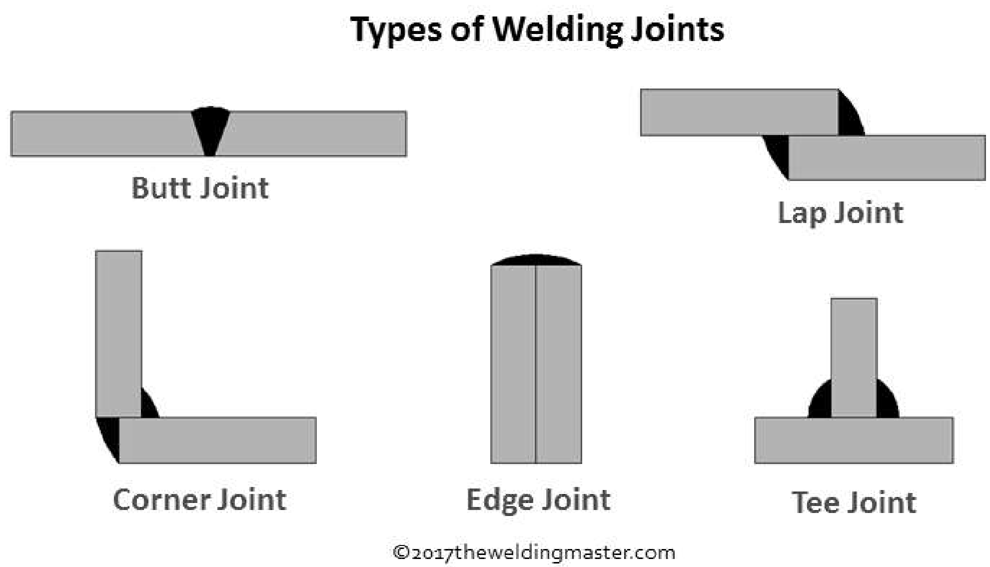
# Joining and Additive Manufacturing Processes

# Why is Joining Important?

- Required for final assembly of components
- Joints are failure initiation sites
- Add to cost of final product significantly

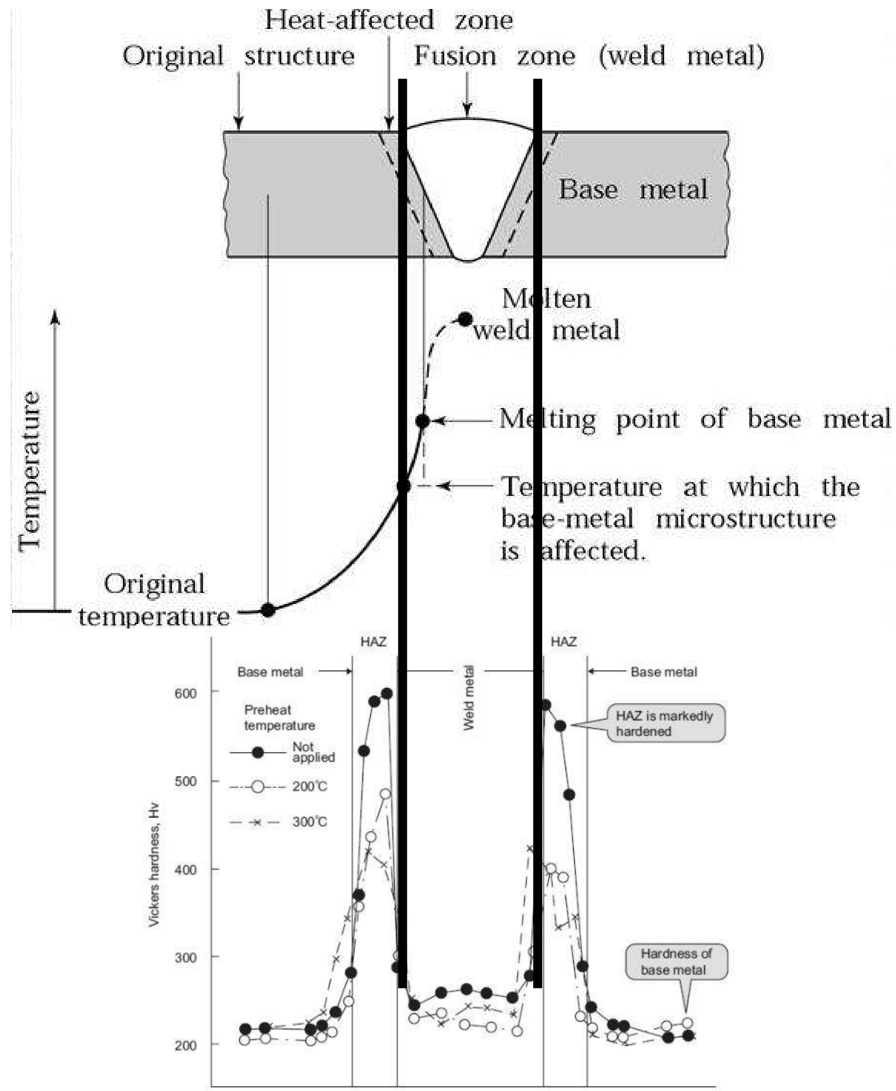
# What is Fusion Welding?

- Fusion Welding involves the joining of two pieces of metal by melting and fusing adjacent surfaces.
- The process can be performed with or without filler metal, depending on joint geometry and welding process
- Joining occurs at the end of a manufacturing process, so scrapped material at this stage is expensive.



# Weld Solidification

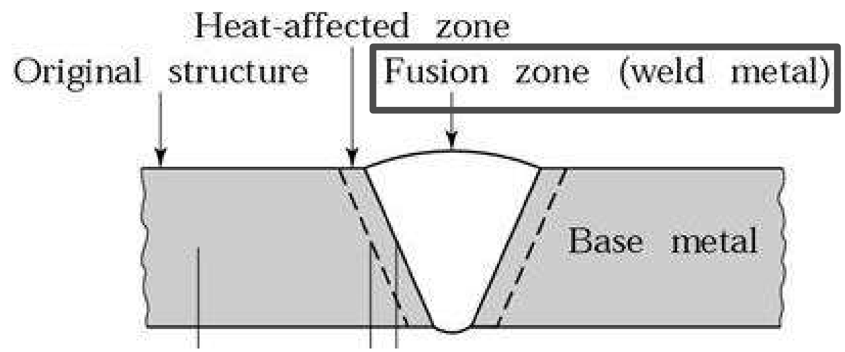
- Similar to casting
- Alloys solidify over a range of temperatures, resulting in grain size and local compositional differences
- A weld has three main zones:
  - Fusion zone
  - Heat-affected zone
  - Base metal

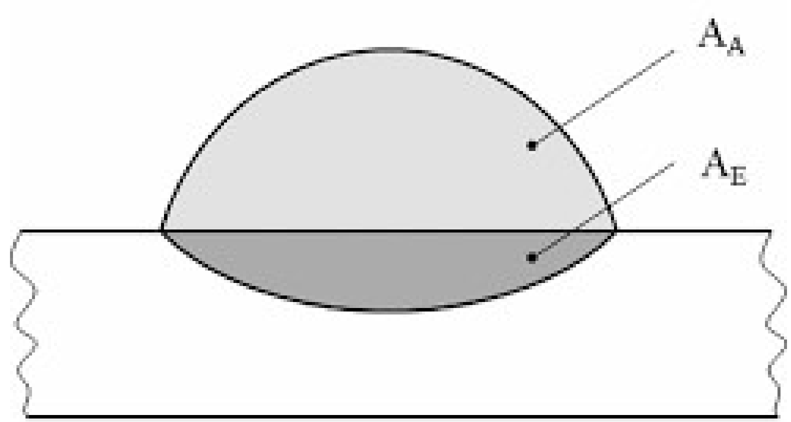



Kalpakjian and Schmid, Manufacturing Engineering and Technology, 2013
Kobelco, Welding of Medium/High Carbon Steels and Special Steels, 2020

# Fusion Zone

- Area where the filler and base metal are fully melted and mixed.
- Dilution – describes ratio of filler to the entire fusion zone in a joint.



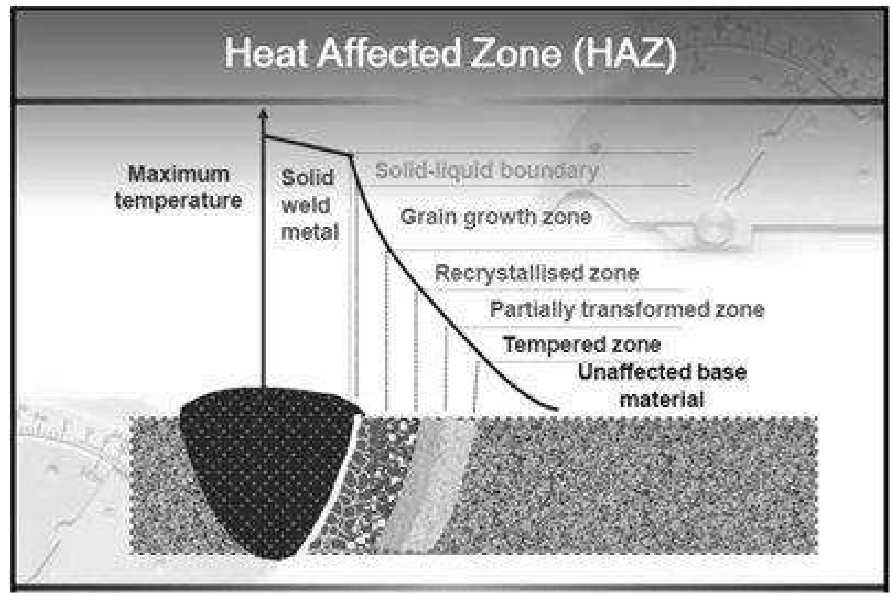

Dilution rate A [%]

$$A = \frac{A_E}{A_E + A_A} * 100$$

Kalpakjian and Schmid, Manufacturing Engineering and Technology, 2013
Günther et al, Supplement to the Welding Journal, 2018

# Heat Affected Zone

- Portion of base metal extending from interface of fusion zone to interface with un-affected base metal.
- HAZ metal got hot enough to undergo metallurgical transformation, but not hot enough to melt.
- These changes affect properties of the weld:
  - Reduced ductility
  - Higher hardness (brittle)
  - Increased yield strength




The Welding Institute, “What is the Heat Affected Zone?”

# Base Metal

- Base metal selection for welding is also important.
- The metal must meet design specification requirements as well as be sufficiently weldable.
- Base metal must be **clean** before any welding operation. Paint, mill scale, grease, oil, and oxides negatively impact weld quality
  - AC welding on aluminum breaks up the oxide layer

# Filler Metal

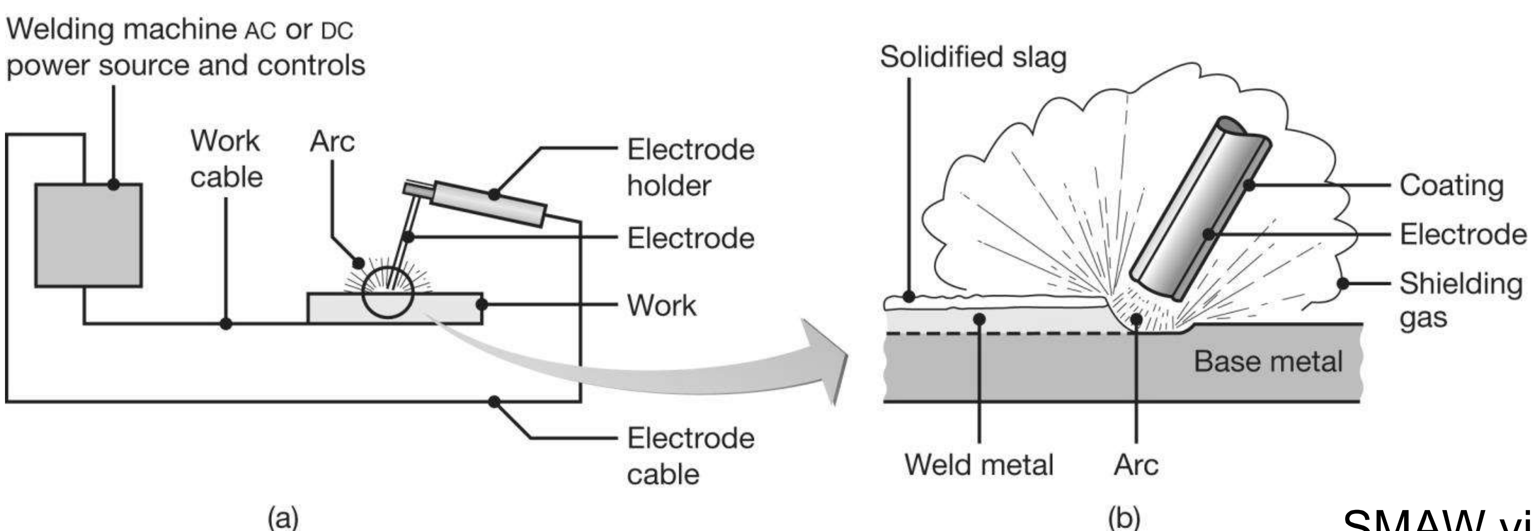
- Filler metal typically matches the base metal. Weld design should try to match the parent metal properties as closely as possible
- Some alloy systems benefit from using filler metals with different alloying elements to improve weldability.
  - 2xxx and 6xxx series aluminum alloys use 4xxx or 5xxx series filler metal to reduce cracking
- Dissimilar welding is used to provide a new property that the base metal does not have
  - Hardfacing (Co alloys on steel)
  - Corrosion resistance (Ni alloys on steel)
  - Joining two different alloys such as steel and titanium using nickel alloy filler

# Weldability of Metals and Alloys

- Materials with “good” weldability can be reliably welded on a production scale. This is a function of 4 interacting factors:
  - Type of welding process
  - Environment
  - Alloy composition
  - Joint design and size
- Weldability describes how susceptible the weld joint is to cracking.
- High performance alloys are usually difficult to weld, unless they were specifically designed as a welding alloy
  - Alloys that are used for forging or machining, for instance, are often difficult to weld (and vice-versa). Free-machining steel – P and S content, inclusions form during solidification.
  - Casting alloys are not always weldable due to the high cooling rates found in welding.

# Fusion Welding – Arc Welding

- An electric arc is created between an electrode and workpiece through an electric connection (AC or DC)
- Heat generated by arc melts the metal
- Variants include Shielded Metal Arc Welding, Submerged Arc Welding, Gas Tungsten Arc Welding

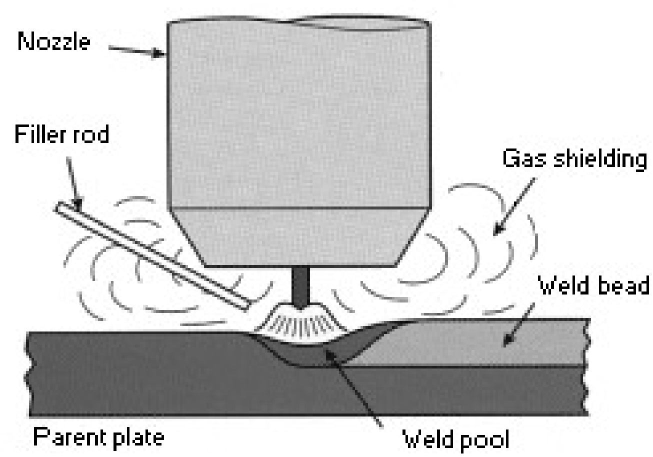





SMAW video

# Gas Tungsten Arc Welding (GTAW)

- Also commonly known as TIG (Tungsten Inert Gas) welding
- GTAW uses a non-consumable tungsten alloy electrode, which provides a well-controlled arc
- The weld pool is protected from the atmosphere by inert gas
- High quality, precision welds on thin sections due to lower heat input
- Filler wire supplied by hand (performed by a **skilled** worker), or it can be automated to varying degrees (NC workpiece control with a stationary torch or fully robotic system)



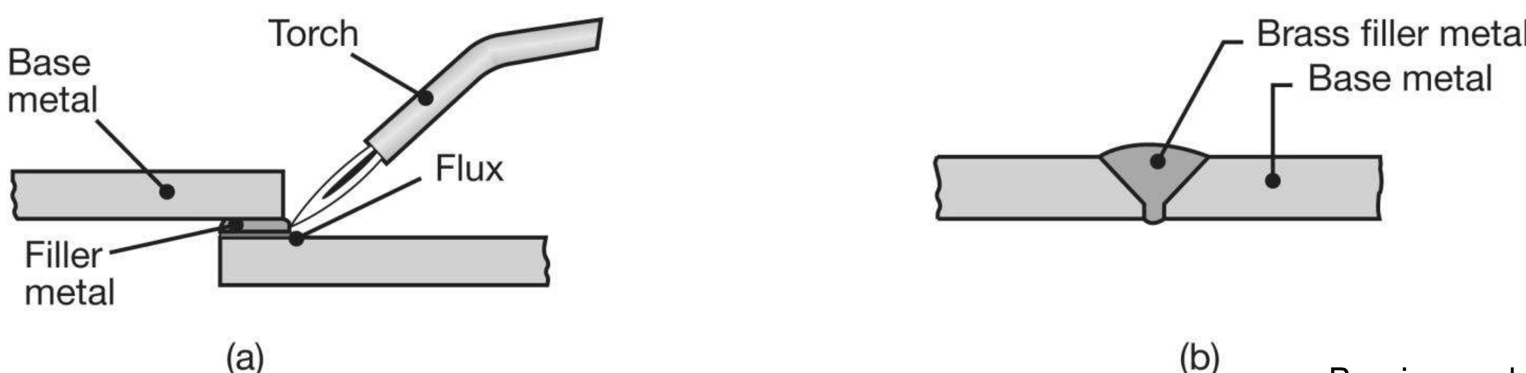

GTAW video

# Weld Inspection

- Like all manufacturing processes, welds have to be inspected for defects before being put into service.
- Most codes have three classes of welds: Class A (critical), Class B (semi-critical), and Class C (non-critical). Inspection requirements and acceptance criteria vary based on class.
- Defects: cracks, pores, craters, geometrical problems
- Inspection methods include:
  - Visual – surface defects such as cracks, pores, craters, bead geometry
  - Dimensional – distortion, bead geometry
  - Penetrant inspection – Fluorescent particle inspection and magnetic particle inspection detect small cracks. Can be quickly performed in the field to find cracks smaller than can be seen with visual
  - Subsurface methods – X-ray, computed tomography, and ultrasonic inspection to detect pores, cracks and voids
- Acceptance criteria is code-based and subject to the Engineering Authority

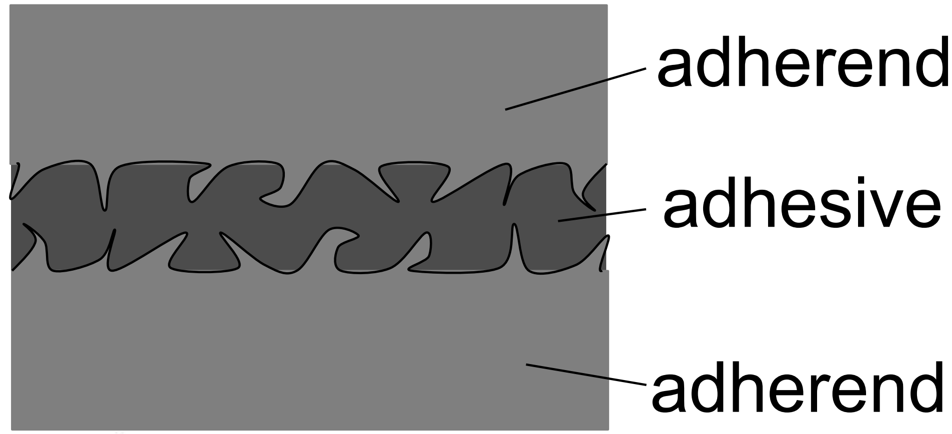
# Brazing and Soldering

- Brazing and soldering are very similar processes
- Brazing is defined as having a filler with liquidus temperature > 450 ºC
- Soldering uses a filler with liquidus temperature < 450 ºC
- Capillary action drives molten filler metal into cavities(-0.025mm to 0.2mm clearances)
- Wide range of alloy families can be brazed or soldered
- Low distortion due to low temperatures




Brazing and soldering video

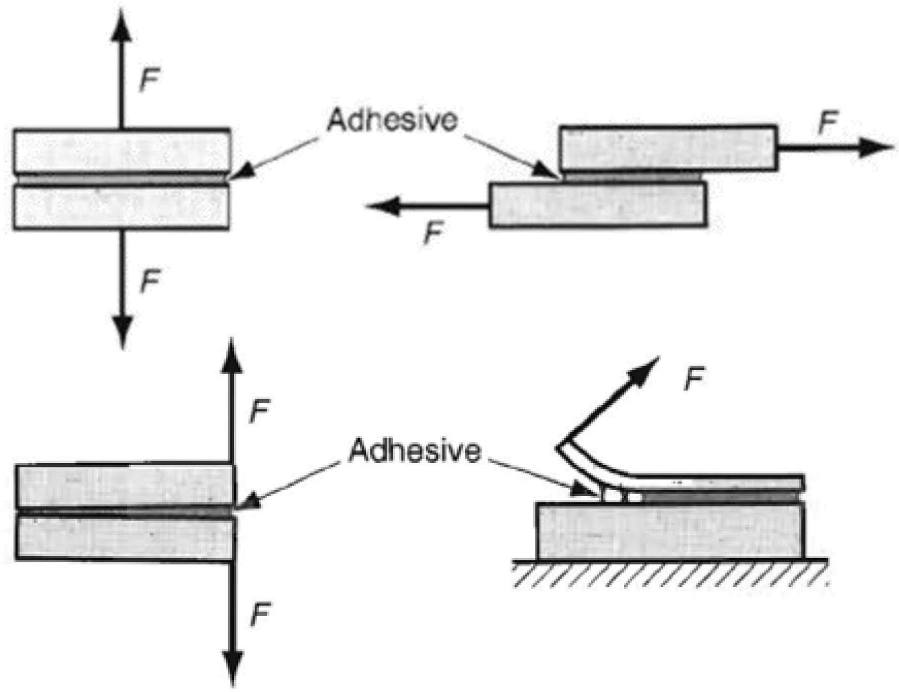
# Adhesive Bonding




Mechanisms
- Chemical bonding
- Mechanical interlocking

Advantages
- Bonds dissimilar materials
- Can be flexible after bonding
- Bond can be over the entire surface of the part

Disadvantages
- Comparatively weaker bonds
- Long curing time
- Permanent bond
- Extremely sensitive to environment



# Mechanical Fastening

**Fastening**: materials are joined together using fasteners (e.g., screws, nails, nuts, bolts)

- Advantages:
  - any shape or material
  - can be disassembled for routine maintenance and inspection
  - often the least expensive method for volume production
- Disadvantages:
  - do not develop the full strength of the base material
  - do not produce hermetic seals
  - fasteners are extra parts
  - need to drill holes(stress concentration)

# Metal Additive Manufacturing (AM)

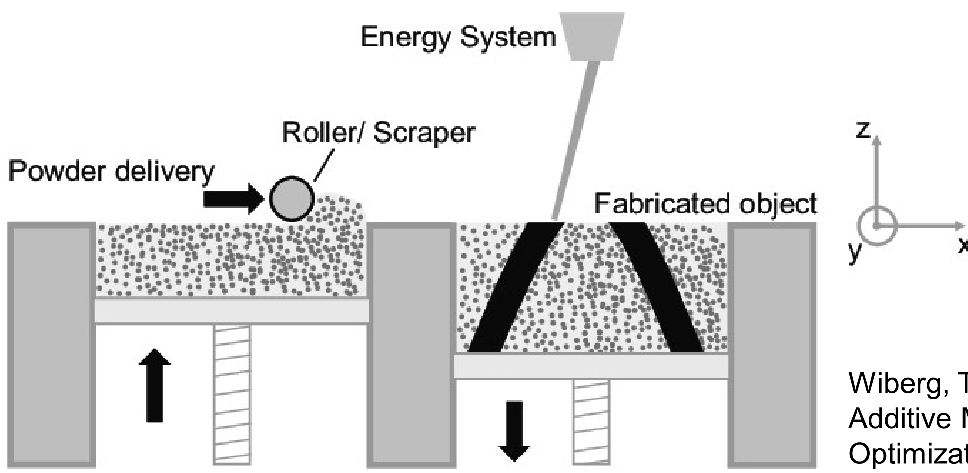
- Near net shape fabrication of parts without the need for molds, dies, or machining fixtures
  - Almost always needs finishing process to go from a near net shape to a part ready for service
- Uses techniques borrowed from welding, thus analysis is similar
- Typically layer-by-layer addition of material, but non-planar addition is also possible
- Metal AM is emerging into a usable manufacturing tool, but it requires understanding of the mechanical properties.
  - As-built properties are not isotropic
  - Post-build heat treatments can provide more uniform mechanical properties
- Parts designed for other manufacturing processes must be re-designed to take advantage of weight savings while maintaining strength and stiffness

# Metal AM Processes

- Separated into energy source types, stock material type, and feed introduction.
- Energy sources:
  - Laser and electron beam (high energy density)
  - GTAW and GMAW (arc)
  - Ultrasonic and friction stir (solid state)
- Stock type
  - Powder
  - Wire
  - Strip
- Generally, deposition rate and part size is inversely related to resolution.

# Powder Bed Fusion

- A laser or electron beam melts and fuses 2D cross sections with a set thickness to form a 3D structure.
- The finished part is essentially made entirely of weld metal, thus cracks, pores, and voids, etc., can form at any location in the part.
- Powders with 15 to 45 μm diameter are typically used. The high surface area to volume ratio means the powders are reactive and must be stored and handled properly to prevent oxidation or explosion.

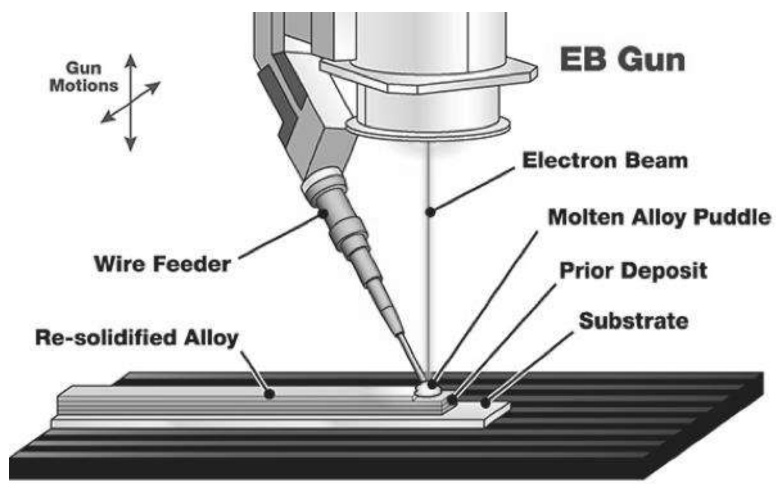



Laser PBF video

Wiberg, Towards Design Optimization for Additive Manufacturing: A Multidisciplinary Optimization Approach, 2018

# Directed Energy Deposition

- Arc welding, laser, or electron beam welding-based additive manufacturing process.
- Feed stock can be wire or powder
  - Electron beam DED systems are wire-only due to powder being blown using an inert carrier gas. The beam of electrons would impact gas molecules, reducing the amount of electrons impacting the part.
- DED systems are not necessarily restricted to planar deposition
  - Multi-axis tool and workpiece handling systems can perform conformal deposition (consider adding layers to a curved part).

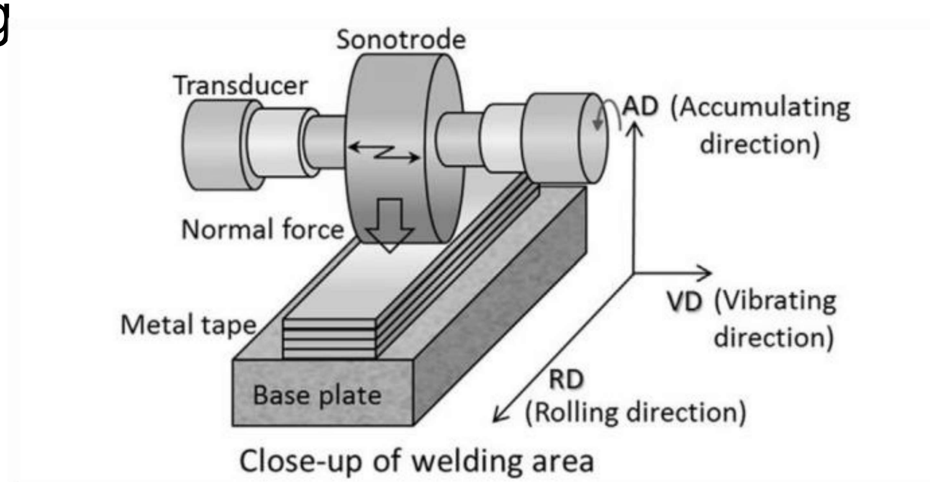



DED video

Digital Alloys, Digital Alloys' Guide to Metal Additive Manufacturing, 2019

# Ultrasonic Additive Manufacturing

- A clean strip of metal is placed on top of the clean build plate (and subsequently bonded strips) and a sonotrode oscillates (at > 20kHz frequency), creating heat through friction.
- The heat caused by friction provides energy to create a metallurgical bond between strips, similar to friction welding.
- Hard to weld materials can be ultrasonically fabricated because there is no bulk melting.
- Other solid-state additive manufacturing methods exist based on friction stir welding




S. Shimizu, H.T. Fujii, Y.S. Sato, H. Kokawa, M.R. Sriraman, S.S. Babu, Mechanism of weld formation during very-high-power ultrasonic additive manufacturing of Al alloy 6061 , Acta Materialia 74 (2014) 234–243