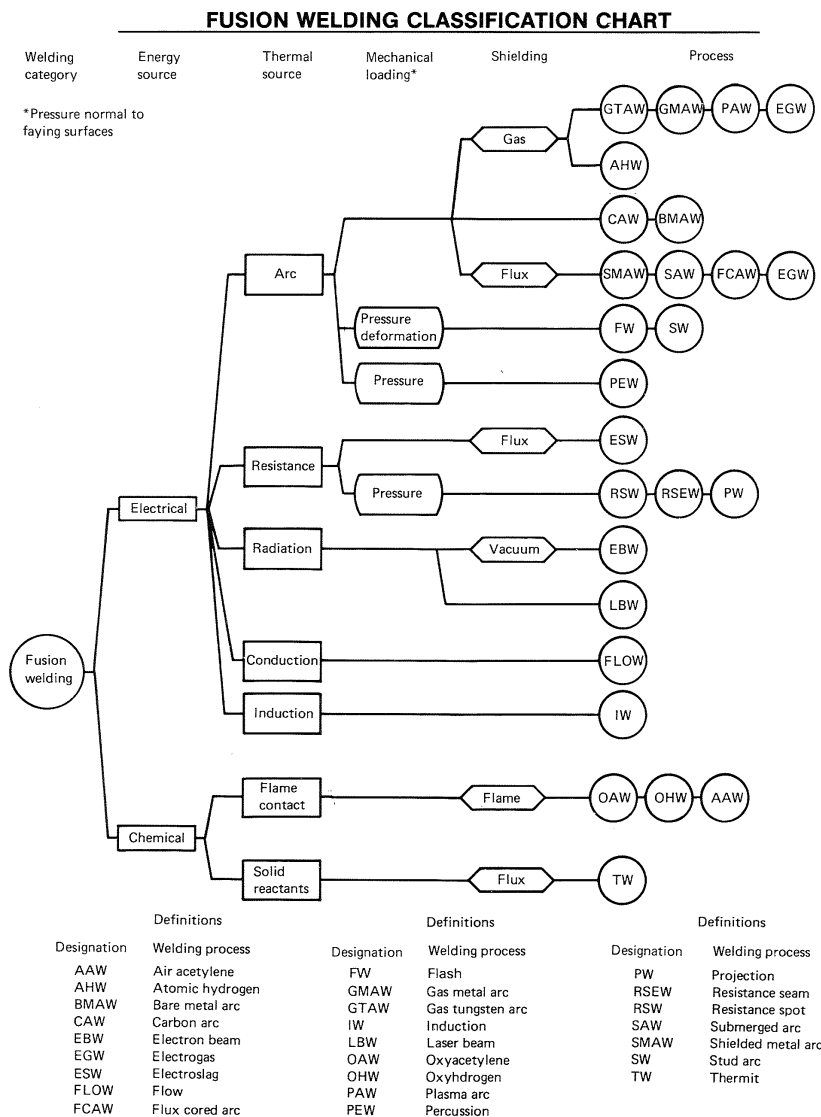
Get to Know the Other Course Participants

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

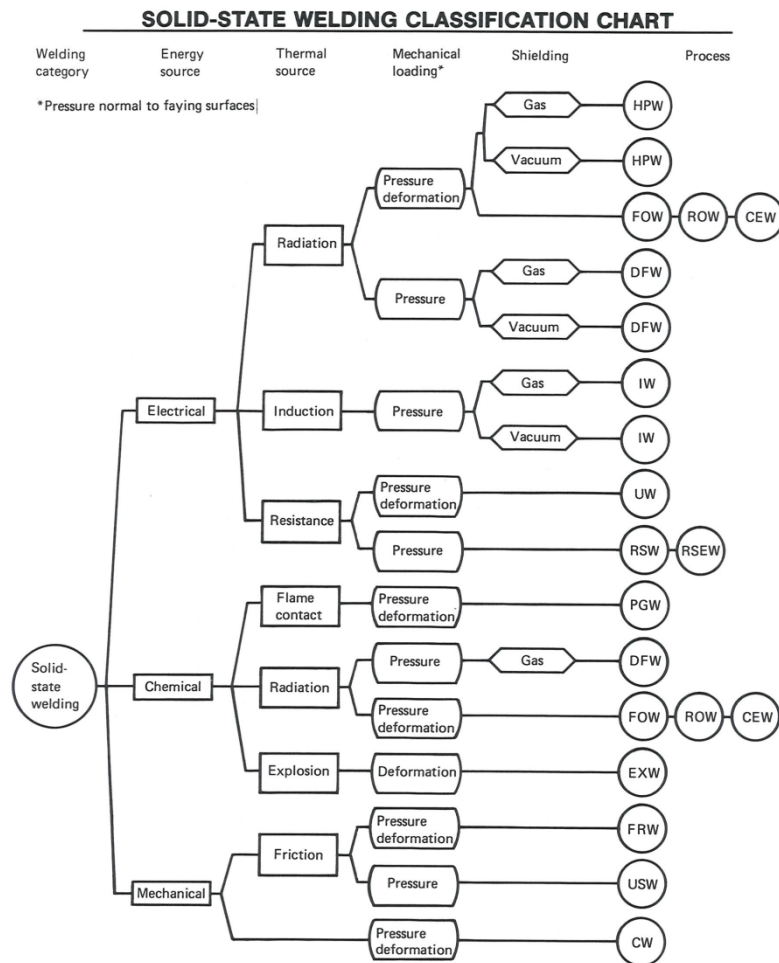
Welding and Cutting Processes Overview

Module 1A

Fusion Welding

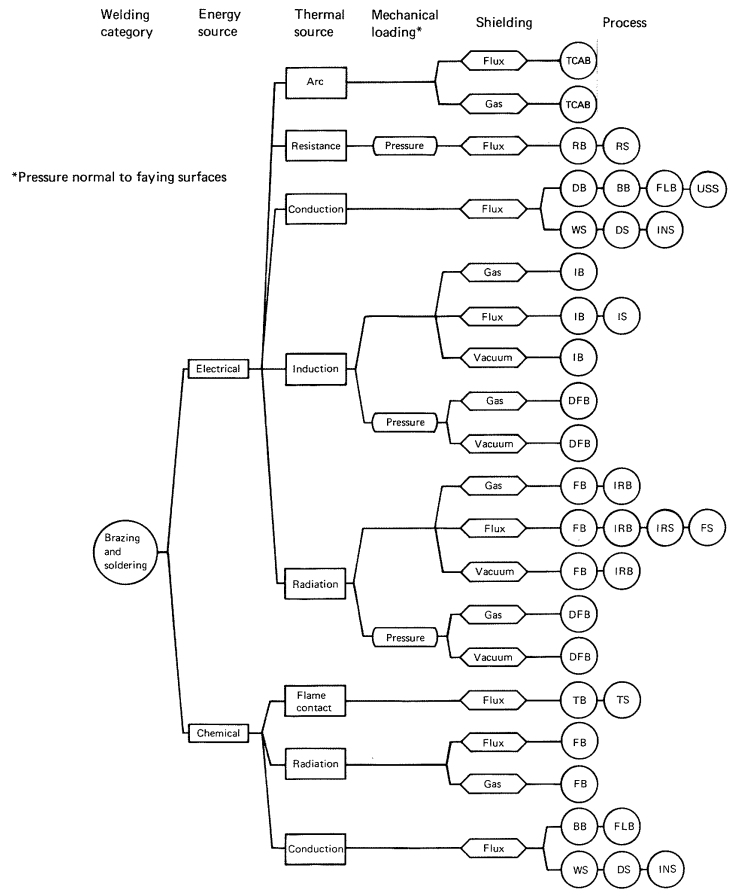


Solid-State Welding



Brazing and Soldering

BRAZING AND SOLDERING CLASSIFICATION CHART



Definitions

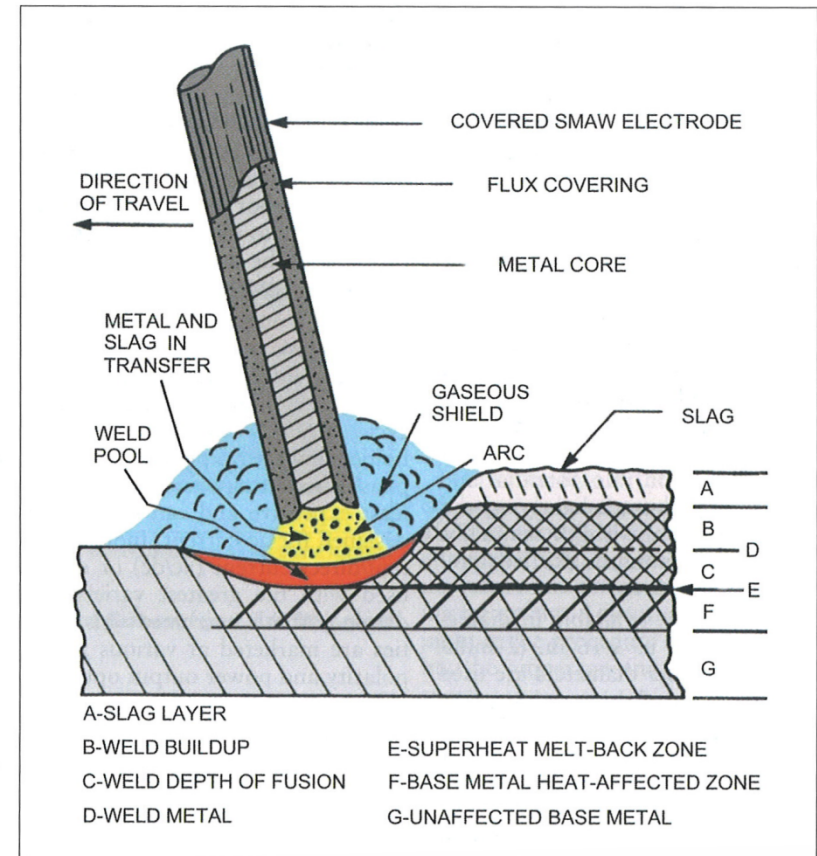
Designation	Process
AB	Arc brazing
BB	Block brazing
TCAB	Twin carbon arc brazing
DB	Dip brazing
DS	Dip soldering
DFB	Diffusion brazing
FB	Furnace brazing
FS	Furnace soldering
FLB	Flow brazing
IB	Induction brazing

Definitions

Designation	Process
IS	Induction soldering
IRB	Infrared brazing
IRS	Infrared soldering
INS	Iron soldering
RB	Resistance brazing
RS	Resistance soldering
TB	Torch brazing
TS	Torch soldering
USS	Ultrasonic soldering
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

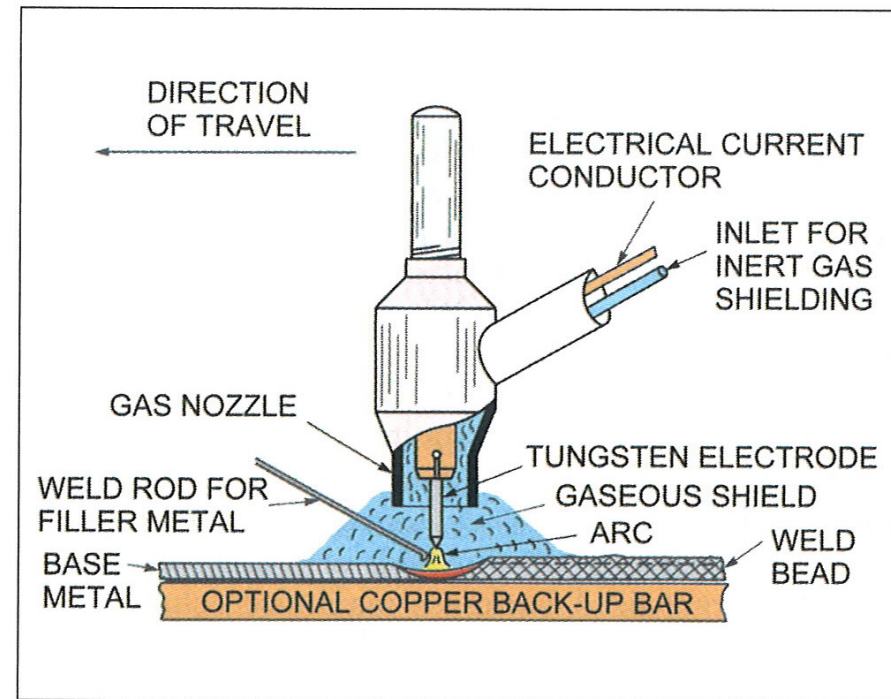


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding

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

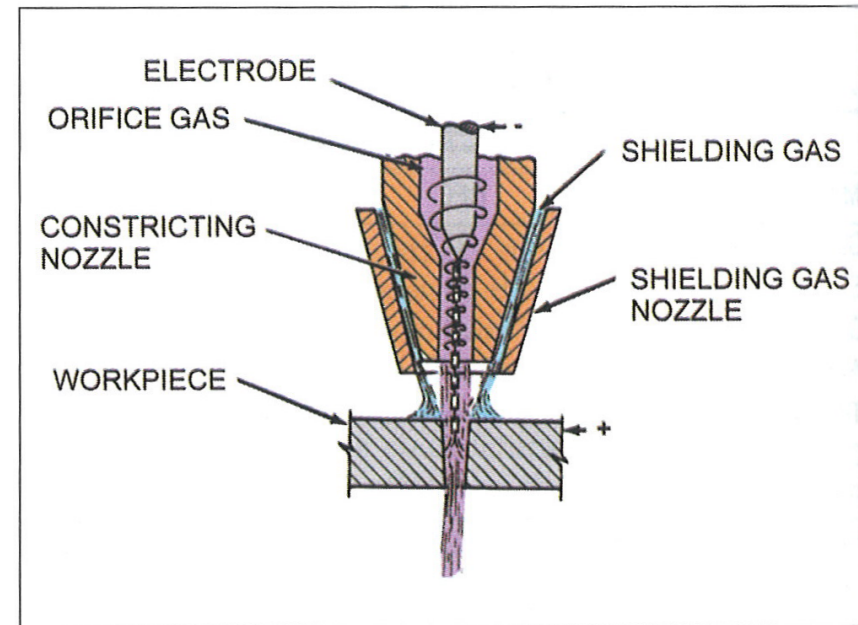
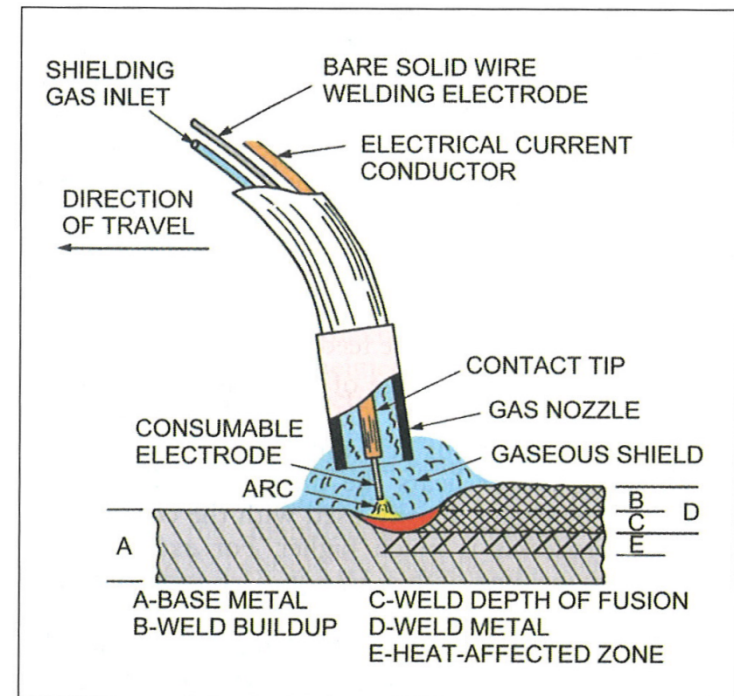


Figure 1.54—Schematic Representation of Plasma Arc Cutting

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



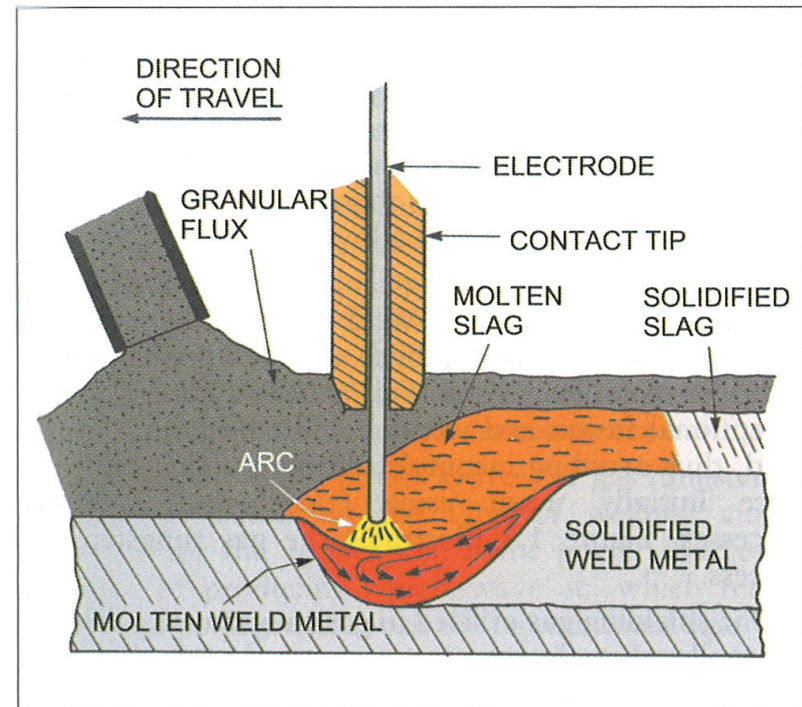
Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.12.

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



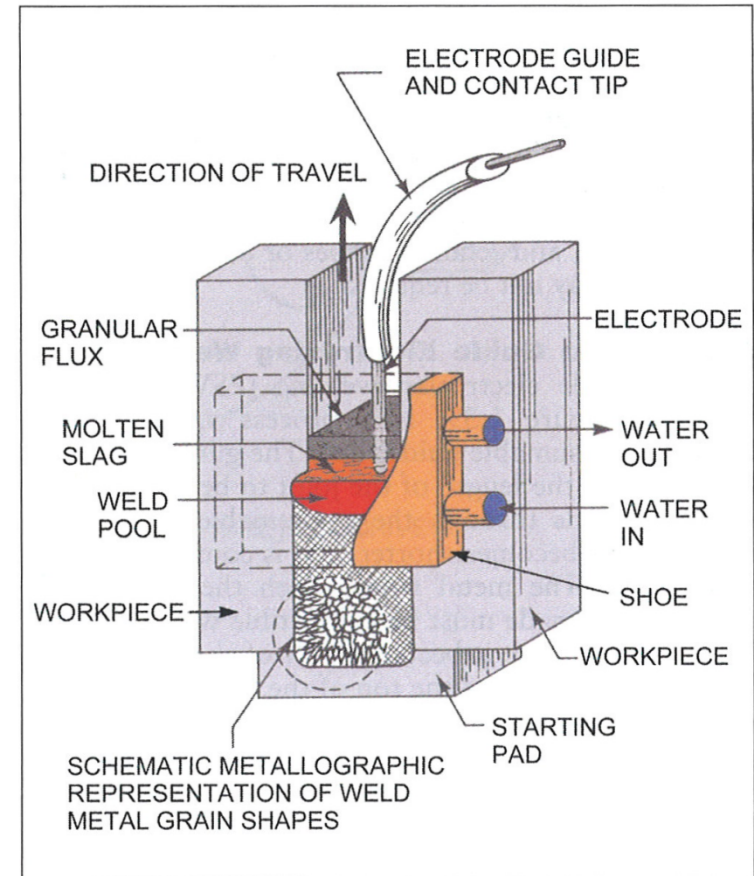
Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.18.

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



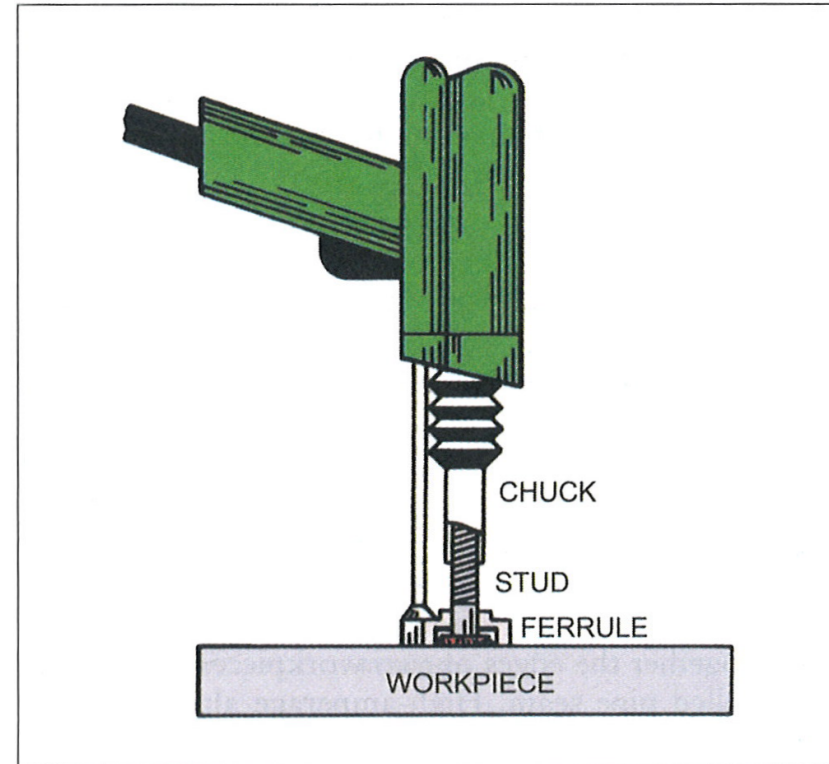
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.51.

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



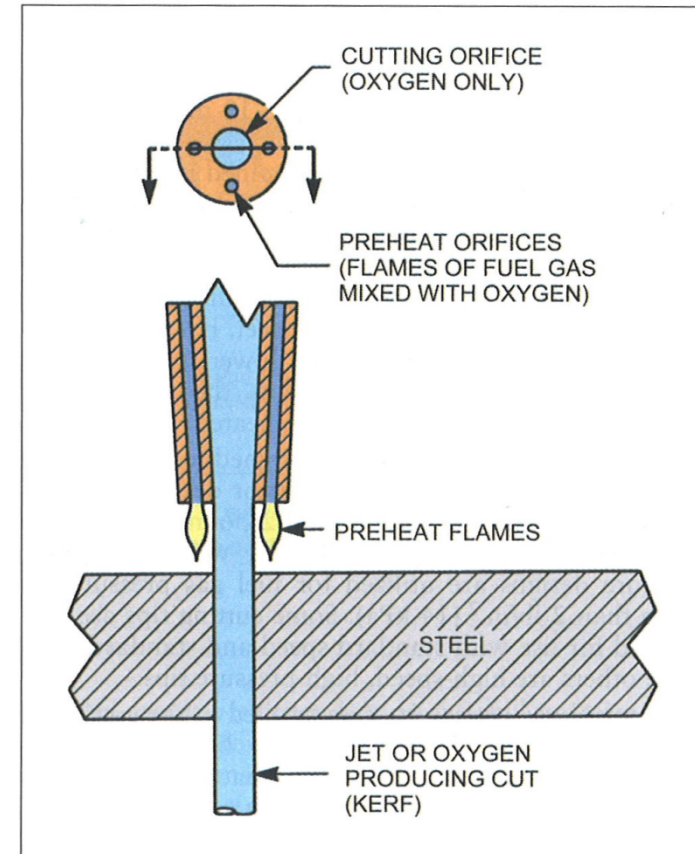
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.63.

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



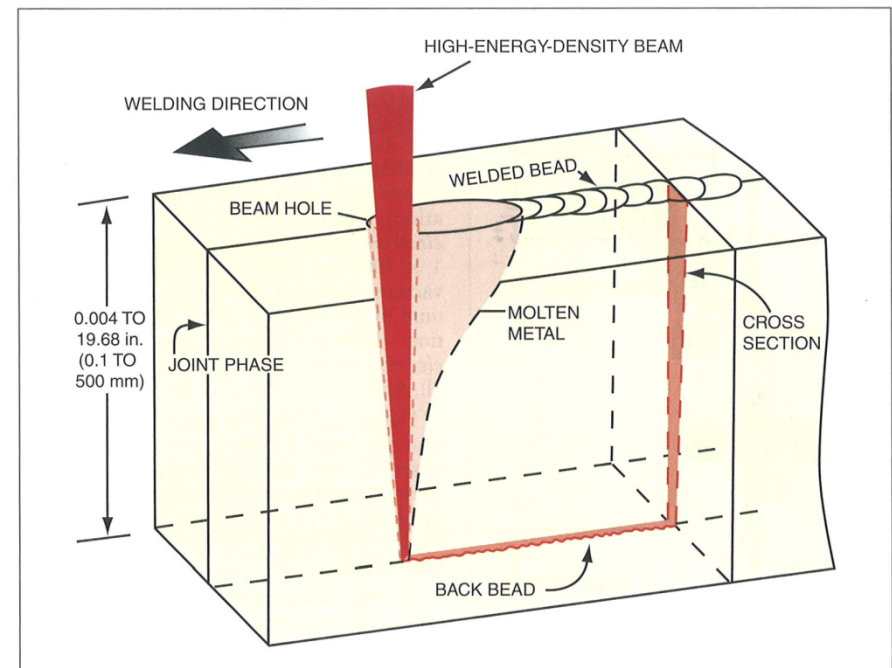
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.82.

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

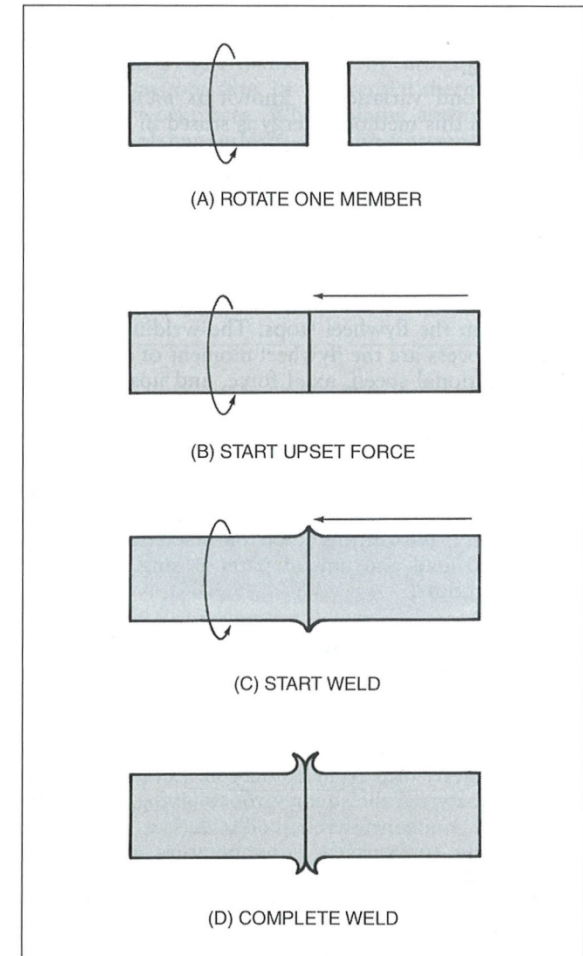


Figure 1.26—Schematic Illustration of Friction Welding

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

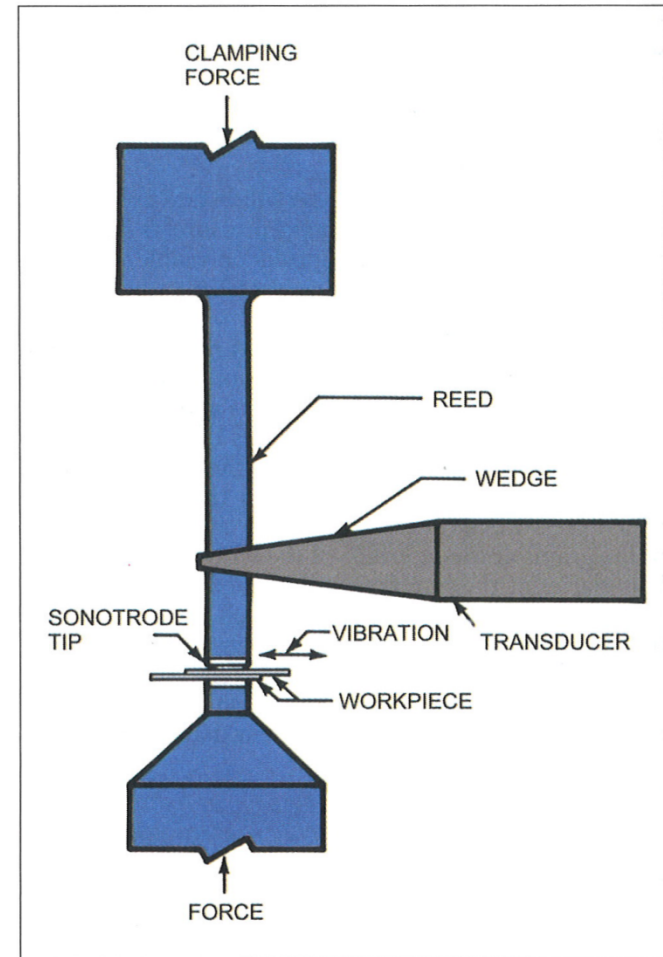
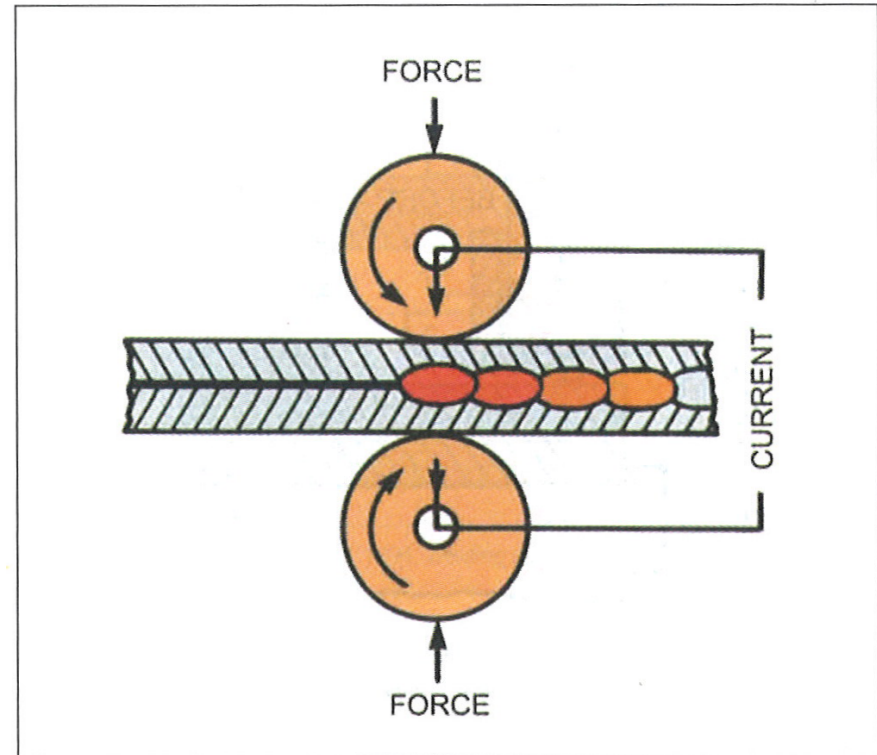


Figure 1.29—Schematic Representation of Ultrasonic Welding

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



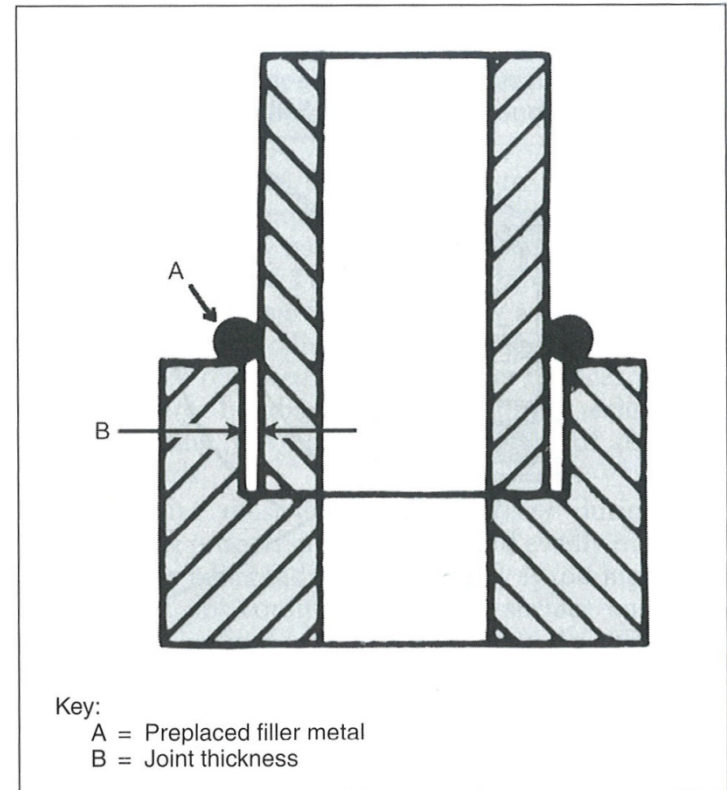
Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(B).

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 $> 450^{\circ}\text{C}$
 - Soldering: filler metal liquidus $< 450^{\circ}\text{C}$
- 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

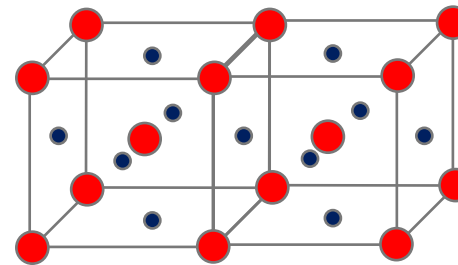
- Defects
- Solid Solutions

■ Phase Diagrams

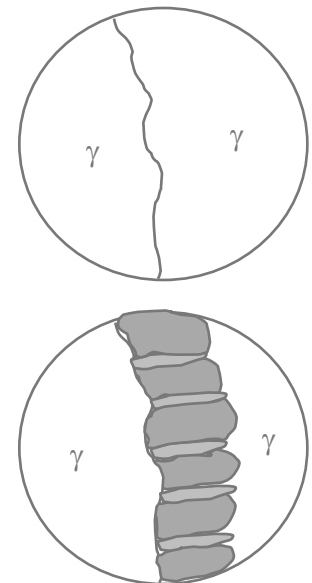
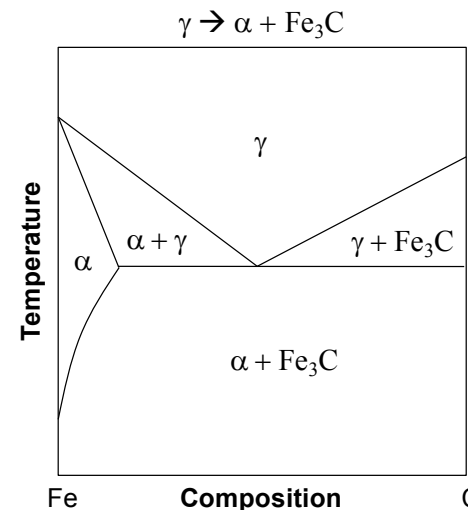
■ Diffusion

■ Strengthening Mechanisms

- Grain Size
- Solid Solutions
- Cold Work (Strain Hardening)
- Precipitation



- Fe is the solvent
- C is the solute



Physical Metallurgy Concepts

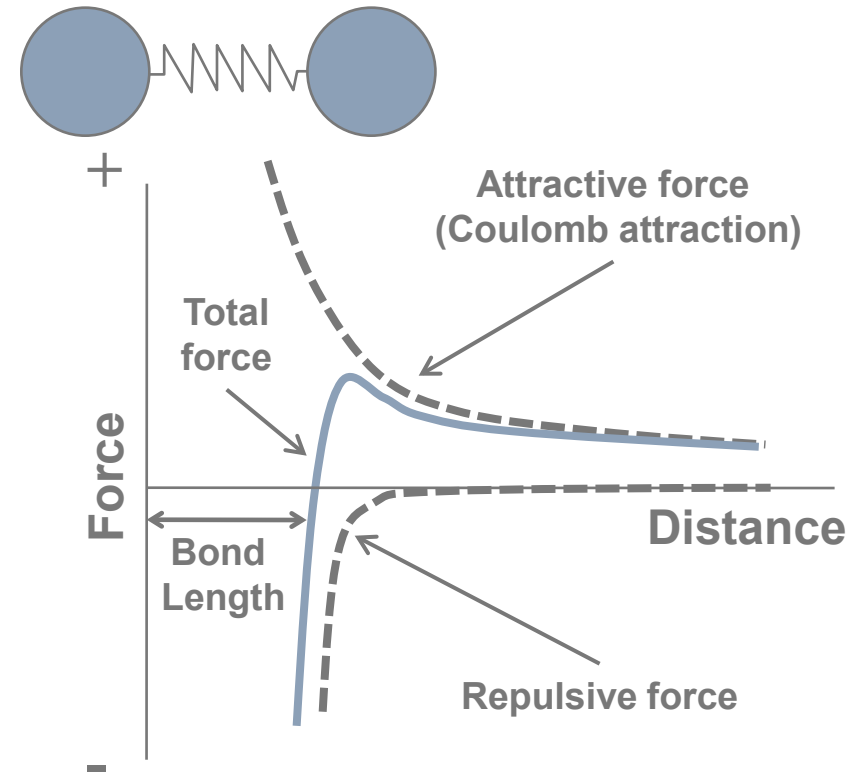
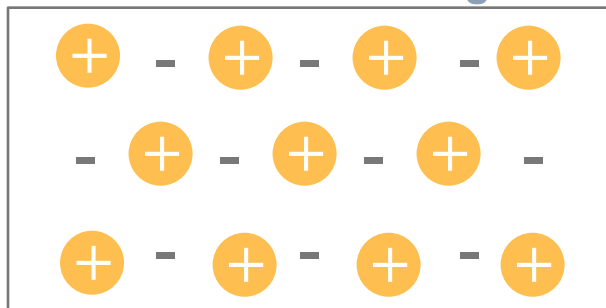
■ Atomic bonds

- Ionic, covalent, metallic
- Metallic bonding
 - ◆ Free electrons
 - ◆ Elastic behavior

Metal ions

“Sea” of electrons

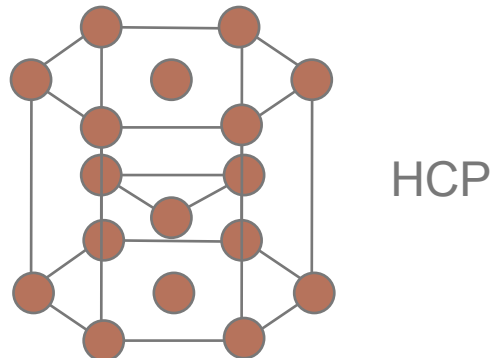
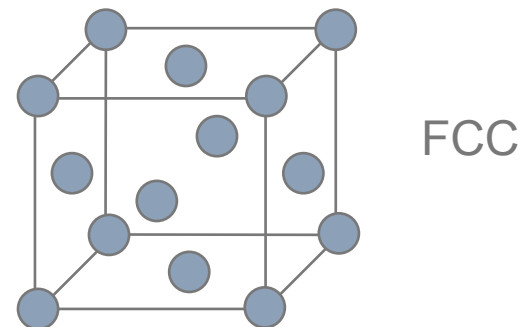
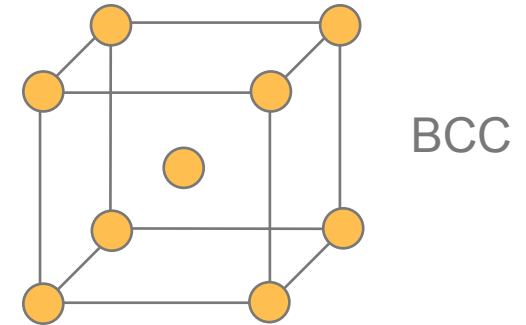
Metallic Bonding



Physical Metallurgy Concepts

■ Crystal structures

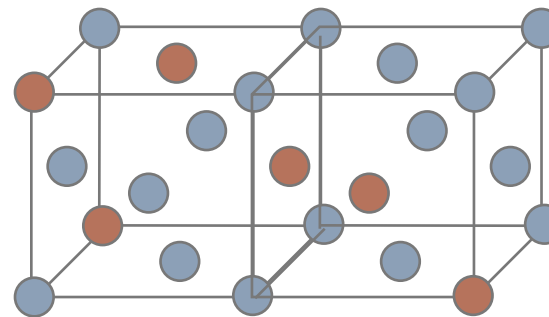
- BCC
 - ◆ Iron & ferritic steels
- FCC
 - ◆ Ni alloys & Al alloys
- HCP
 - ◆ Ti (alpha alloys) & Zr



Physical Metallurgy Concepts

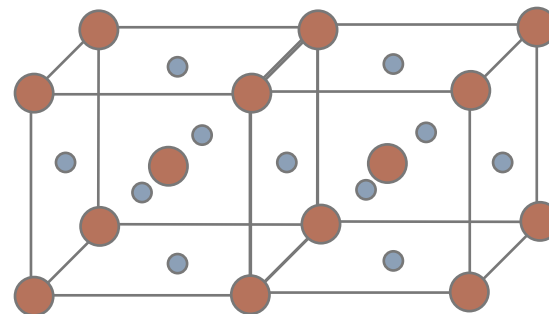
■ Solid solutions

- Substitutional
 - ◆ Ni-Cu alloys
- Interstitial
 - ◆ Steels



● Ni is the solvent
● Cu is the solute

Substitutional



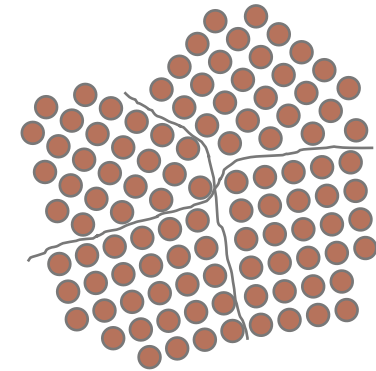
● Fe is the solvent
● C is the solute

Interstitial

Physical Metallurgy Concepts

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

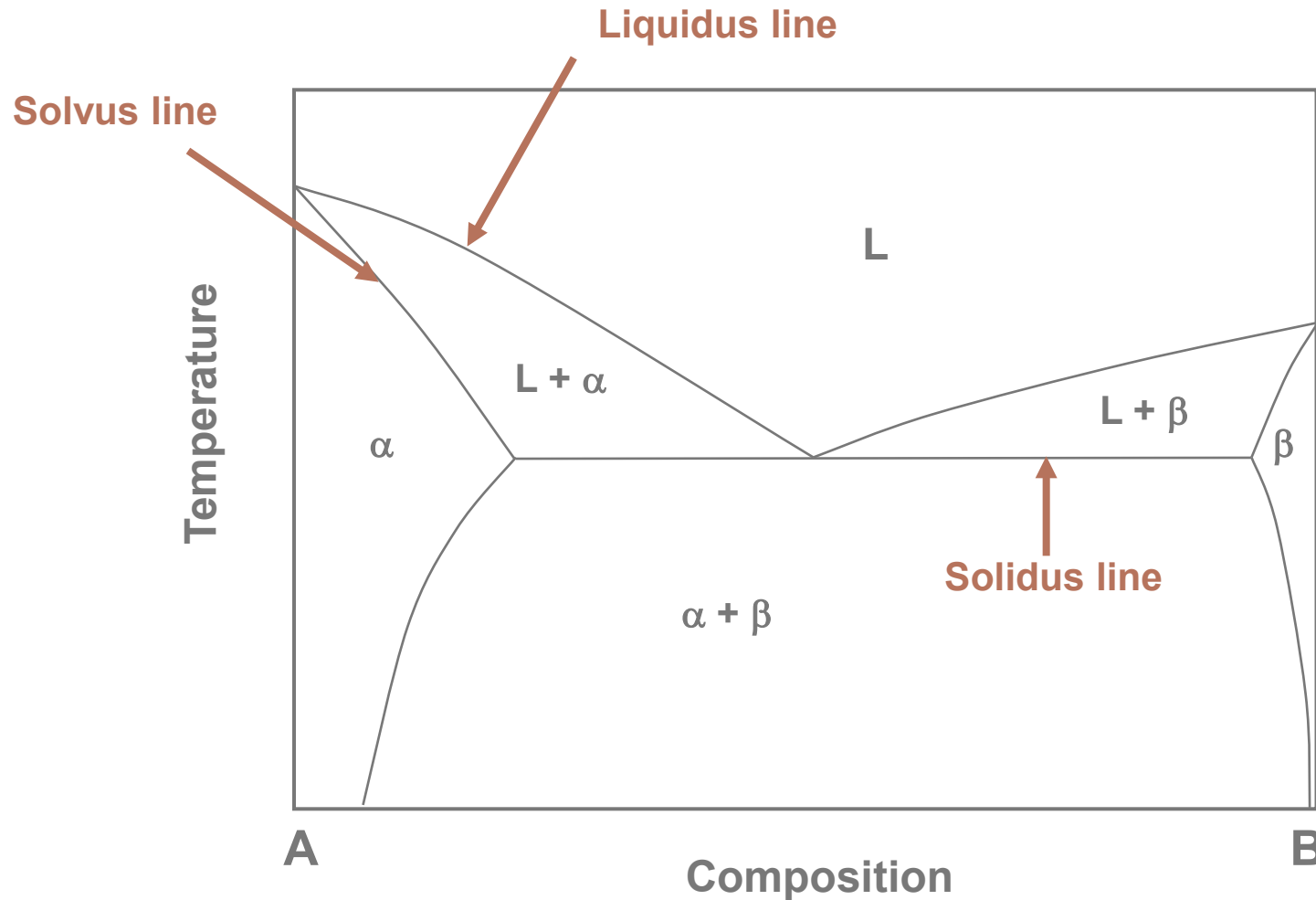
Grain boundaries



Cold work expressed in terms of area reduction:

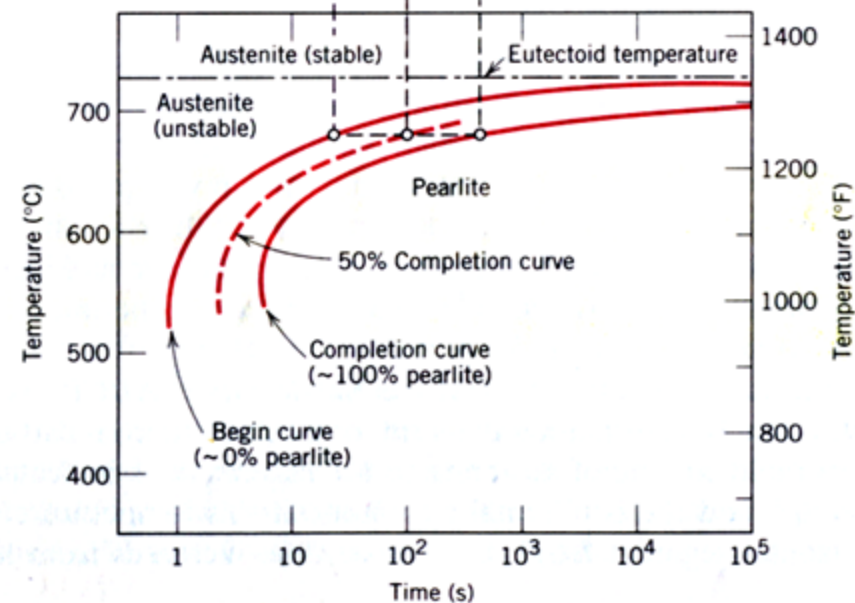
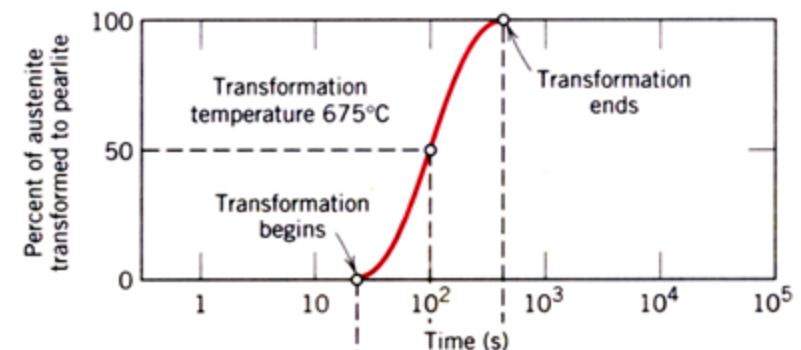
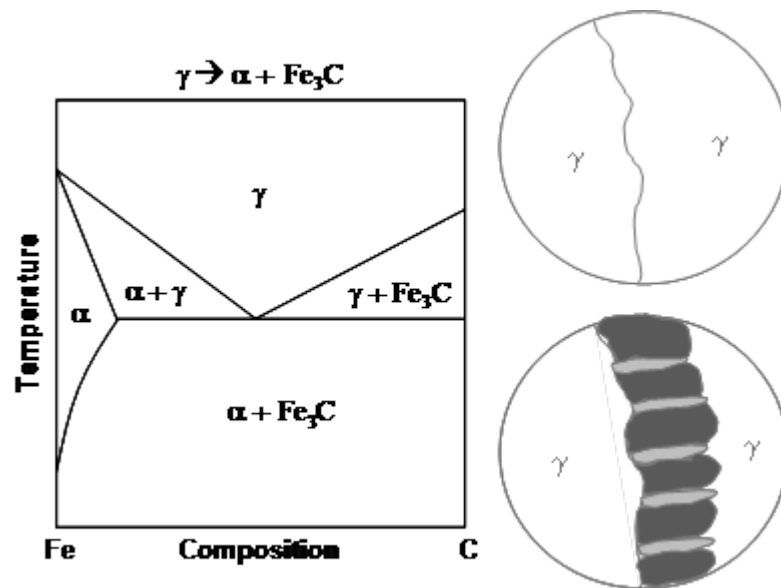
$$\%CW = \left(\frac{A_{initial} - A_{final}}{A_{initial}} \right) * 100$$

Phase Diagrams



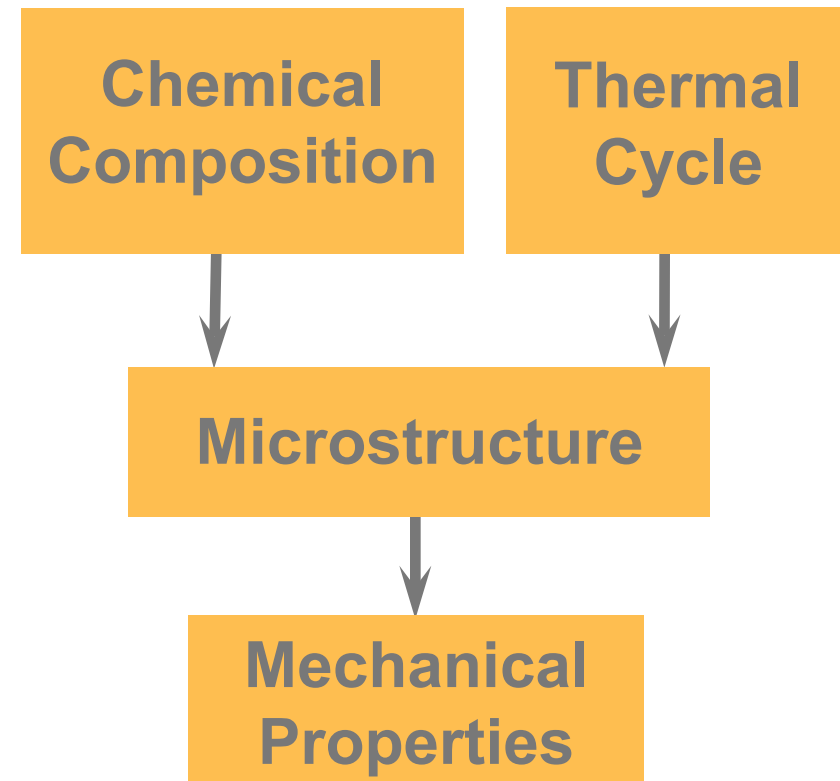
Phase Transformations

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



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



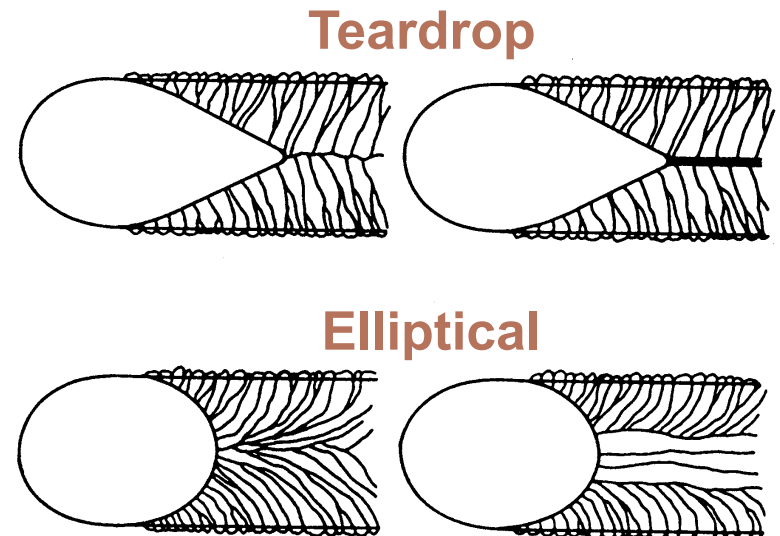
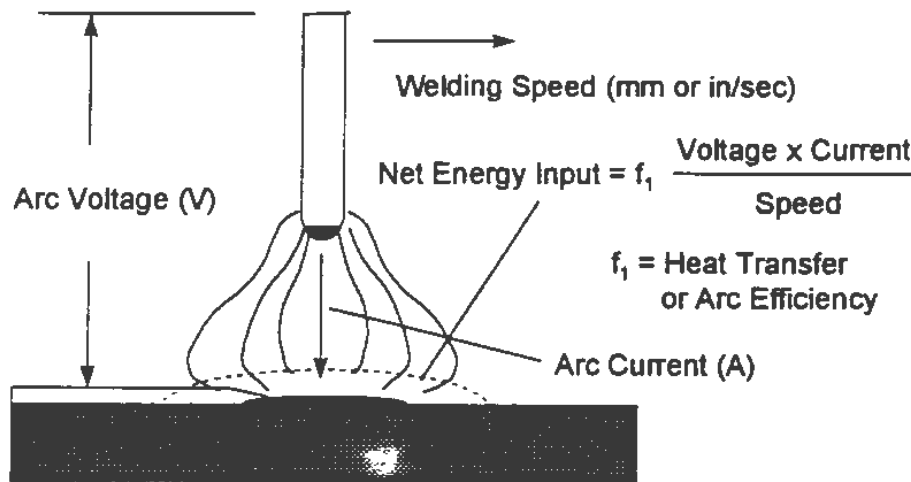
Solidification

■ Nucleation

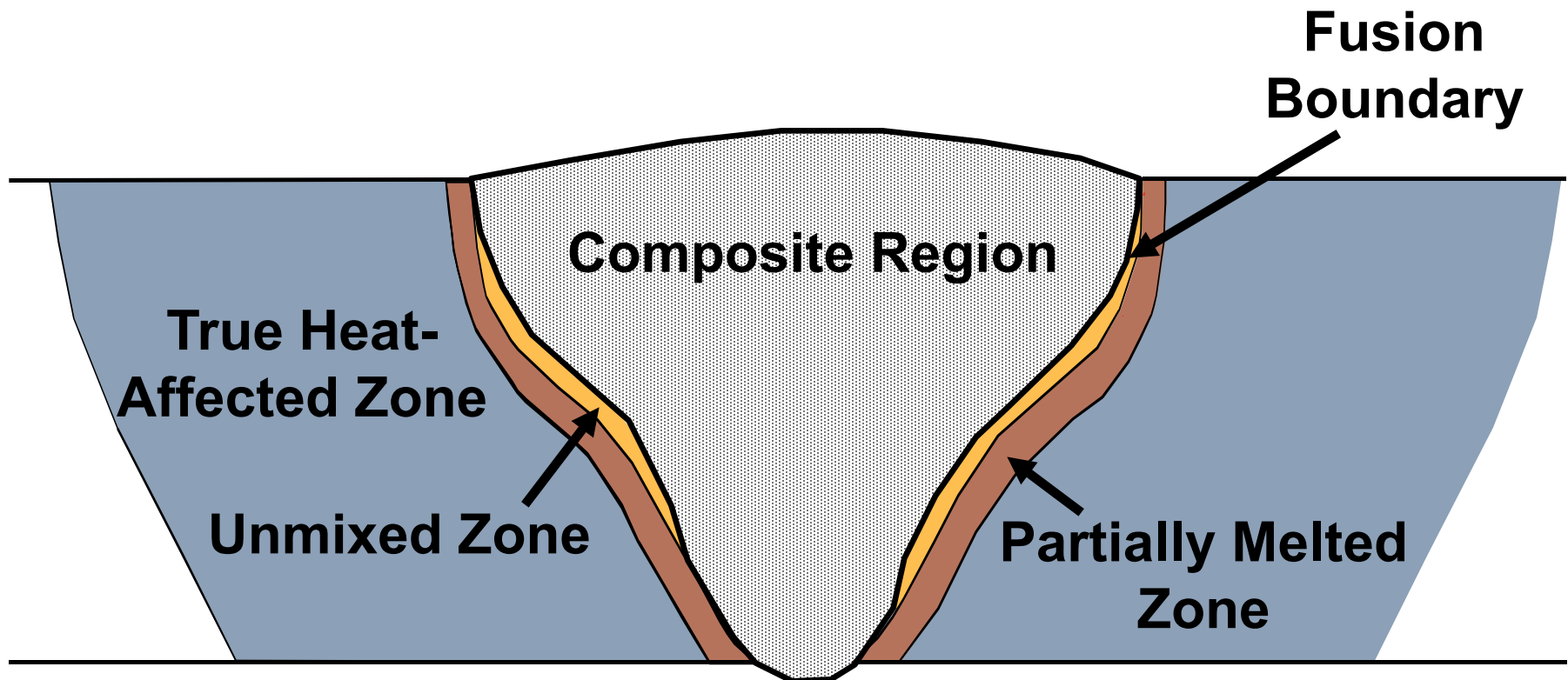
- Heterogeneous nucleation is dominate in welding
 - ◆ Occurs from a foreign particle (oxide, nitride, sulfide, etc.)

■ Weld pool shape

- Teardrop vs. elliptical



Regions of a Fusion Weld



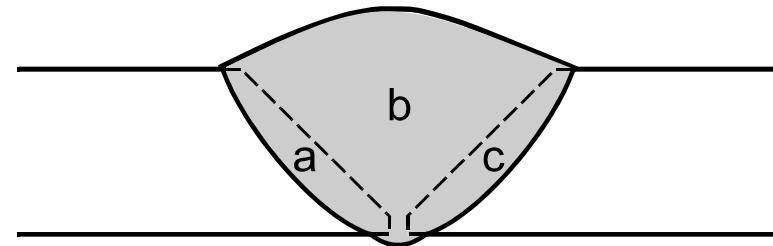
Fusion Zone Principles

■ Dilution

- Amount of melted base metal mixed with the filler metal
- Significant effect on microstructure and properties

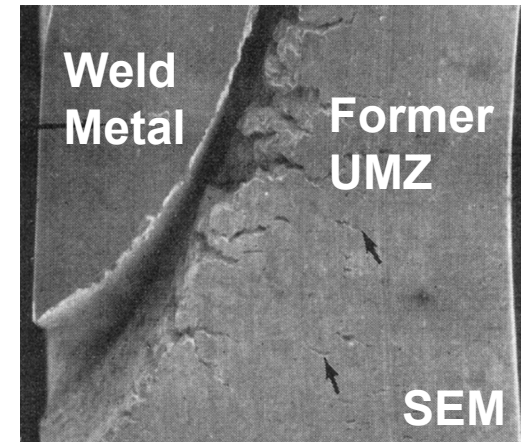
■ May exhibit three regions

- Composite zone
- Transition zone
- Unmixed zone



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

**Austenitic
Stainless Steel**



True Heat-Affected Zone

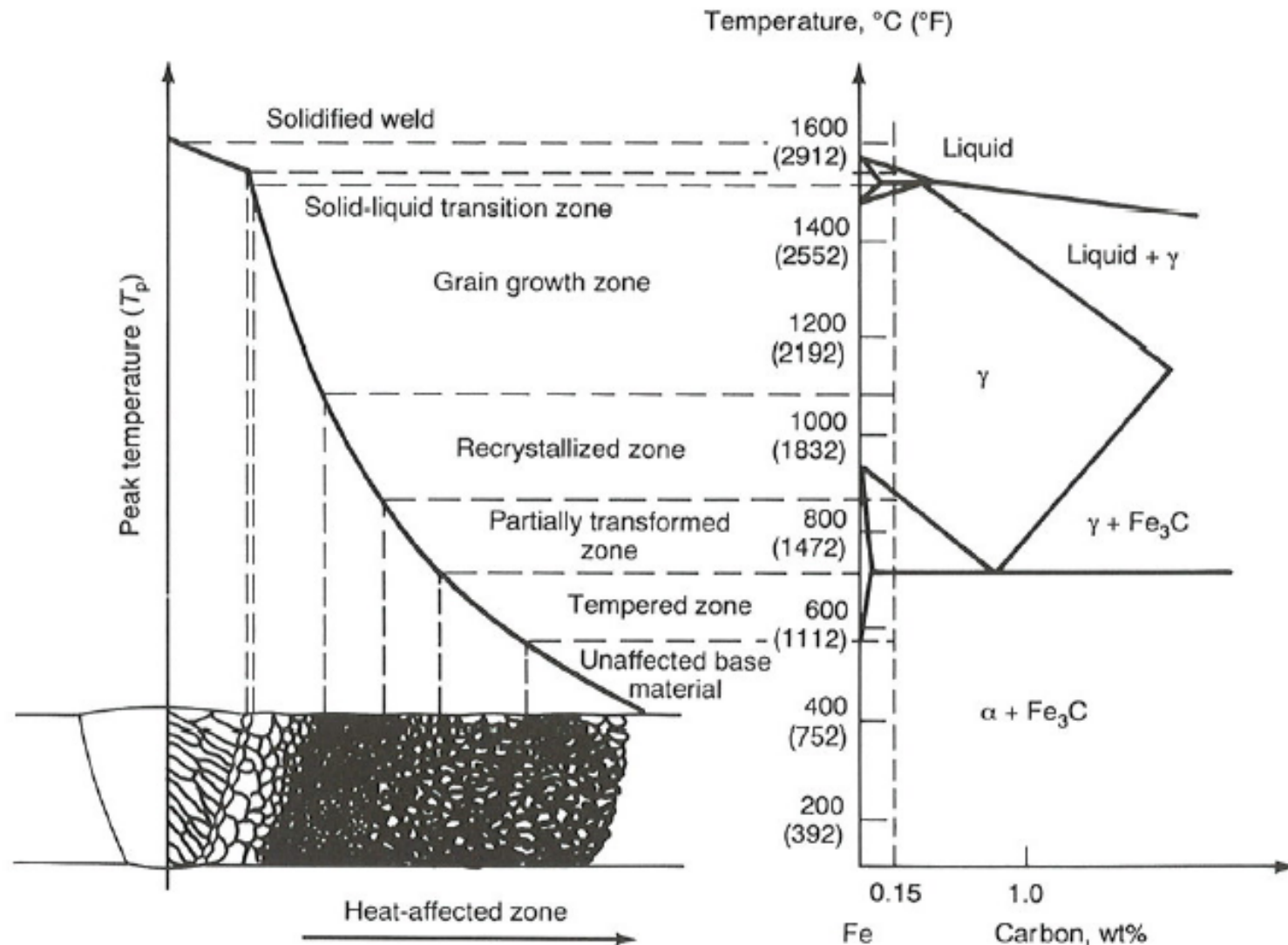
- All metallurgical reactions occur in the solid-state
- Strongly dependent on weld thermal cycle and heat flow conditions
- Solid-state metallurgical reactions
 - Recrystallization
 - Grain growth
 - Allotropic/phase transformations
 - Dissolution/overaging of precipitates
 - Formation of precipitates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

Alloys

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

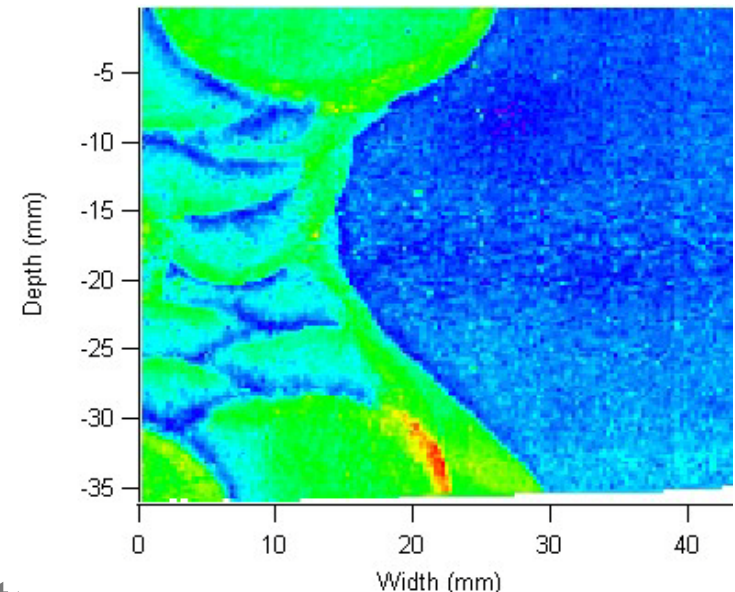


Welding Metallurgy of Carbon Steels



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



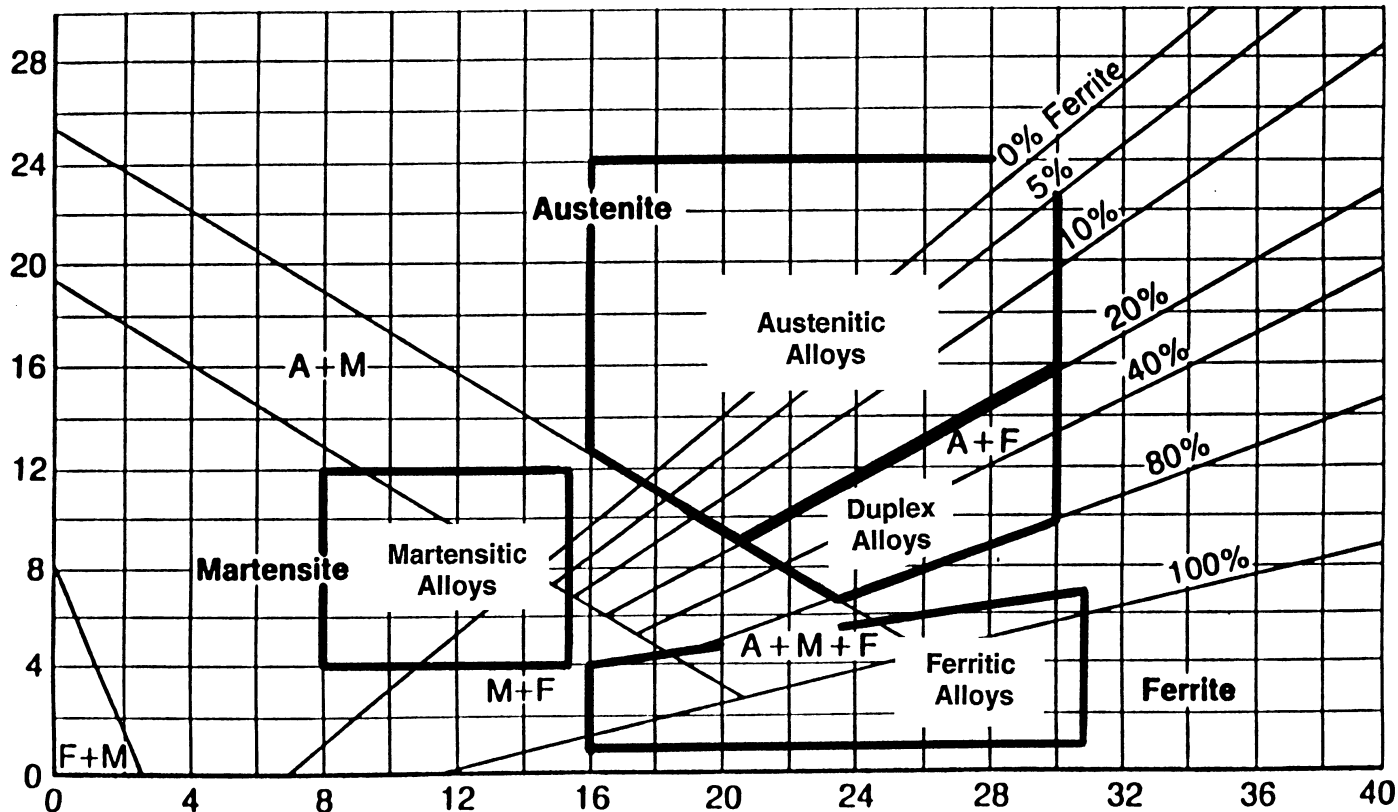
Highest
Hardness

Intermediate
Hardness

Lowest
Hardness

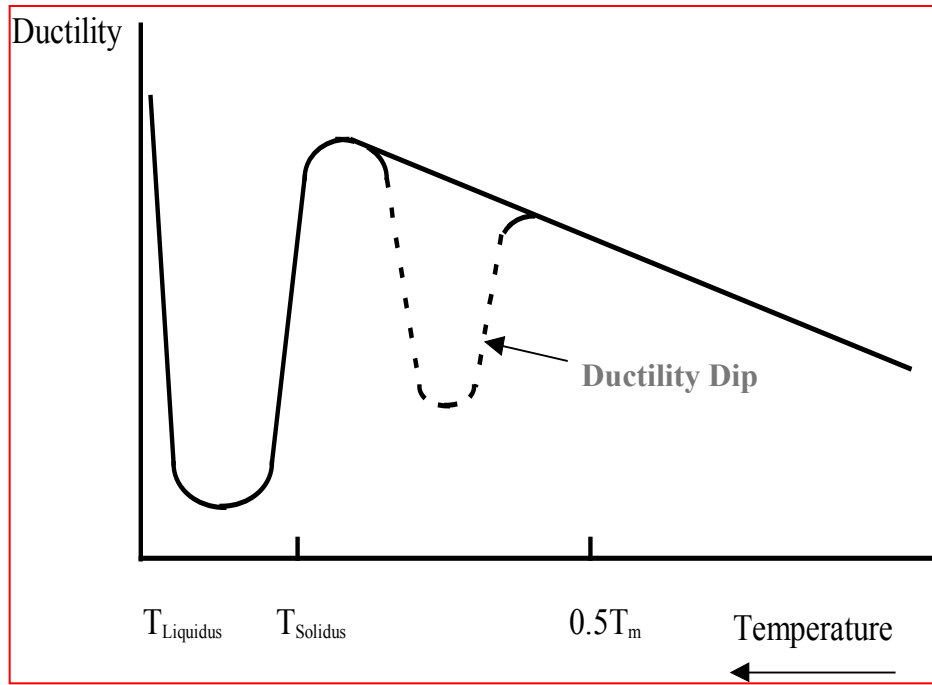
Welding Metallurgy of Stainless Steels

Nickel Equivalent = $\%Ni + 30 \times \%C + 0.5 \times \%Mn$

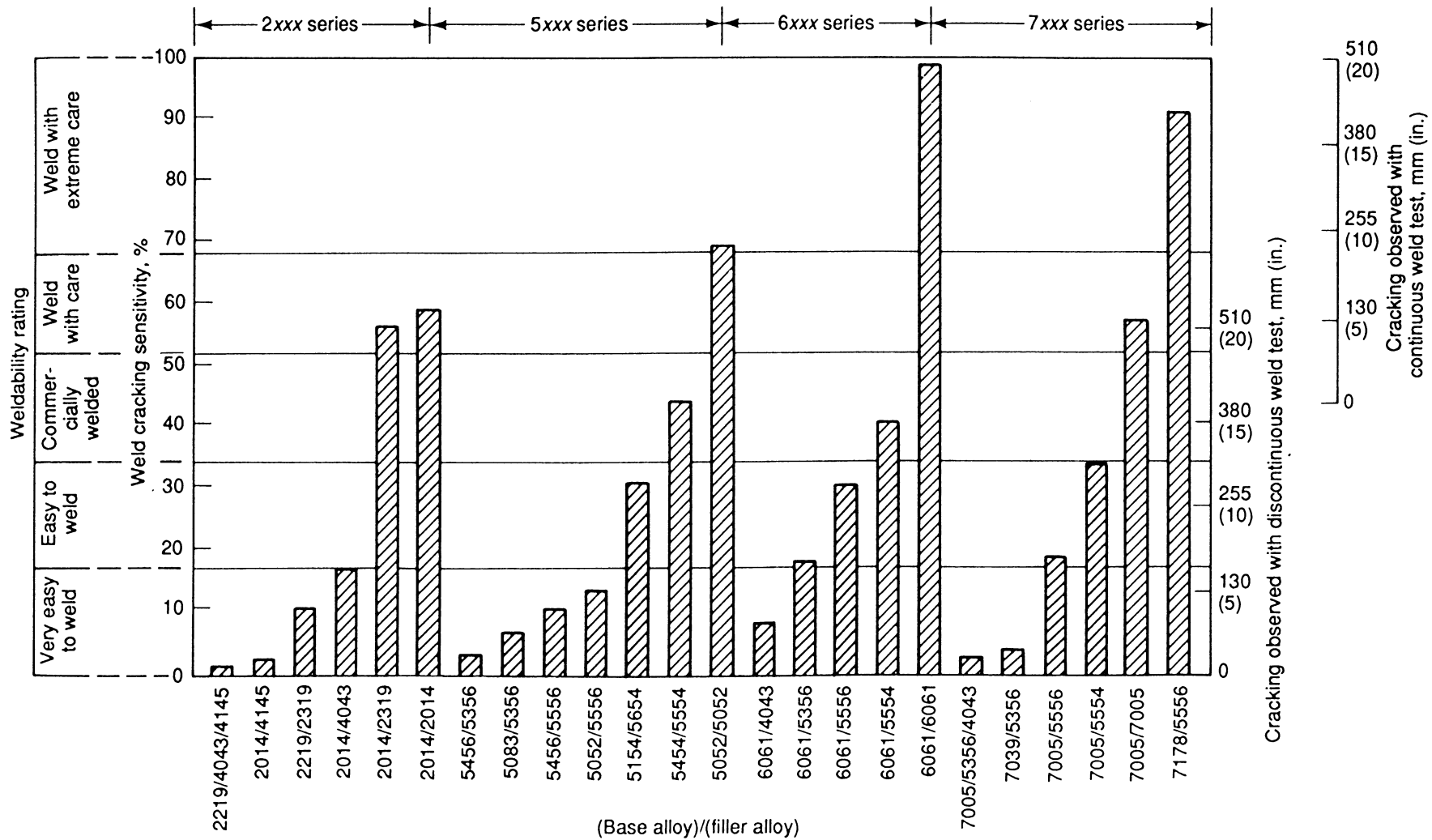


Chromium Equivalent = $\%Cr + \%Mo + 1.5 \times \%Si + 0.5 \times \%Nb$

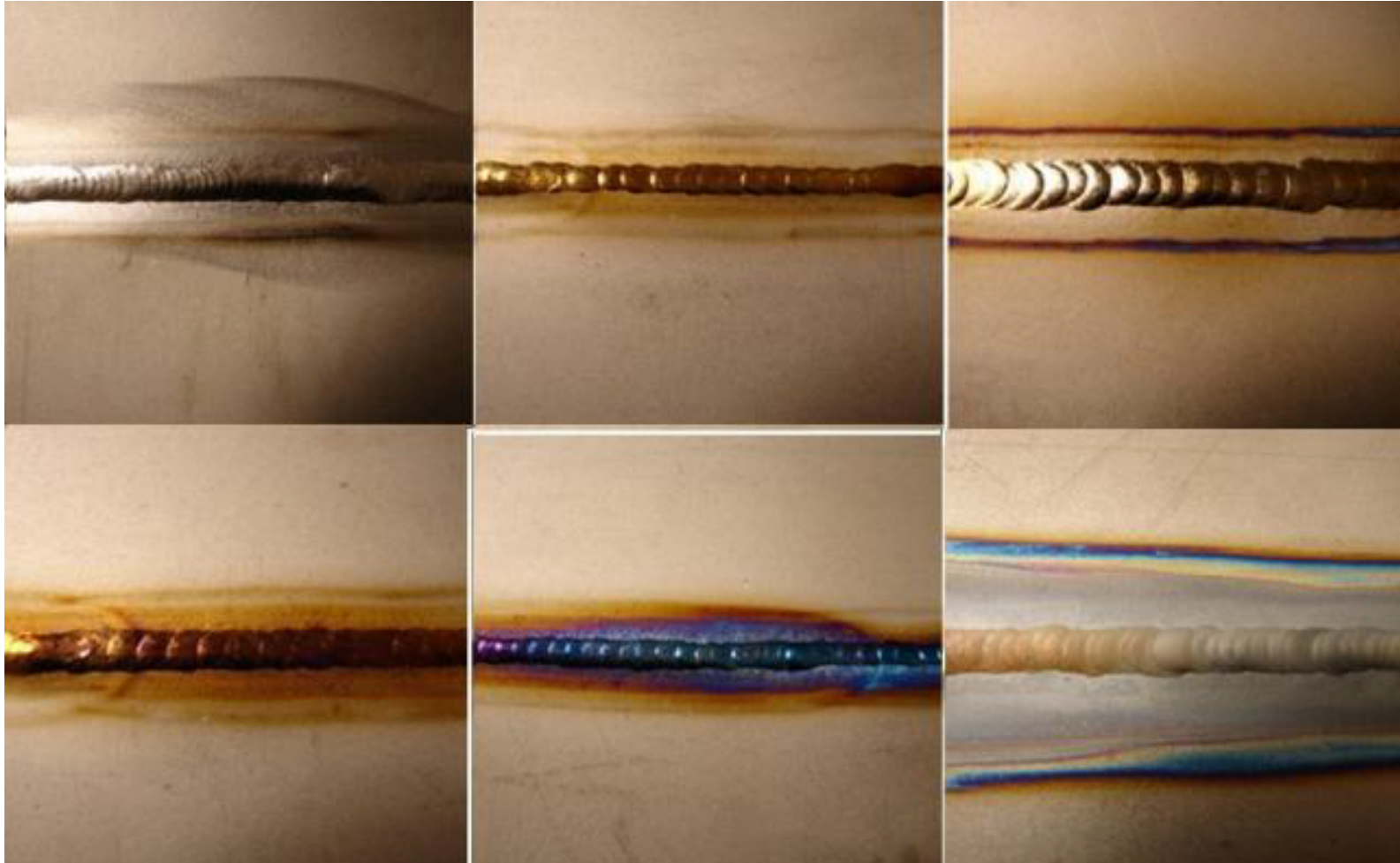
Welding Metallurgy of Nickel-based Alloys



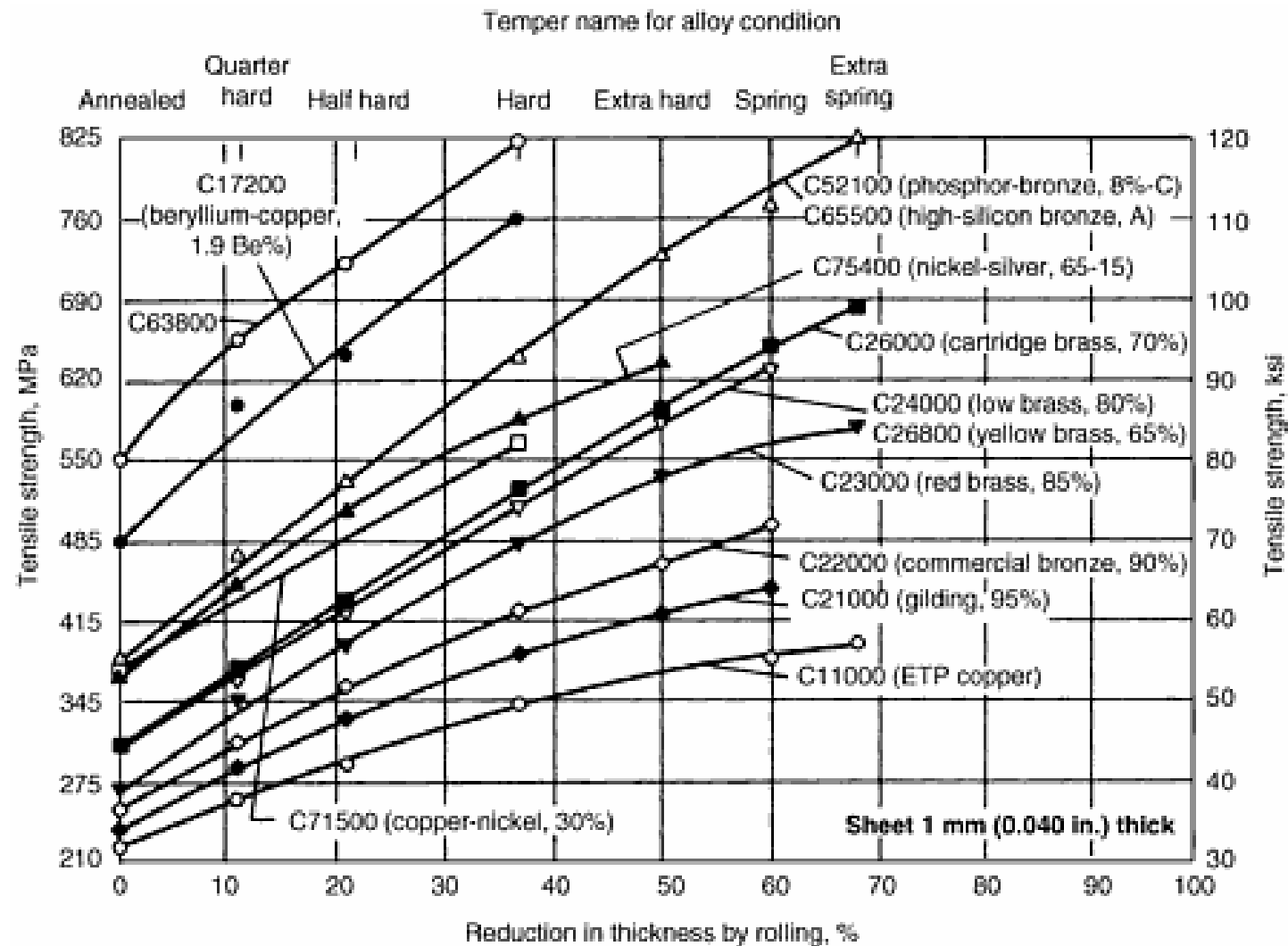
Welding Metallurgy of Aluminum Alloys



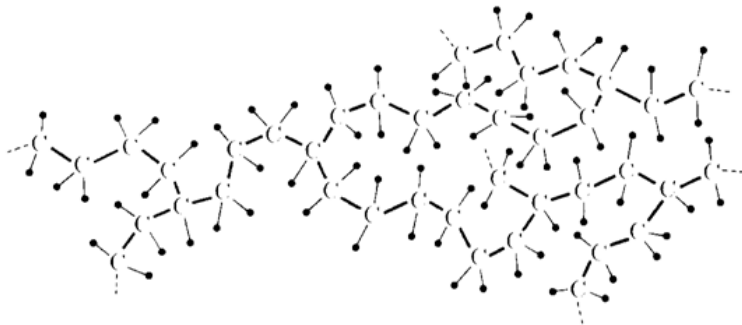
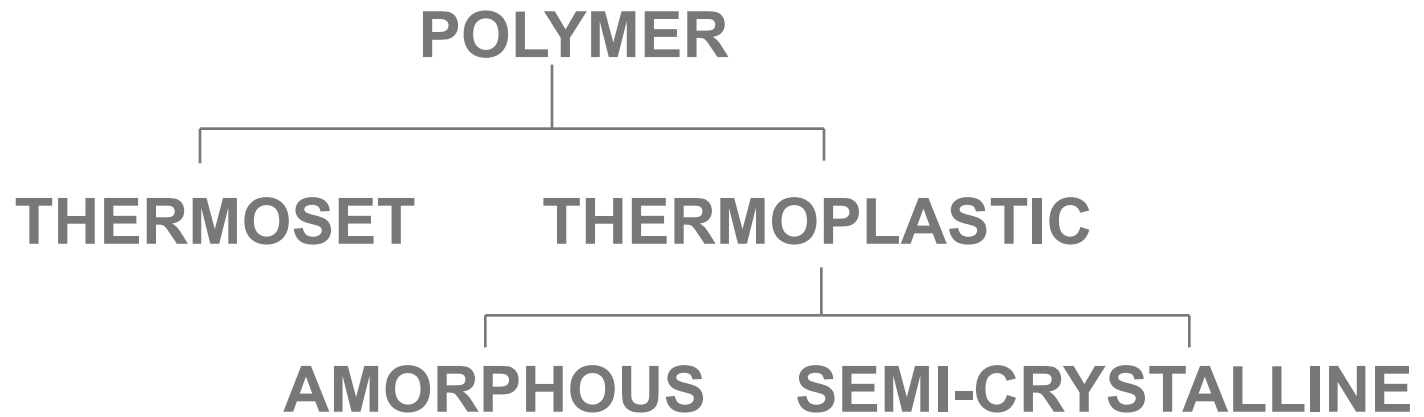
Welding Metallurgy of Titanium Alloys



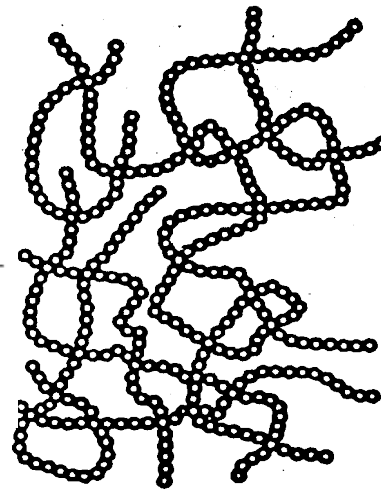
Welding Metallurgy of Copper Alloys



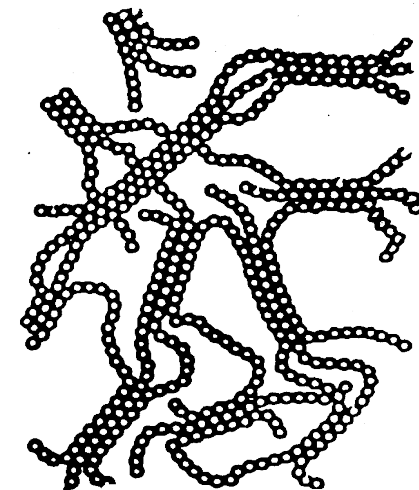
Welding Metallurgy of Polymers



Thermoset



Amorphous



Semi-crystalline