Metal Welding Overview for Battery Packs

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Resistance and Solid-State Welding (RSSW)

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About the Author

- Olga V. Eliseeva, Project Engineer, Resistance and Solid-State Welding, EWI
  - Ph.D. Materials Science and Engineering, Texas A&M, 2020
  - BSE, Materials Science and Engineering, Case Western Reserve, 2016

- Areas of Research
  - Resistance Sintering
  - Additive Manufacturing of Functional Gradients
  - Machine Learning for Additive Manufacturing
  - Design of the Active Layer of Organic Solar Cells
  - Degradation of Aromatic Polymers in Solar Panels

- Specializations: Resistance Welding, Data Science, Design of Experiments (DOE), Dissimilar Materials Joining, and Additive Technologies

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About EWI

- *Founded in 1984, 501(c)(3)*
- Improve Your Manufacturing Competitiveness
- Advance your ideas from concept to production faster, and with less risk

Columbus
OHIO

Joining
Forming
Materials Engineering
Structural Integrity
Modeling
Inspection
Polymers
Testing

Buffalo
NEW YORK

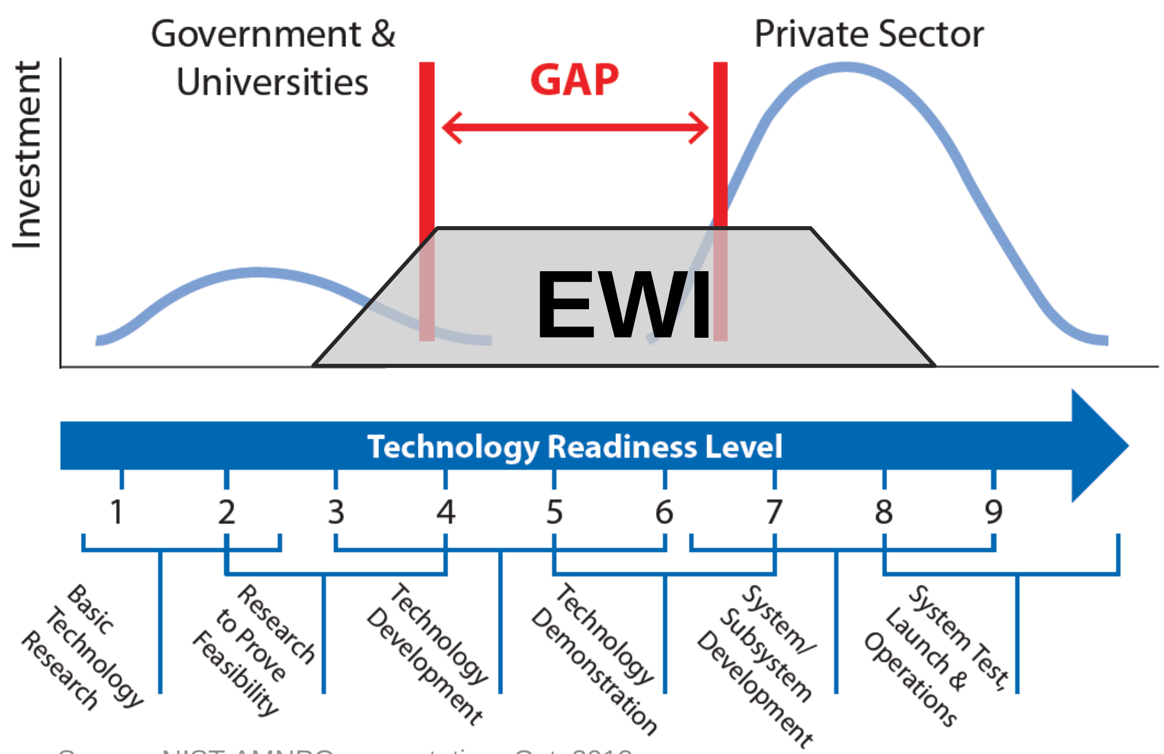
Additive Manufacturing
Automation
Data Science
Workforce Training

90+
Technical Experts
14 PhD, 28 MS, 37 BS

$40M+
Capital Equipment

160,000
Total Square Feet

Cross the Technology Valley of Death



Source: NIST AMNPO presentation Oct. 2012

EWI spans the gap between research and implementation serving commercial, government, and university clients

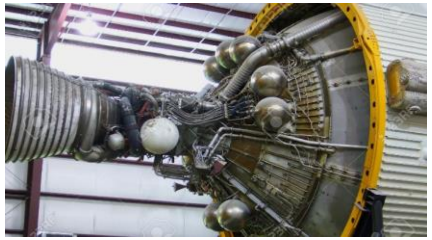
Benefit from Diverse Market Experience


Aerospace


Oil & Gas

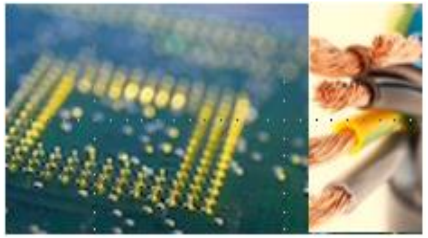

Automotive


Medical Devices

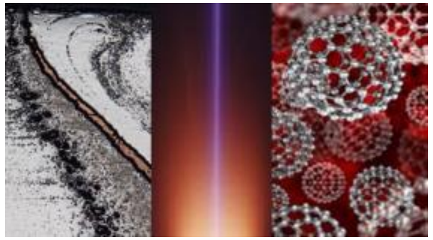

Space Exploration


Advanced Energy


Transportation


Consumer Electronics


Defense

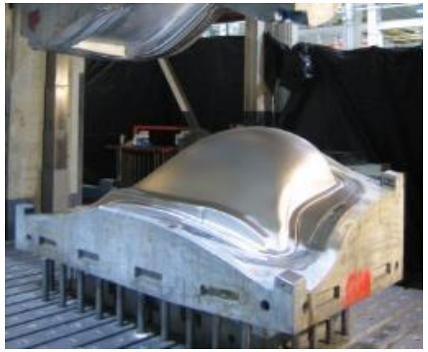

Government


Heavy Industry

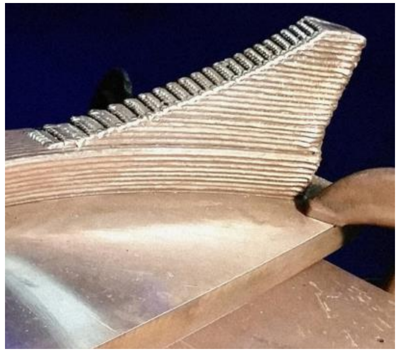

Packaging

Access Technology

Materials Joining



Forming



Additive Manufacturing

Structural Integrity

Inspection Technologies

Testing & Characterization

Advanced Automation

Engage with EWI

Technology Development
Single Sponsor Projects

Consortia
Joint Industry Programs

Engineering Consultation

Training

Lab Services

Technology Commercialization

Batteries

Market and Focus

Global Energy Forecast

[1]

Segment	Current share of road transport CO2 emissions	Current estimated global fleet size	Zero-emission vehicle (ZEV) fleet share in 2050 – Economic Transition Scenario
Two- and three-wheeled vehicles	5%	1.1 billion	Two wheelers: 74% Three wheelers: 94%
Municipal buses	1%	3.8 million	84%
Passenger vehicles	53%	1.3 billion	69%
Light commercial vehicles	11%	160 million	75%
Medium + heavy commercial vehicles	30%	80 million	29%

- Large, growing market
  - Passenger electric vehicle (EV) sales rising from 6.6 million sold in 2021 to 21 million in 2025
  - Megawatt-scale charging stations implementation
  - Emergence of higher energy density batteries
- Short implementation time
  - 10% reduction in kilometers travelled by car by 2050 alone would lead to 200 million fewer cars on the road

[1] "Net-Zero Road Transport By 2050 Still Possible, As Electric Vehicles Set To Quintuple By 2025," *BloombergNEF*, Jun. 01, 2022. https://about.bnef.com/blog/net-zero-road-transport-by-2050-still-possible-as-electric-vehicles-set-to-quintuple-by-2025/ (accessed Oct. 19, 2022).

Current and Planned Hybrid and Electric Vehicles in the U. S. Market

Hybrid Electric Vehicles (HEV):

- 2011 Mercedes E Class Hybrid
- 2011 Porsche Cayenne S Hybrid
- 2011 Toyota Camry Hybrid
- 2011 Toyota Prius V Hybrid
- 2011 Audi A8 Hybrid (likely introduction)
- 2011 BMW 5-Series Active Hybrid
- 2011 Honda CR-Z sport hybrid coupe
- 2011 Lexus CT 200h Hybrid Hatchback
- 2011 Suzuki Kizashi Hybrid
- 2011 Audi Q5 Crossover Hybrid
- 2011 Hyundai Sonata Hybrid
- 2012 Ford C-MAX Hybrid
- 2012 Infiniti M35 Hybrid
- 2014 Ferrari Hybrid

Battery Electric Vehicles (BEV):

- 2010 Mitsubishi i
- 2010 Nissan LEAF
- 2010 Ford TRANSIT connect electric
- 2010 Tesla Motors Roadster Sport 2.5
- 2011 TH!NK City
- 2011 Coda Automotive Sedan
- 2011 Tesla Motors Model S
- 2011 Ford Focus electric
- 2011 BMW ActiveE
- 2012 Fiat 500 minicar
- 2012 Audi etron
- 2012 Honda Fit EV
- 2012 Audi R8 EV
- 2013 Mercedes SLS E-Cell AMG
- 2013 Volkswagen Golf Blue-e-motion
- 2013 BMW i3
- 2016 Tesla Motors EV

Extended Range Electric Vehicles (EREV):

- 2010 Chevy Volt Extended Range EV

Plug-in Hybrid Vehicles (PHEV):

- 2010 Fisker Karma S Plug-in Hybrid
- 2011 BYD F3DM Plug-in Hybrid
- 2012 Toyota Prius Plug-in Hybrid
- 2012 Bright Automotive IDEA Plug-in Hybrid
- 2012 Ford Escape Plug-in Hybrid
- 2012 Ford C-MAX Energy
- 2013 BMW Vision
- 2013 BMW i8
- 2013 Cadillac Converj

2012 onward to many models to list


[1]


[1]

[1]

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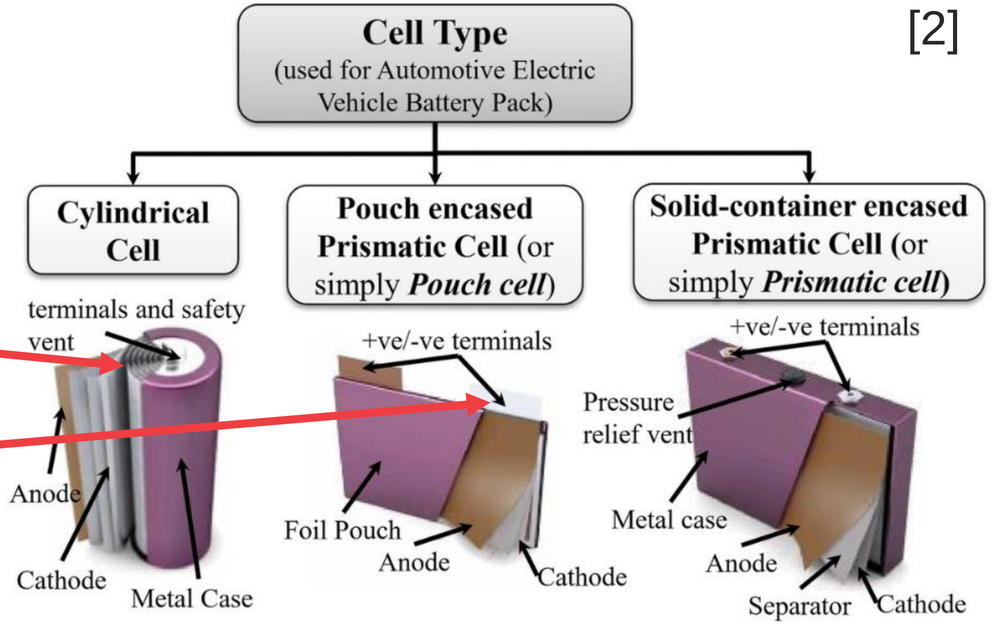
[1] Electric Drive Transportation Association, vehicle announcements through Jan 25, 2011.

Weld Type and Locations

- Foil to Foil welding
- Foil to Tab welding
- Tab to Tab welding
- Can closure
- Tab to Bus welding

[2]



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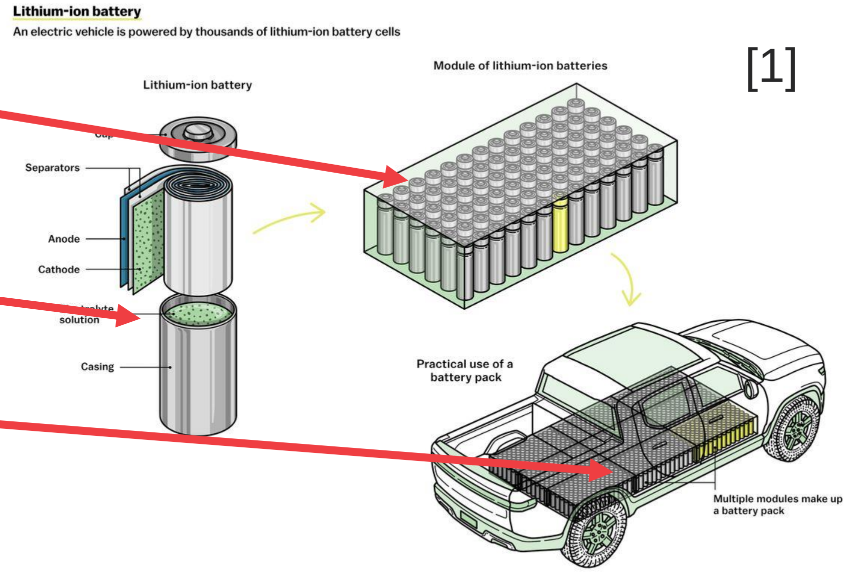

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[1] D. Castelvecchi, “Electric cars and batteries: how will the world produce enough?,” *Nature*, vol. 596, no. 7872, pp. 336–339, Aug. 2021, doi: 10.1038/d41586-021-02222-1
[2] “Welding,” E-Mobility Engineering, May 04, 2021. https://www.emobility-engineering.com/ev-battery-welding/ (accessed Oct. 19, 2022).

Welding Technologies

[1]

Joining Technology	Advantages	Disadvantages	Issues and Concerns
Ultrasonic welding	Fast process, high strength and low resistance, able to join dissimilar materials, low energy consumption	Only suitable for pouch cells, two sided access, slow joining	Access of anvil and sonotrode needs to be well designed
Resistance spot/projection welding	Fast process, low cost, good quality control, easy automation	Difficult for highly conductive and dissimilar materials	Difficulty to produce large joints, joining of more than two layers
Micro-TIG/pulsed arc welding	Low cost, high joint strength and low resistance, able to join dissimilar materials, easy automation	High thermal input and heat affected zone, porosity	Difficult to join Al to steel
Ultrasonic wedge bonding	Fast process, acting as fuses, able to join dissimilar materials, low energy consumption and easy automation	Only suitable for small wires, low wire and joint strength	Clamping of the batteries is critical
Micro-Clinching	Cold process, no additional part, clean process, able to join dissimilar materials	Only suitable for pouch cells, two side access, slow joining	Loosening under vibration, moisture ingress
Soldering	Joining dissimilar materials, wide spread in electronics industry	High heat, fluxes required	Joint strength, debris, neutralisation of fluxes
Laser welding	High speed, less thermal input, non-contact process, easy Automation	High initial cost, additional shielding system may required	Need good joint fit-up (intimate contact), high reflective materials
Magnetic pulse welding	Solid state process, able to join dissimilar materials, high joint strength, dissimilar materials	Potential large distortion, rigid support required	Possibility of eddy current passing through the cells
Mechanical assembly	Easy dismounting and recycling, easy repair, cold process	Additional weight, high resistance, expensive	Potential mechanical damage and go loose

[1] "Welding," E-Mobility Engineering, May 04, 2021. https://www.emobility-engineering.com/ev-battery-welding/ (accessed Oct. 19, 2022).

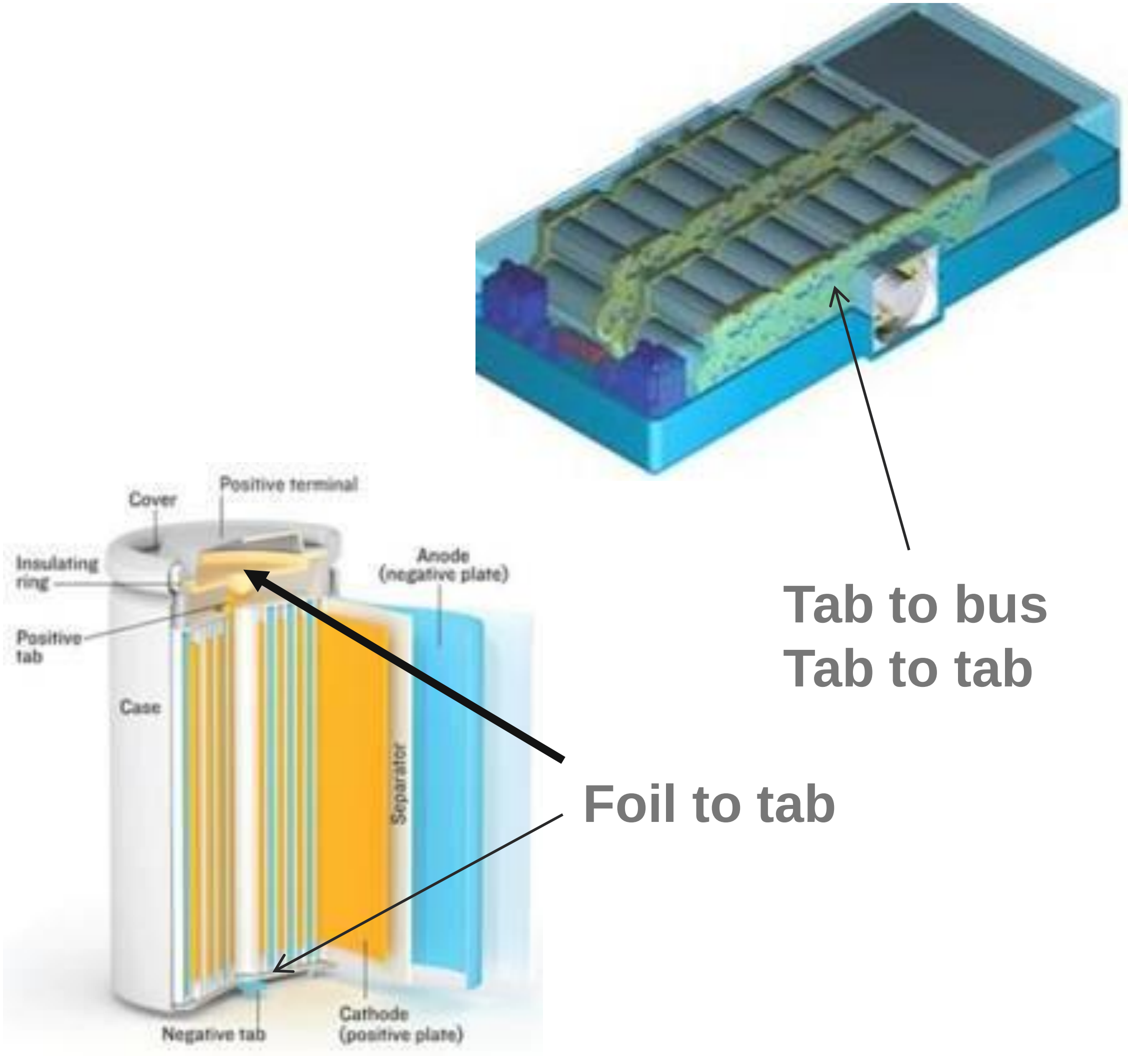
Metals

Conductivity vs Strength

Materials for Batteries

- Controlling current flow is important
- Foils, tabs, and bus bar need to be conductive
- All materials containing the battery need to be nonconductive or have high resistance
- Only a few good options available

Material	Copper	Aluminum	Nickel
Thickness	Foil (0.001 in.)	Tab (0.005 in.)	Bus (0.032 in.)
Process	Laser Beam	Resistance Spot	Ultrasonic Metal



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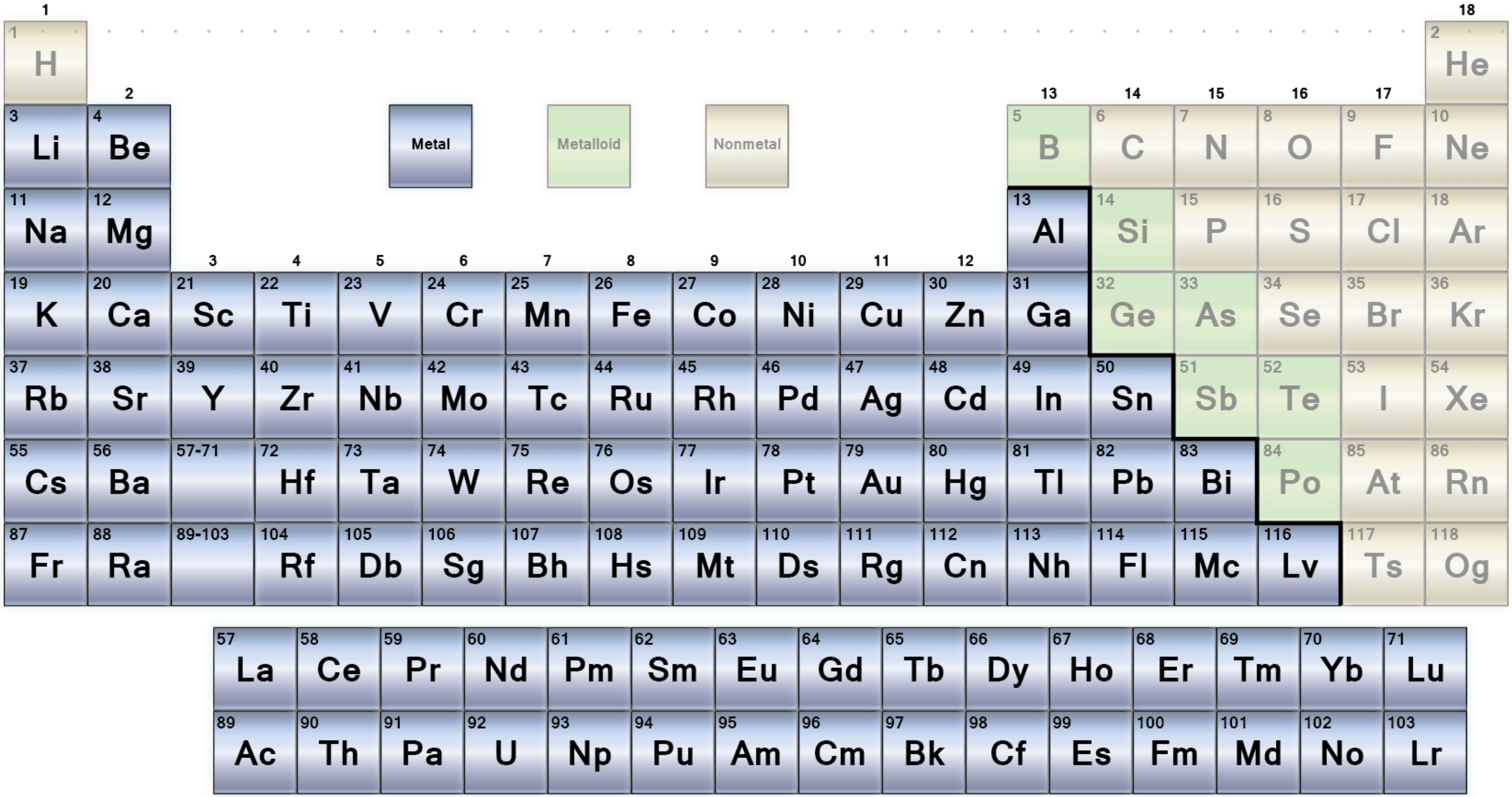
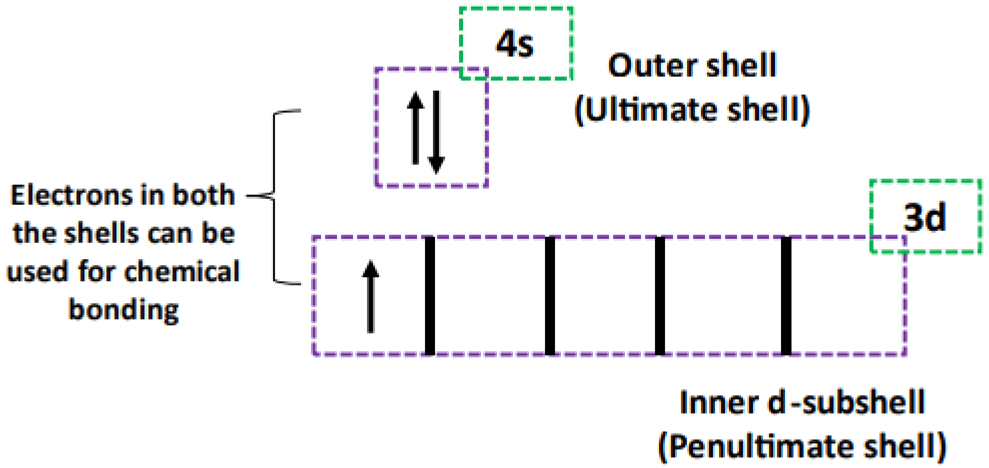


[1] “List of Metals.” https://sciencenotes.org/list-metals/ (accessed Oct. 20, 2022).

Oxidative States

Valence electrons of transition metals

Transition metal element	Electronic configuration	Total number of valence electrons	Preferrable valencies
^{21}Sc	[Ar] $3d^1 4s^2$	3	3 (Sc^{3+})
^{22}Ti	[Ar] $3d^2 4s^2$	4	3 (Ti^{3+}) and 4 (Ti^{4+})
^{23}V	[Ar] $3d^3 4s^2$	5	2 (V^{+1}), 3 (V^{2+}), 4(V^{4+}) and 5 (V^{5+})
^{24}Cr	[Ar] $3d^5 4s^1$	6	2 (Cr^{2+}), 3 (Cr^{3+}) and 6 (Cr^{6+})
^{25}Mn	[Ar] $3d^5 4s^2$	7	2 (Mn^{2+}), 3 (Mn^{3+}), 4 (Mn^{4+}), 6 (Mn^{6+}) and 7 (Mn^{7+})
^{26}Fe	[Ar] $3d^6 4s^2$	8	2 (Fe^{2+}) and 3 (Fe^{3+})
^{27}Co	[Ar] $3d^7 4s^2$	9	2 (Co^{2+}) and 3 (Co^{3+})
^{28}Ni	[Ar] $3d^8 4s^2$	10	2 (Ni^{2+})
^{29}Cu	[Ar] $3d^{10} 4s^1$	11	1 (Cu^{+}) and 2 (Cu^{2+})
^{30}Zn	[Ar] $3d^{10} 4s^2$	12	2 (Zn^{2+})

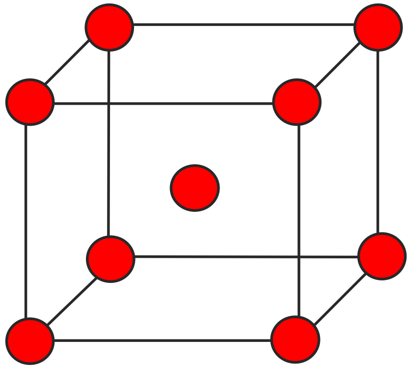


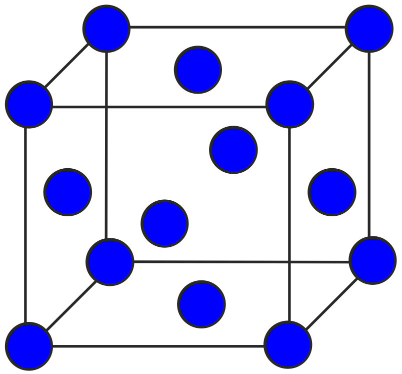
[1]

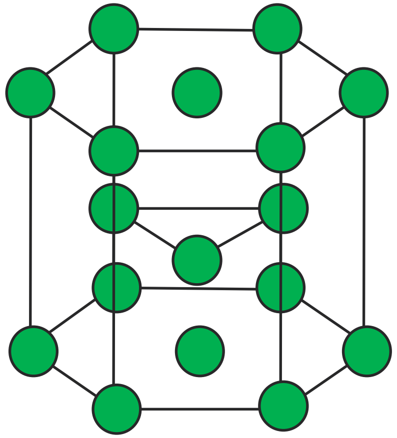
[1] V. Goyal, "Valence electrons of transition metals (d-block elements)," *Topblogtenz*, Aug. 13, 2022. https://topblogtenz.com/valence-electrons-of-transition-metals/ (accessed Oct. 19, 2022).

Crystal Structure

- Atoms arrange themselves into different structures
- Body-centered cubic (bcc) structure
  - Iron
  - Ferritic steels
- Face-centered cubic (fcc) structure
  - Nickel (and its alloys)
  - Aluminum (and its alloys)
  - Copper (and its alloys)
- Hexagonal close-packed (hcp) structure
  - Titanium (room temperature)
  - Magnesium
  - Zirconium

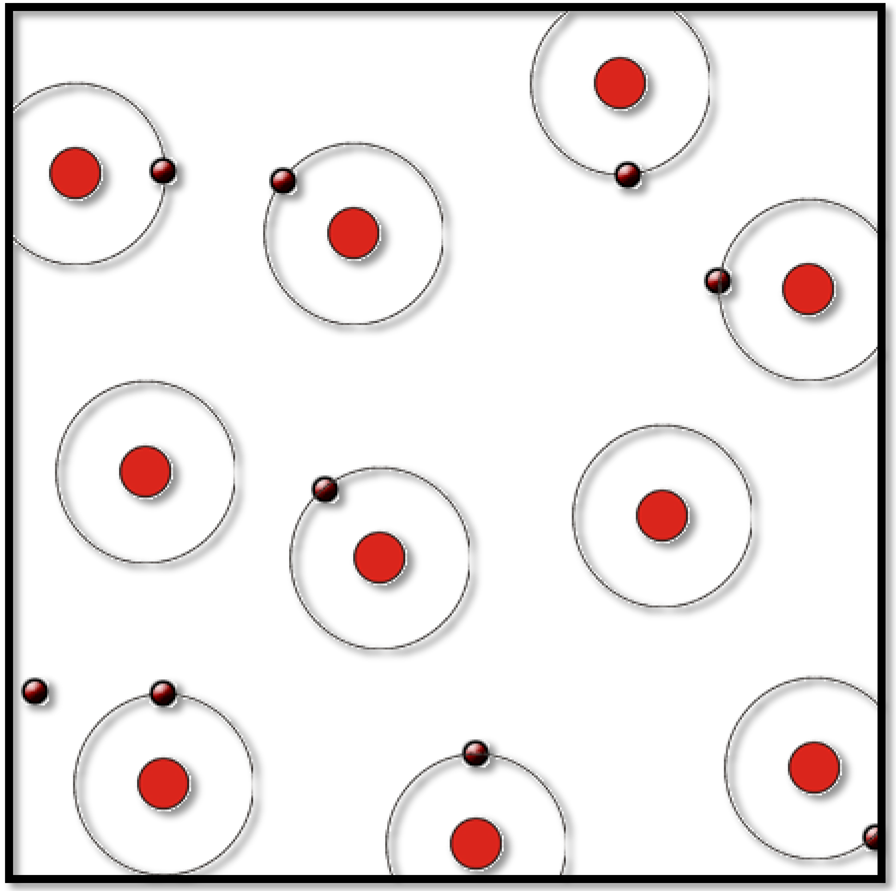

bcc


fcc


hcp

Conductivity

- The electron sea model of election mobility
- More electron in the valance band the more electrons moving between atoms
- The closer the atoms the easier it is for electrons to jump
- Drift velocity of electrons
  - $V_d = \mu_e E$
  - $\mu_e = electron\ mobility$
  - $E = imposed\ electric\ field$
- Conductivity
  - $\sigma = n|e|\mu_e$
  - $e = charge\ of\ electron$
  - $n = number\ of\ free\ electrons\ per\ m^3$



[1]

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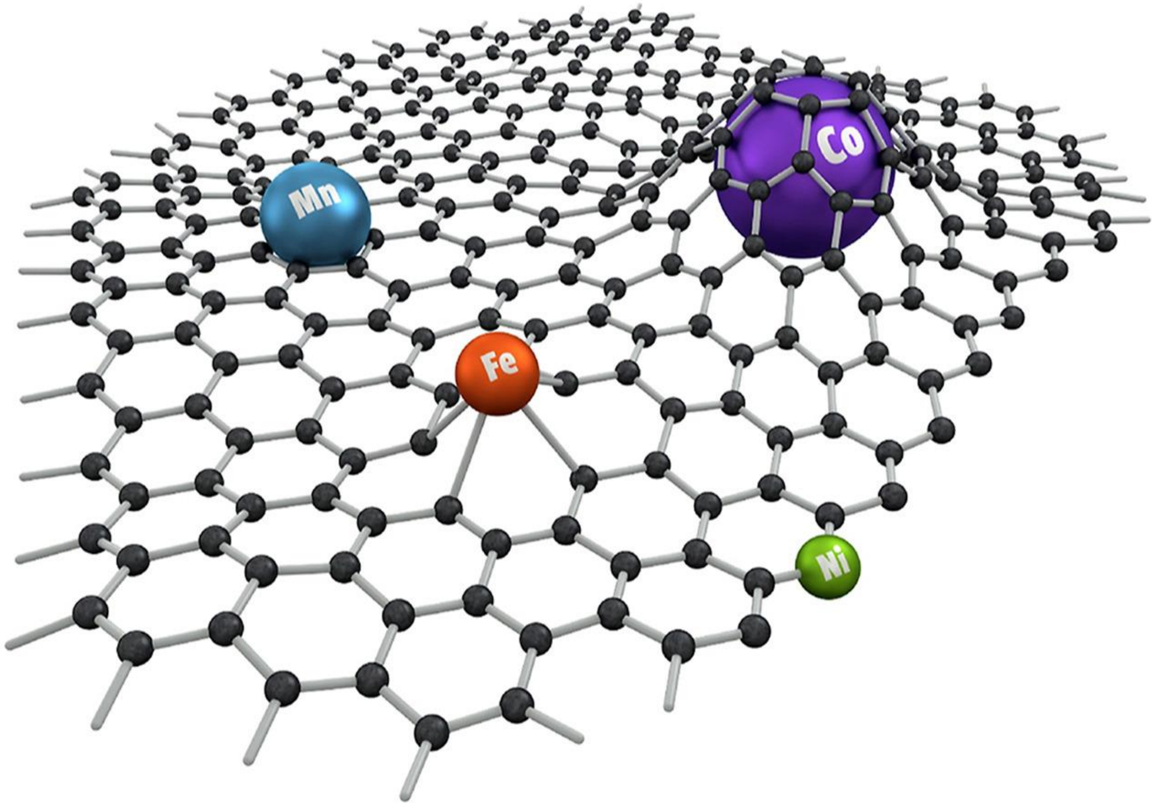
[1] "Nature of Electricity | Electrical4U," *https://www.electrical4u.com/*. https://www.electrical4u.com/nature-of-electricity/ (accessed Oct. 19, 2022).

Defects-1 dimensional

- Substitutional and interstitial impurity
  - Depends on size of atom
  - Creates strain on lattice
  - Area around impurity is slightly charged depending on valance elections
- Vacancies
  - lattice strain
  - Can move in lattice
  - Decreases overall atom density
- All defects
  - Slow down electron flow
  - Decrease over all conductivity with increase in defects



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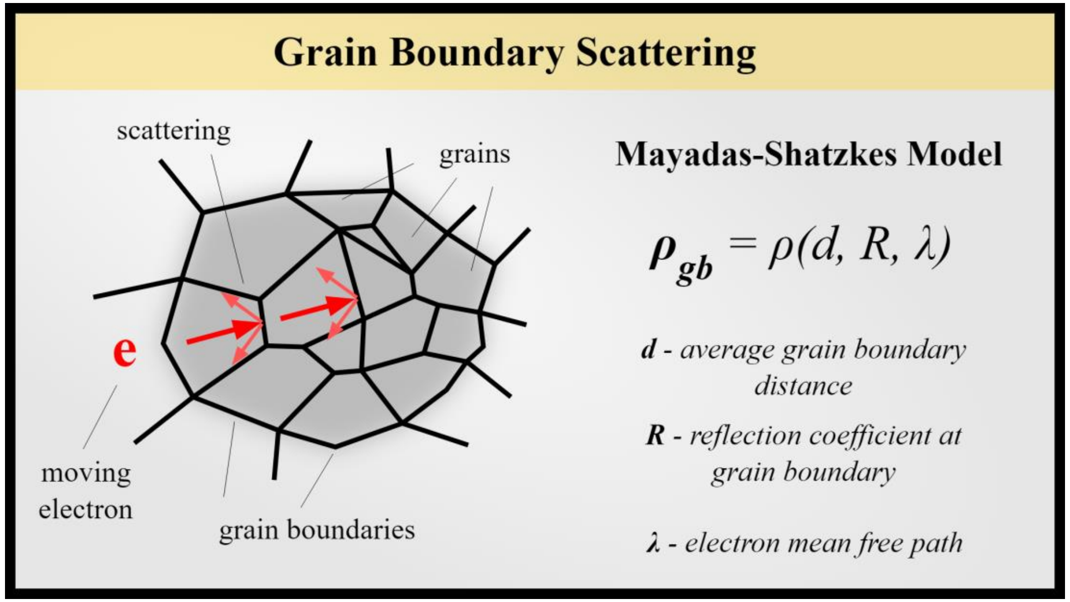
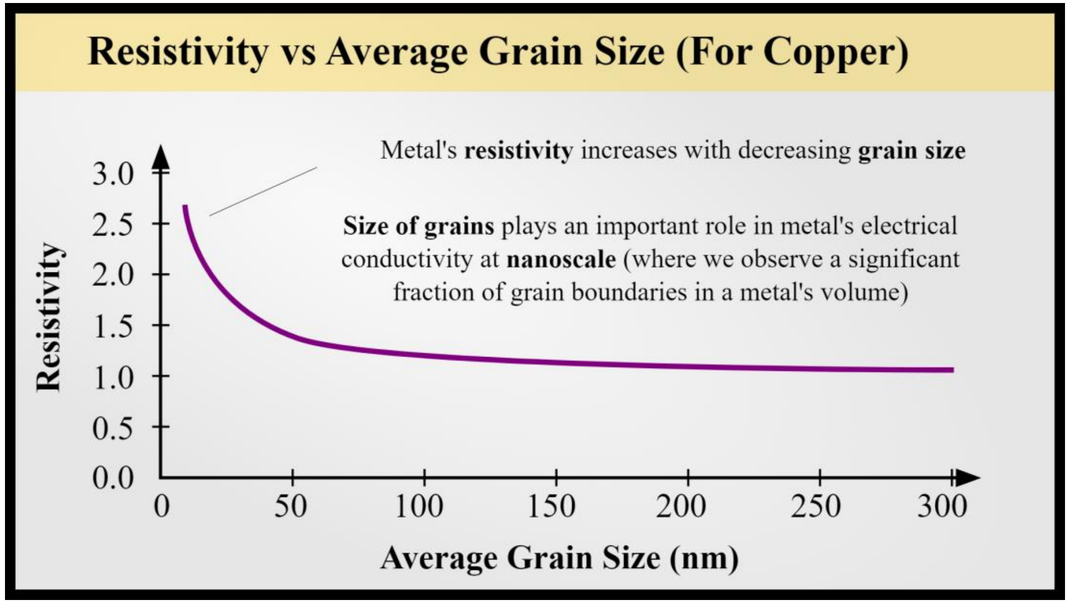
[1] W. Kiciński and S. Dyjak, "Transition metal impurities in carbon-based materials: Pitfalls, artifacts and deleterious effects," *Carbon*, vol. 168, pp. 748–845, Oct. 2020, doi: 10.1016/j.carbon.2020.06.004.

Grain Boundaries

- Most metals are multigrain structures
- A grain boundary is the area were two crystal structures with different orientation come together
- The energy of grain boundary is higher and will interact with the electrons reducing mobility
- Smaller grain size = more grain boundaries
- Resistivity = 1/conductivity

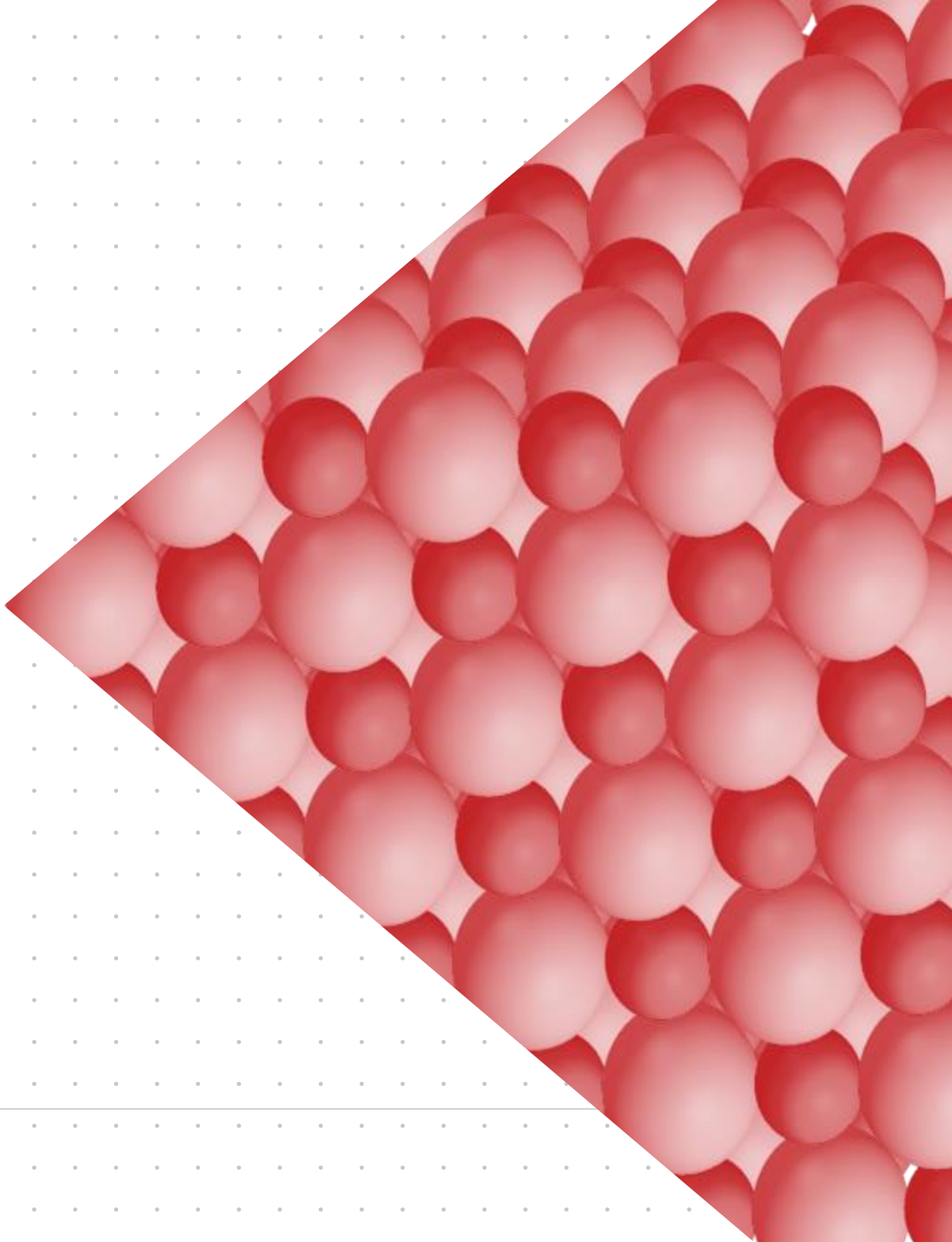
[1]





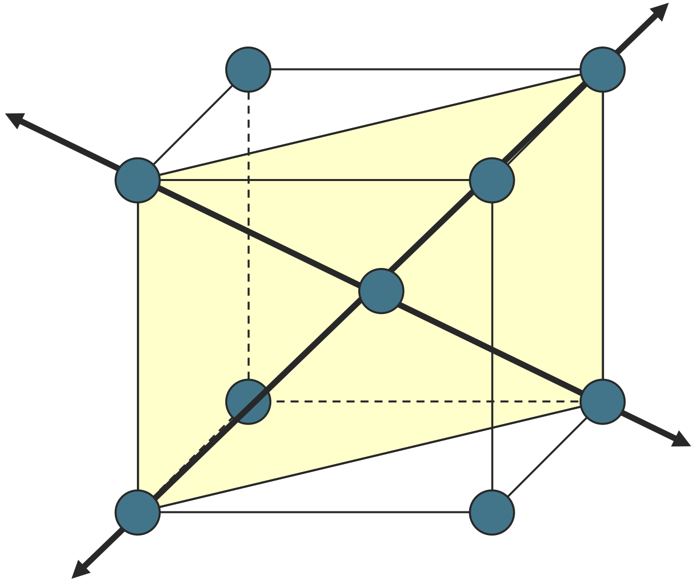
[1] Brandon, "Why Do Metals Conduct Electricity?," *Materials Science & Engineering Student*. https://msestudent.com/why-do-metals-conduct-electricity/ (accessed Oct. 20, 2022).

The things that make a material strong decrease the conductivity, it is a trade off, location and function matter!

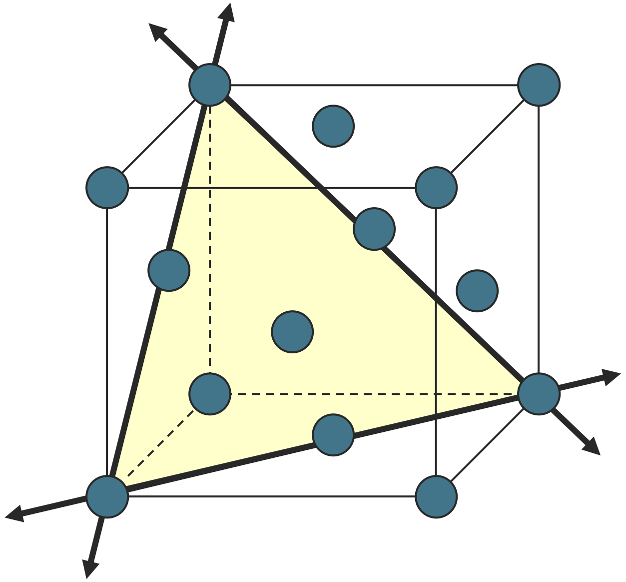


Slip Systems Deformation

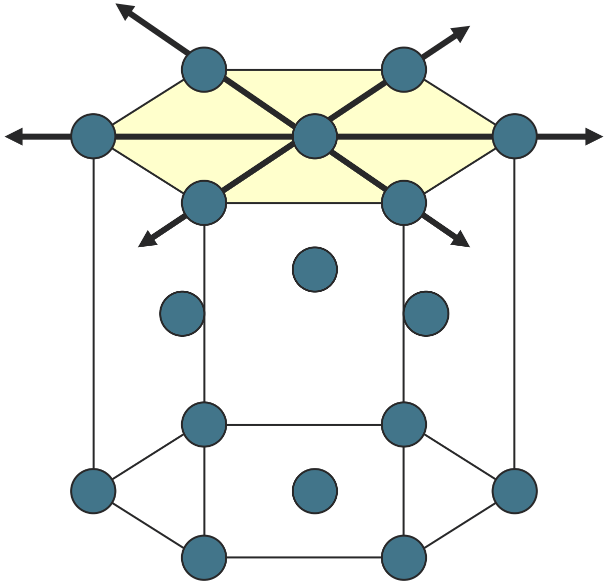
- Deformation (dislocation) occurs on preferential crystallographic planes and directions, called slip systems.
- The slip plane/direction is the plane/direction with the most closely packed atoms.



6x2=12



4x3=12



1x3=3

Slip Systems

- BCC has 6 slip planes and 2 slip directions per plane (12 slip systems), but distance between slip planes is small, therefore the required stress is high. **Good Strength** and moderate ductility, e.g. Steel, Titanium, Molybdenum, Tungsten.

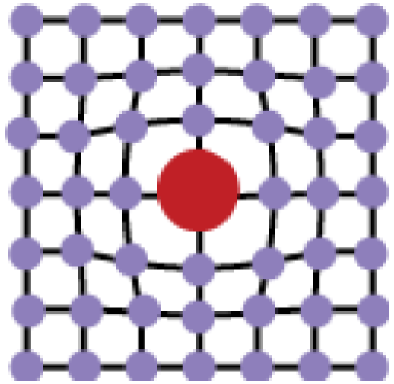
- FCC has 4 slip planes and 3 slip directions per plane (12 Slip Systems), but distance between slip planes is larger than BCC. Therefore, probability of slip is moderate, shear stress to cause slip is low. **Moderate Strength** and Good Ductility, e.g., Aluminum, Copper, Gold, Silver

- HCP has 1 slip plane and 3 slip directions on that plane (3 systems). Low probability of slip. Generally **brittle materials**, e.g., Beryllium, Magnesium, and Zinc

Solid-Solution Strengthening

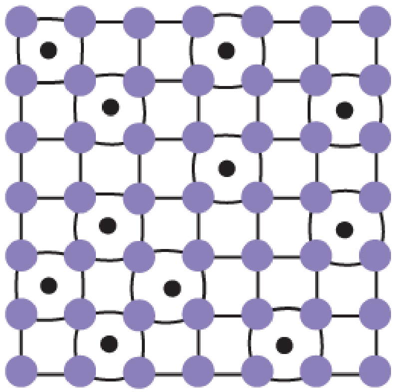
- Intentional alloying with impurity atoms exerts strains on the lattice surrounding the impurity

Substitutional Alloying



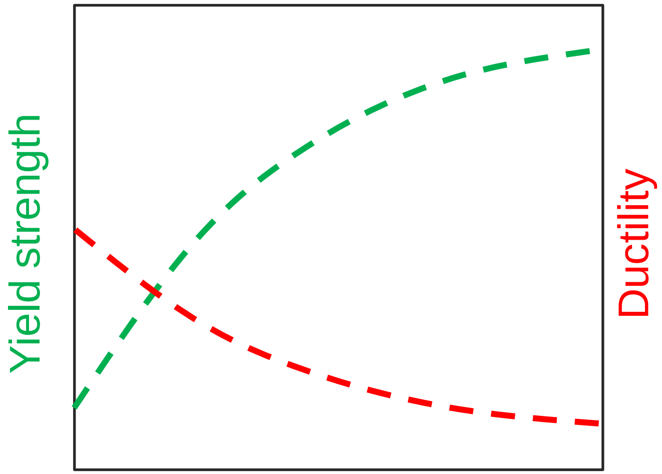
e.g., Mn in Fe

Interstitial Alloying



e.g., C in Fe

Increasing the alloying content results in an increase in yield strength



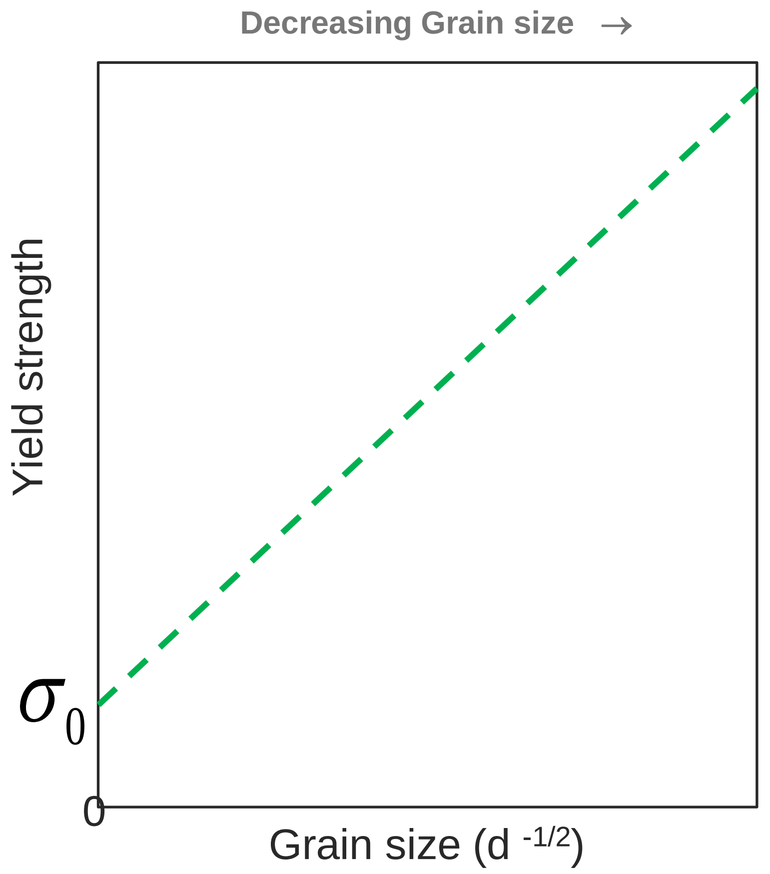
Importance of Grain Size

- Reducing grain size increases yield strength and toughness

Yield strength varies with grain size according to the Hall-Petch equation

$$\sigma_Y = \sigma_0 + kd^{-1/2}$$

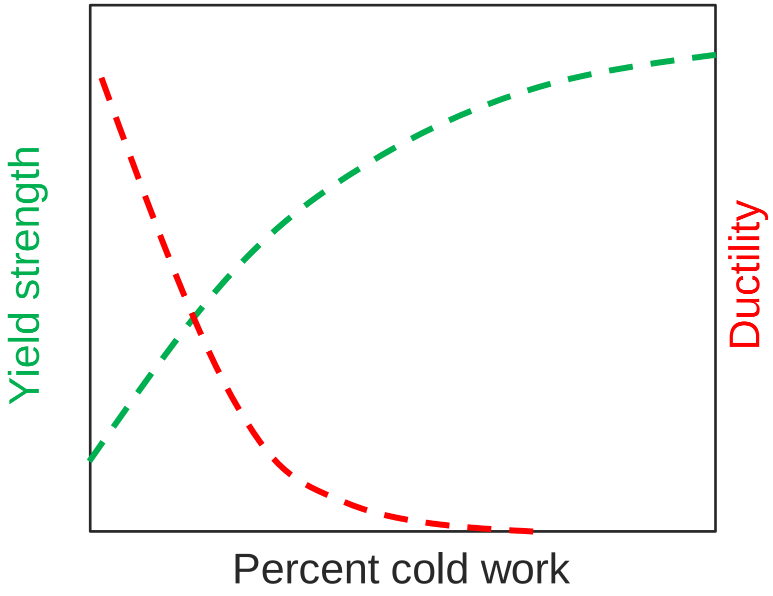
σ_Y, yield strength
σ_o, k, material constants
d, average grain diameter



Strain Hardening

- "Cold work" or "work hardening" is done by plastically deforming a ductile metal at or near room temperature

Increasing the cold work results in an increase in yield strength



Cold work expressed in terms of area reduction:

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

Battery Substrate Materials- Question what fundamentally makes these materials useful in batteries and why?

Property	Cu	Al	Ni
Thermal conductivity (W/m-°K)	390	229	70
Melting point (°C)	1080	652	1430
Thermal expansion coefficient (ppm/°C)	17.3	24.1	12
Heat capacity (J/kg-°C)	386	900	456
Absorption (at 1064 nm%)	2-5	8	32
Conductivity (10^6 S/m)	57	34	18
Resistivity (10^{-6} Ω-cm)	2.11	2.87	9.5
Specific heat (J/kg/°K)	386	238	455
Latent heat of fusion (J/g)	205	388	298
Electrochemical potential (V)	0.34	-1.66	-0.257
Thermal Diffusivity (cm^2/s)	1.14	0.91	0.11
Hardness (Brinell)	44	22	282
Price $/pound 10-19-22	3.32	0.98	9.7

Ultrasonic Metal Welding

Using waves to join metal

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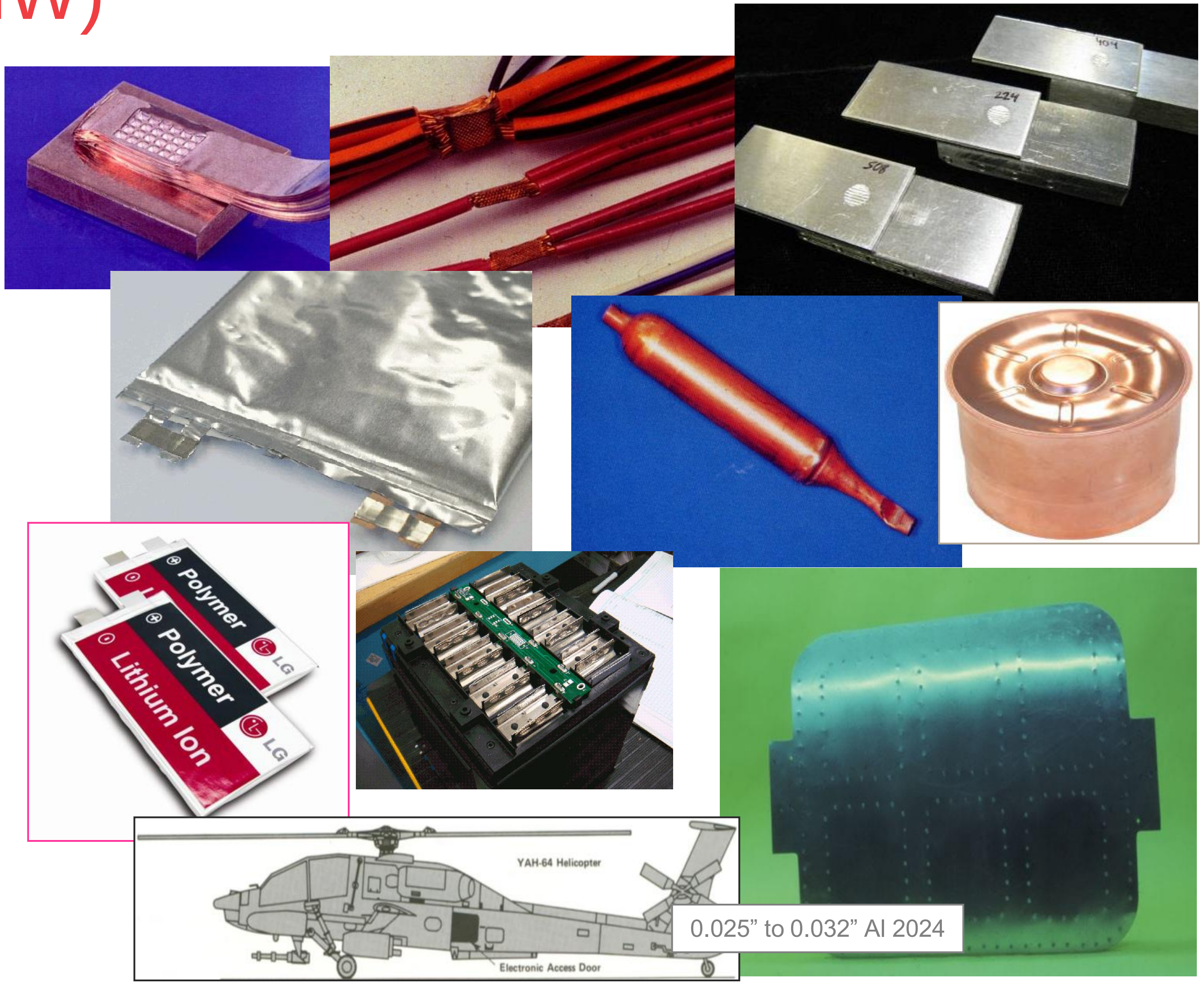
Ultrasonic Metal Welding (UMW)

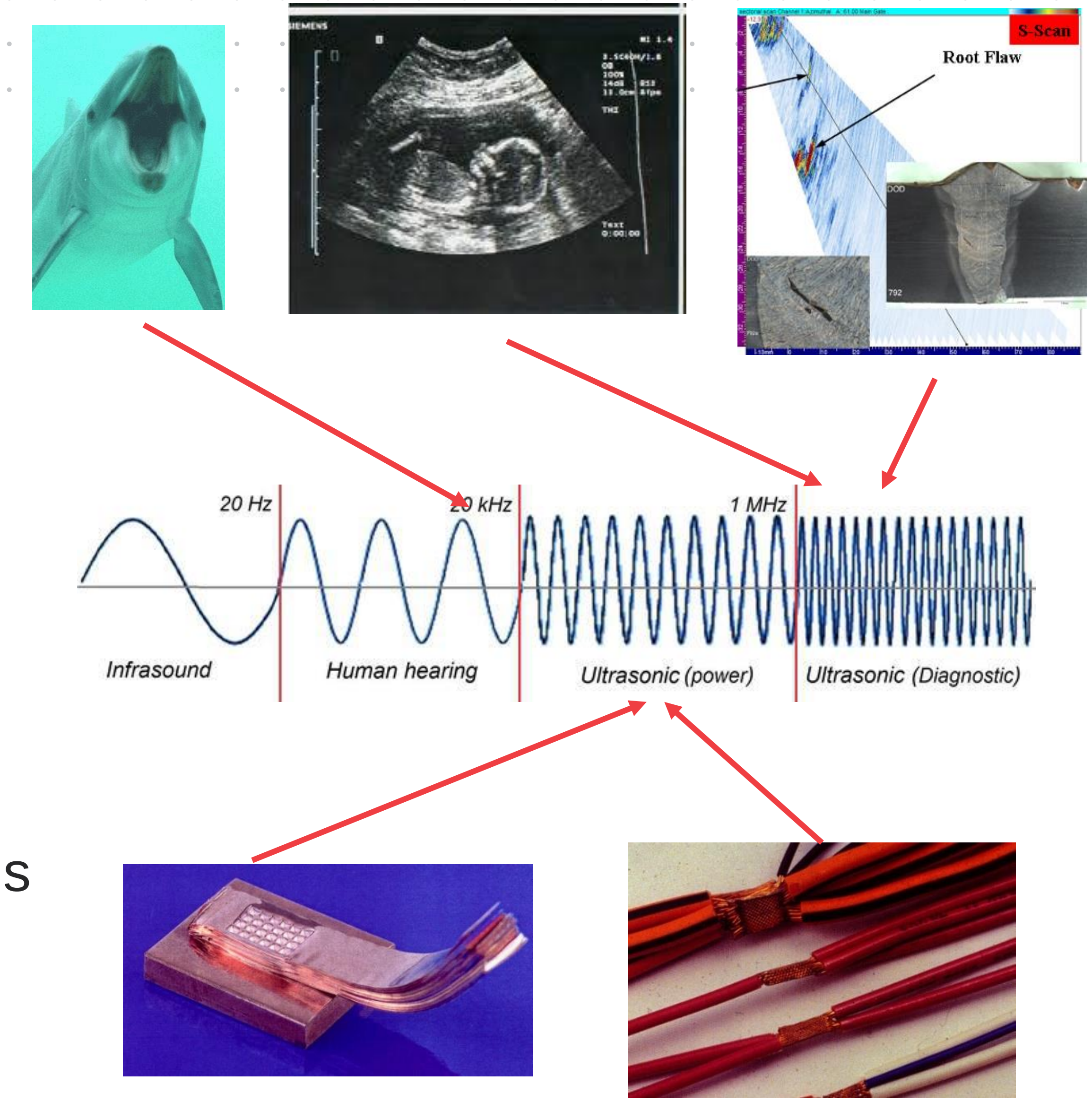
- Well suited for joining soft, highly conductive materials such as copper and aluminum
- Low heat input - can weld next to heat sensitive components
- Join similar or dissimilar material combinations
- Multi-layer, multi-thickness stack ups
- Welds thru oxides and contaminates
- Easily automated



Wave Power and Frequency

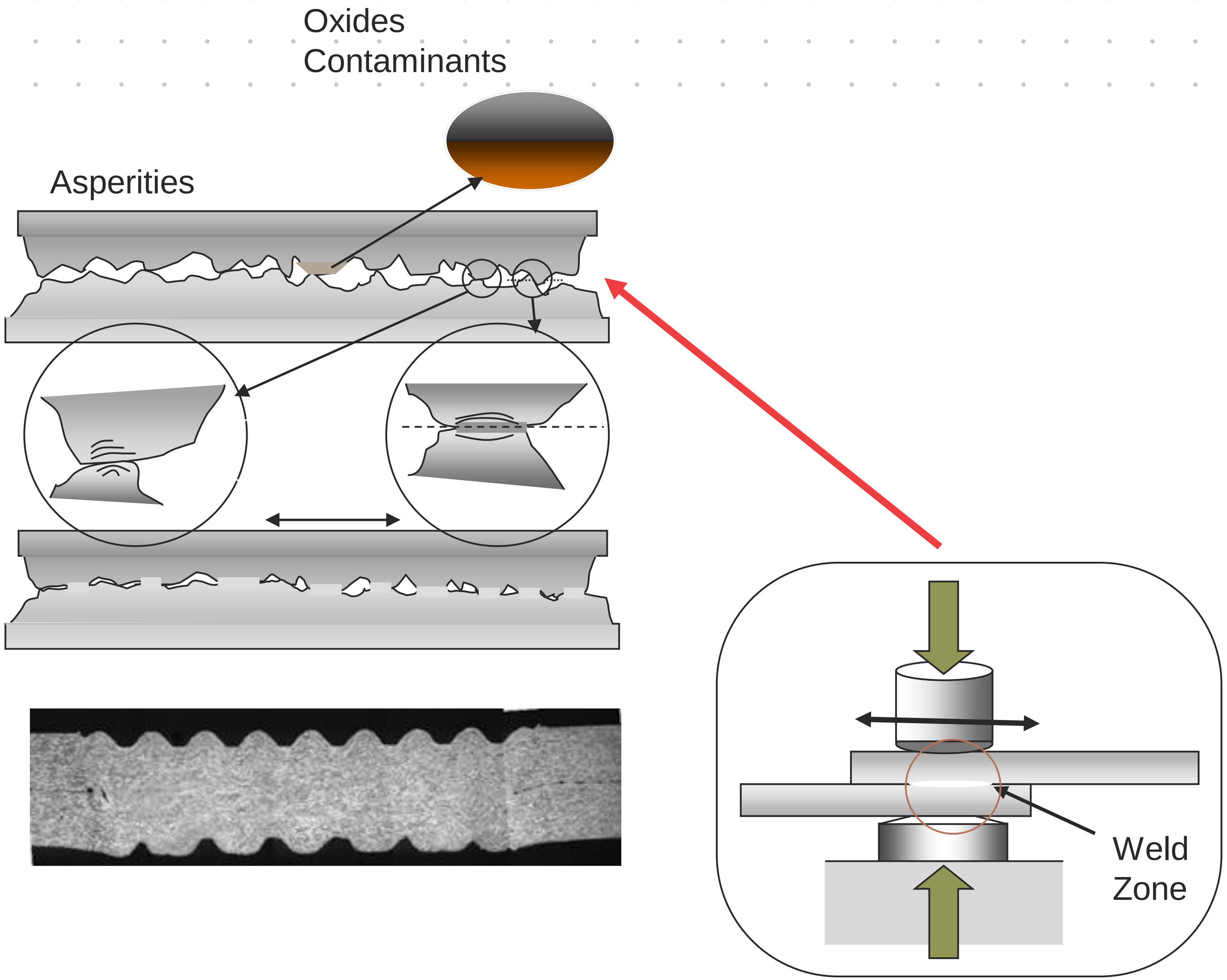
Ultrasonics can be broken into two major categories

- Low power, high frequency
  - Typically used to convey information
  - Power is measured in milliwatts
  - Frequency ranges from MHz to GHz
- High power, low frequency
  - Used to change the physical, chemical, or biological properties of materials or systems
  - Power is measured in watts or kilowatts
  - Frequency ranges from 10 to 500 kHz



Weld Formation

- Dispersion of oxides and contaminants
- Shearing and plastic deformation of asperities
- Surface & bulk heating
- Bring metallurgically clean surfaces into intimate contact under pressure
- Results in a metallic bond

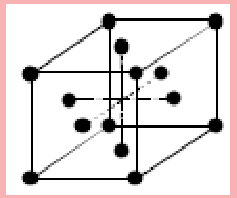


Solid State Welding

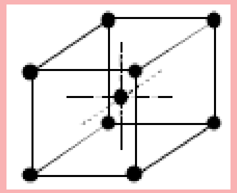
- **UMW is a solid-state welding process (SSW)**
    - AWS - “welding processes that produce coalescence by the application of pressure without melting any of the joint components”
- **Material yield strength, hardness, and oxide properties will play a significant role**

Crystal Structure

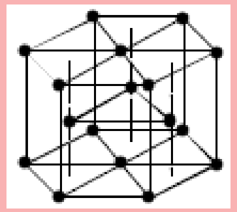
- FCC (Al, Au, Ag, Cu, Ni, Pt)
    - Ductile, most weldable



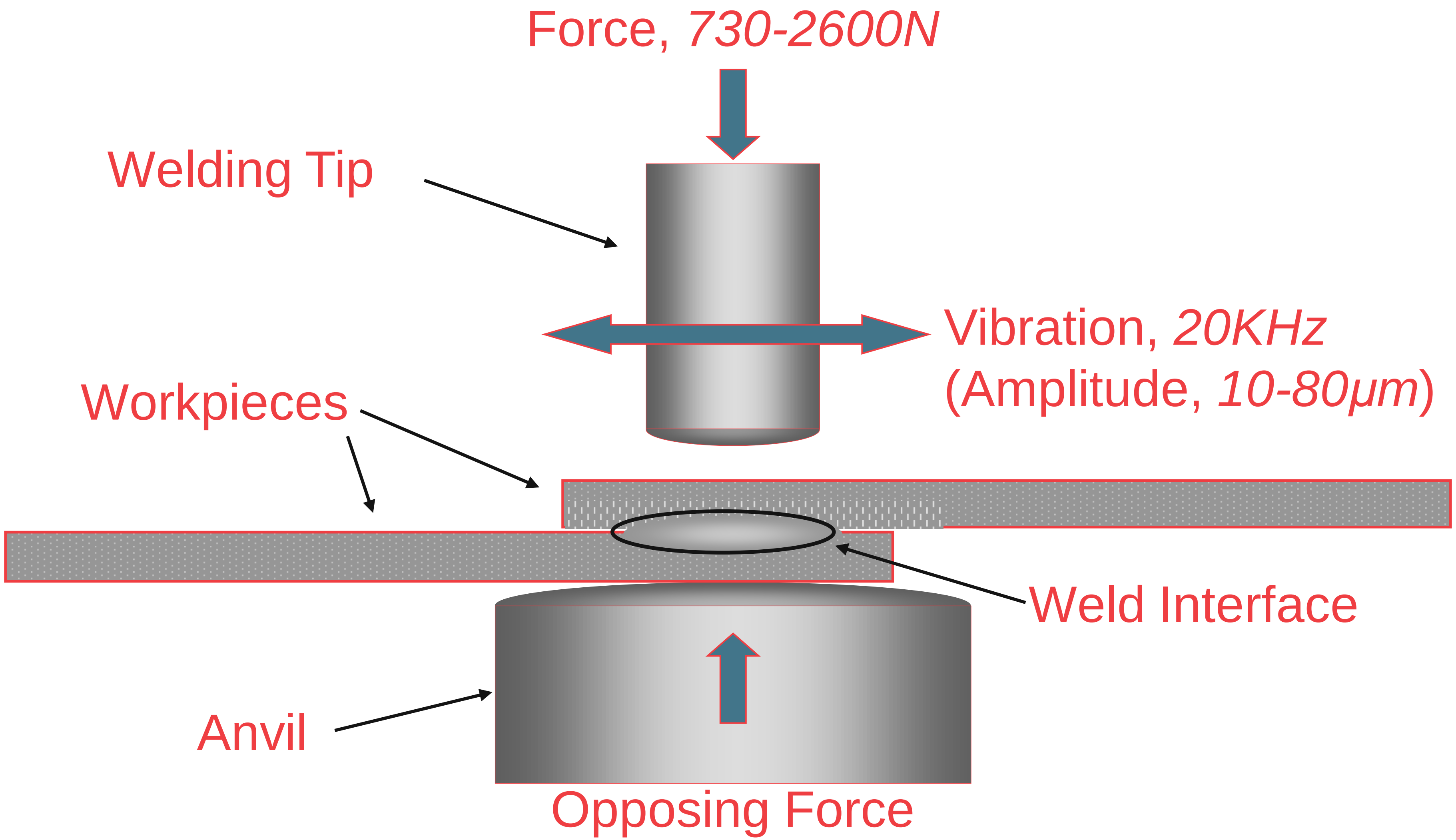
- BCC (Cr, Fe, Mo, W, V)
    - Refractory metals, more difficult to weld

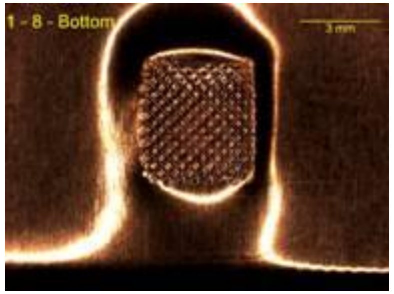


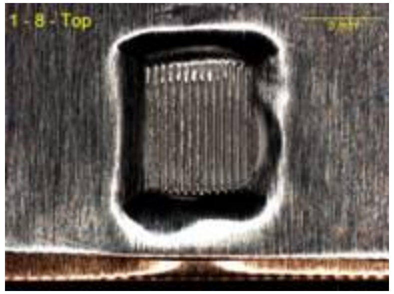
- HCP (Ti, Be, Mg)
    - Brittle, most difficult



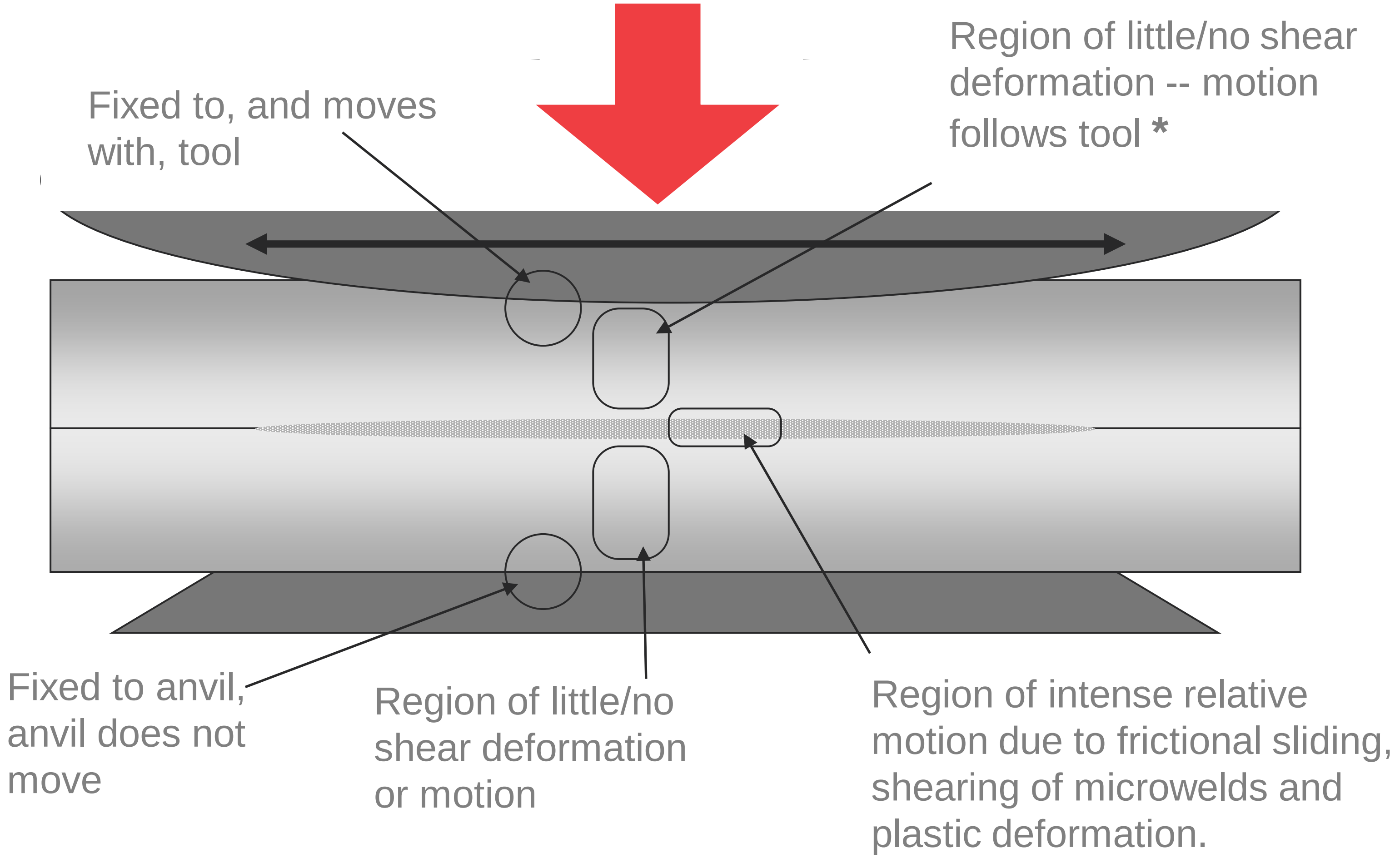
Weld Dynamics





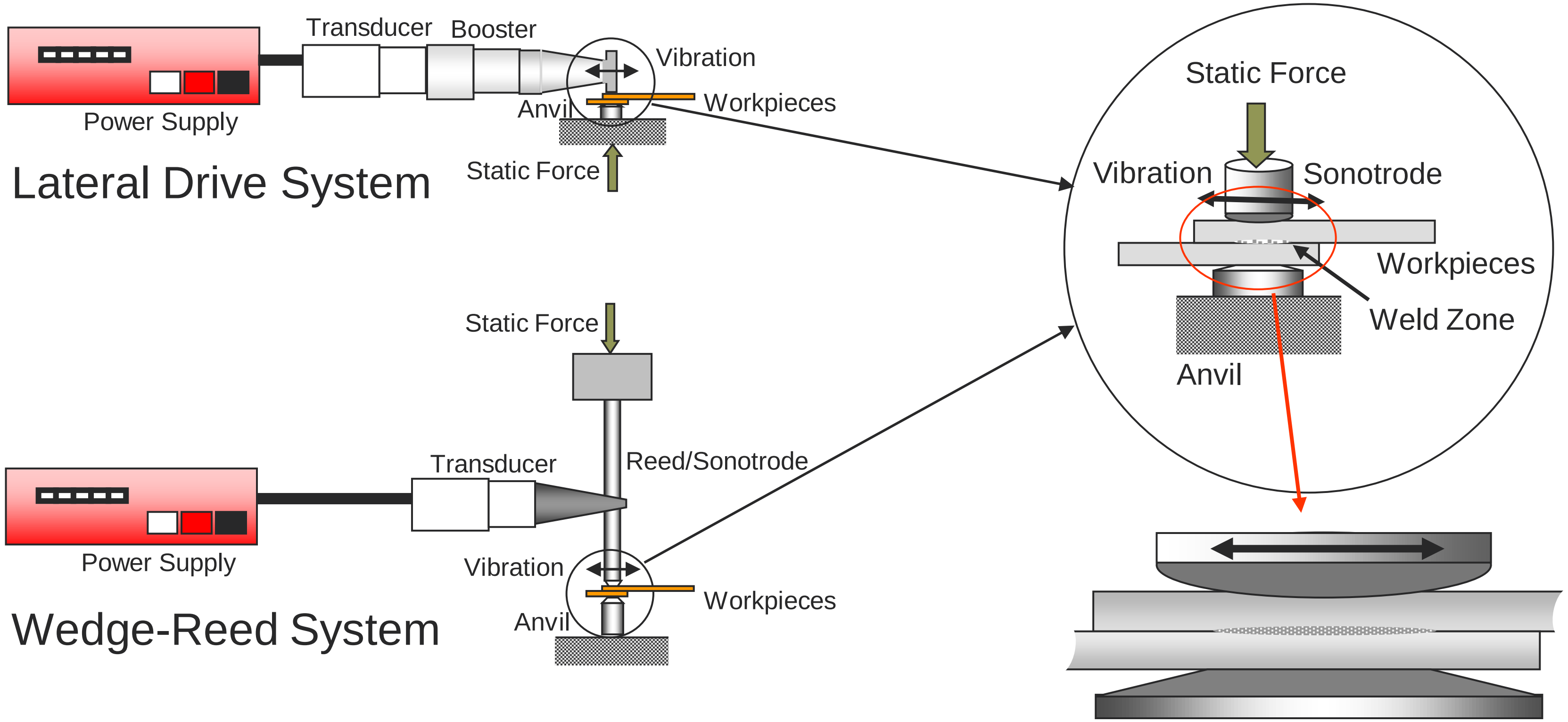


Ultrasonic Metal Welding (UMW) – Mechanics of Weld



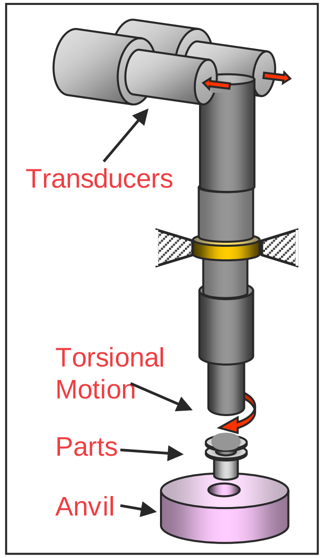
* This heavily dependent on materials, welding conditions

UMW Processes



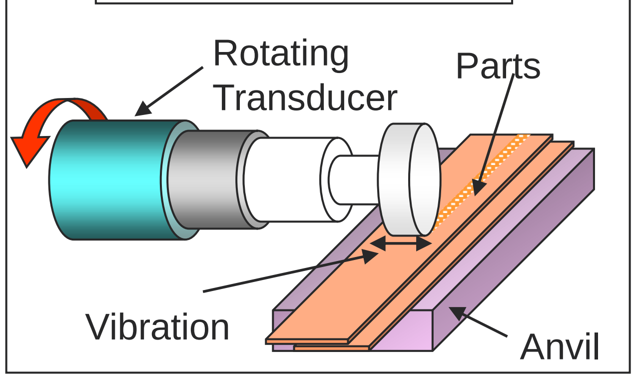
Ultrasonic Metal Welding (UMW)

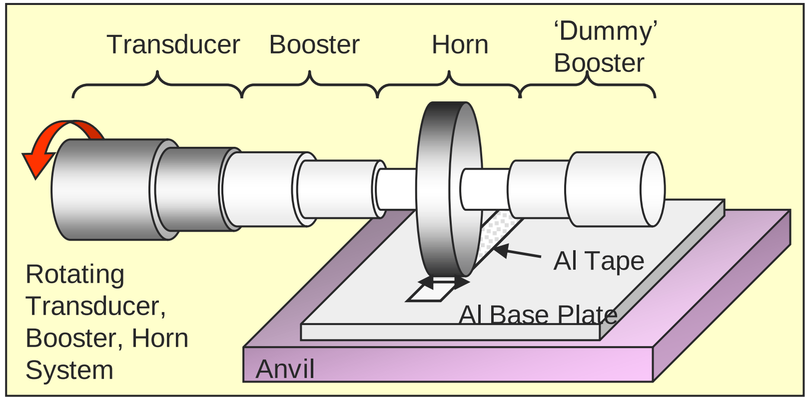
"Standard" Ultrasonic Metal Welder



Ultrasonic Torsion Welder

Ultrasonic Seam Welder

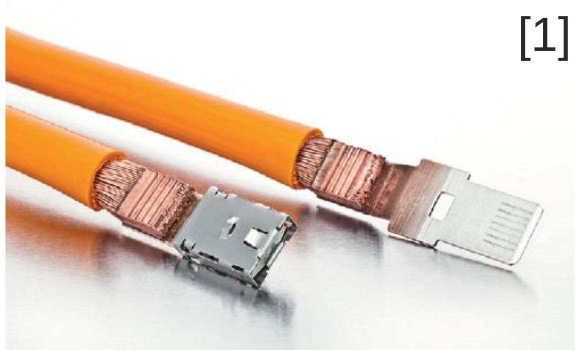




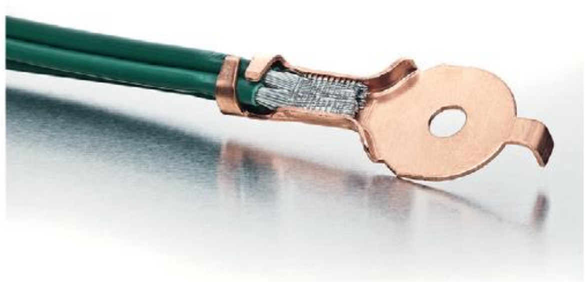
Ultrasonic Additive Manufacturing

Applications - Electrical Connections

Miniature air switch-type terminal commonly used in the automotive industry



[1]



[1]

Multiple stranded aluminum wires on a copper eyelet terminal

A heavy-duty copper–aluminum wire splice connection

[1]

[1] “TELSONIC AG - The Powerhouse of Ultrasonics.” https://www.telsonic.com/ (accessed Oct. 20, 2022).

Applications - Torsion Welding Process

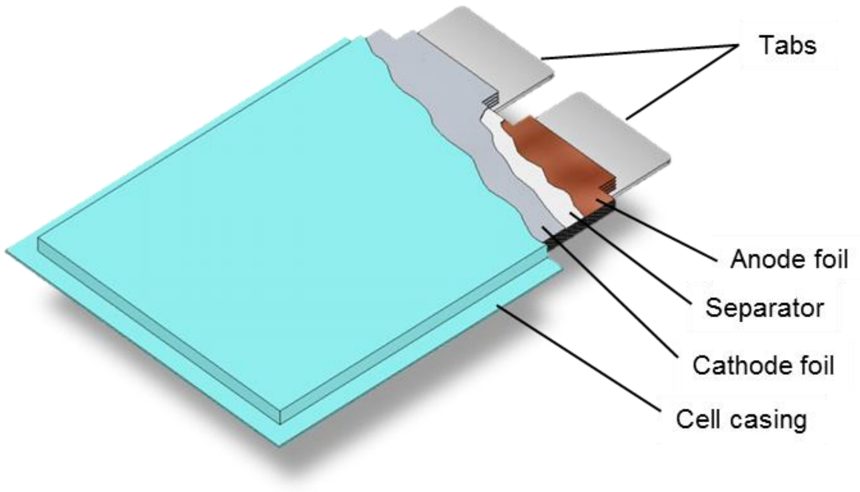
Electrically contacting a ceramic printed circuit board with a long pin (source: Telsonic)

Welding threaded studs to a deep-drawn Al housing (source: Telsonic)

Connecting a bolt to the current conductor (source: Telsonic)

Applications - Battery Packs

- Three most common metal-to-metal joints in a lithium-ion pouch style battery system are:
  - Foil-to-tab
  - Tab-to-tab
  - Tab-to-bus.
- Foil-to-tab is the most difficult to join:
  - Dissimilar materials
  - Dissimilar thicknesses
  - Ranges from 2 to 100 layers
- Lack of heat transfer makes ultrasonic a great technique



Cut-away Diagram of a Pouch Style Lithium-Ion Cell

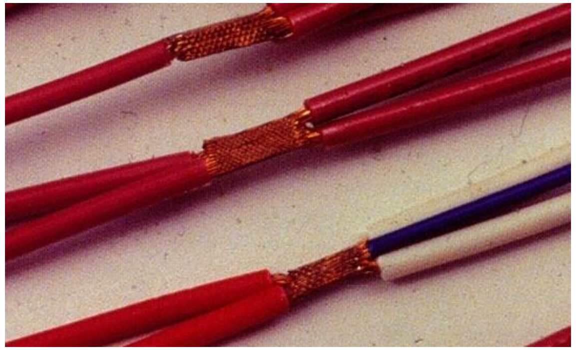
Advantages and Disadvantages

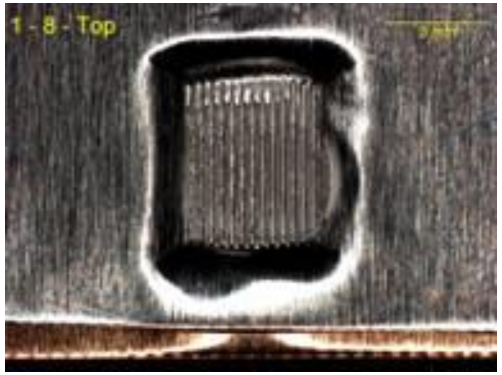
Advantages:

- High conductivity materials (Cu, Al ..)
- Solid state bond, low heat input
- Weld through oxides, contaminants
- Thick-thin material combinations
- Dissimilar materials
- No filler material or special atmospheres
- Low power requirements
- Easily automated

Disadvantages:

- Lap joints
- Joint thicknesses
- Restricted materials
- Deformation
- Noise, part resonance
- Unfamiliarity
- Tool wear





UMW Material Combinations

- AWS weldability chart shows materials that have been joined using UMW
- However, the origin, method, and quality is unknown
- Since there is no melting, detrimental phases do not form
- Great for refectory material and Al alloys

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be Alloys		●	●			●										●		
Cu Alloys			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						●		●	●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo Alloys								●	●		●			●		●	●	●
Ni Alloys									●	●	●			●		●	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														●		●	●	
Sn															●			
Ti Alloys																●	●	
W Alloys																	●	
Zr Alloys																		●

Friction Stir Welding

Using mixing to join metal

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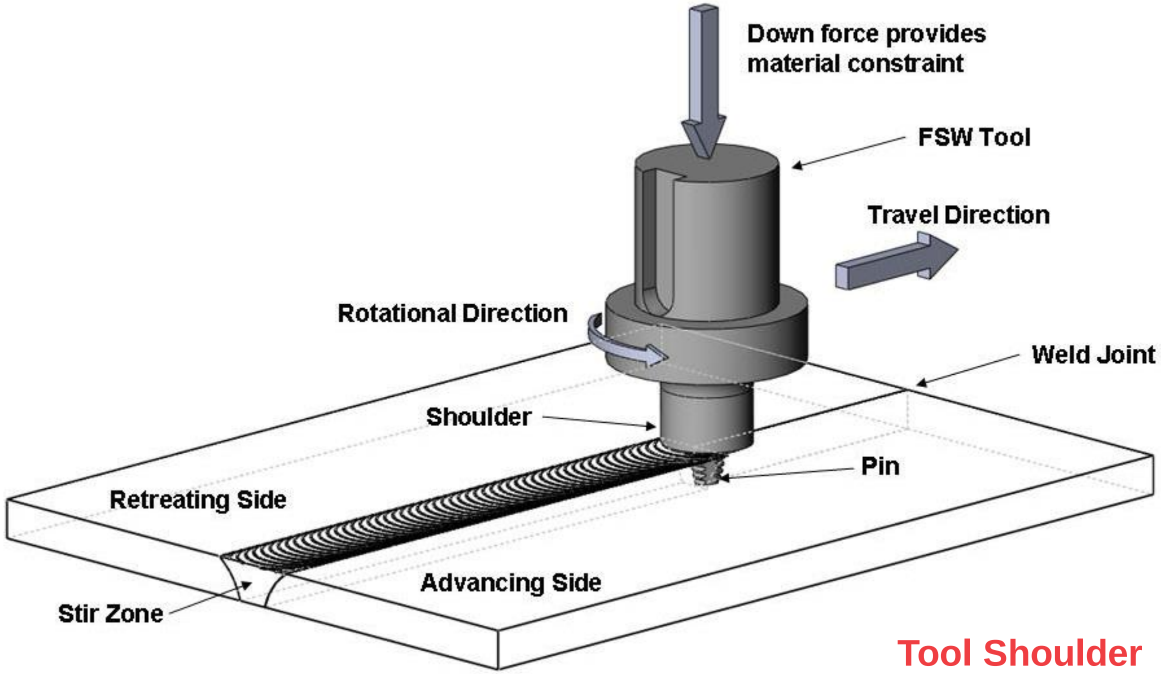
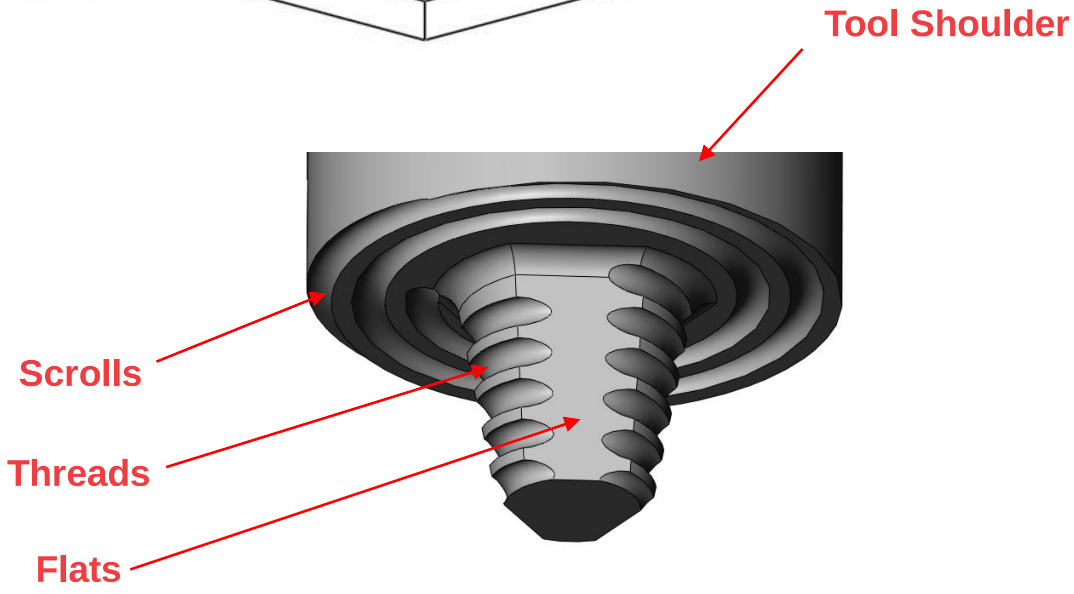
Friction Stir Welding

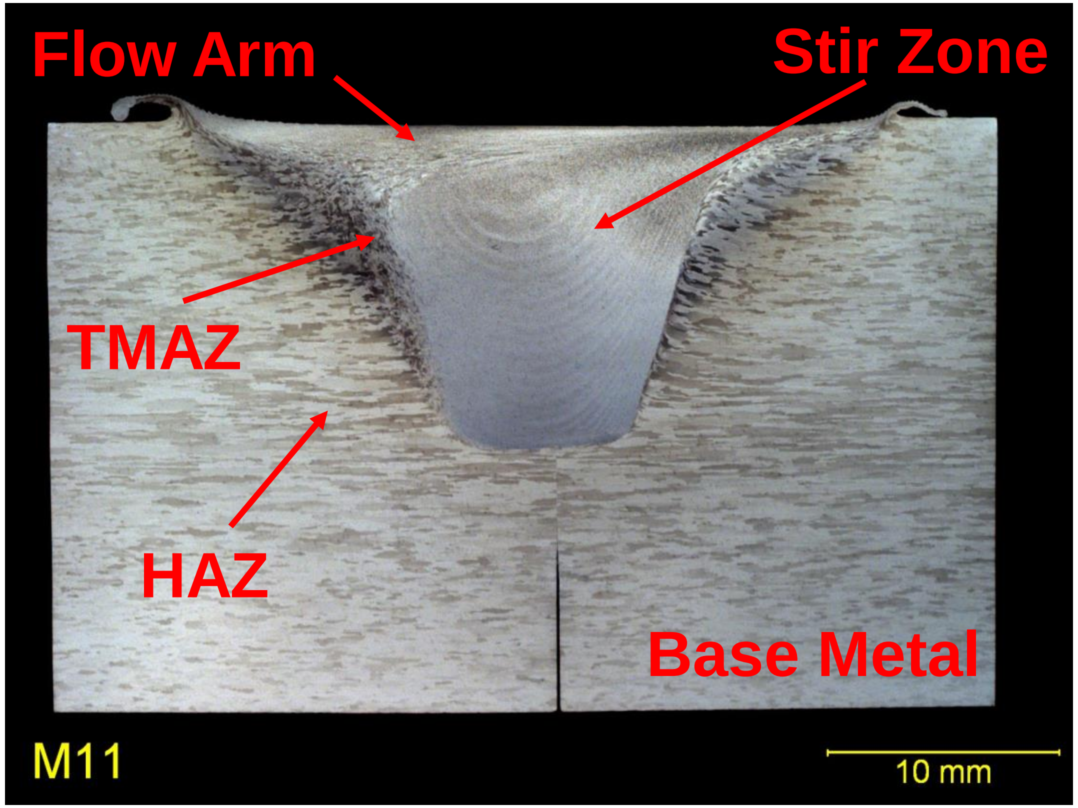
- Solid-state joining process
  - No bulk melting of the substrate
- Capable of joining
  - Aluminum, Magnesium, Copper, Steel, Titanium, Nickel, many more
- Non-consumable tool rotates and traverses along a joint
  - Combination of frictional heating and strain causes dynamic recrystallization
  - Adiabatic heating
- Creates a very fine grain microstructure
  - Low distortion
- Excellent weld properties





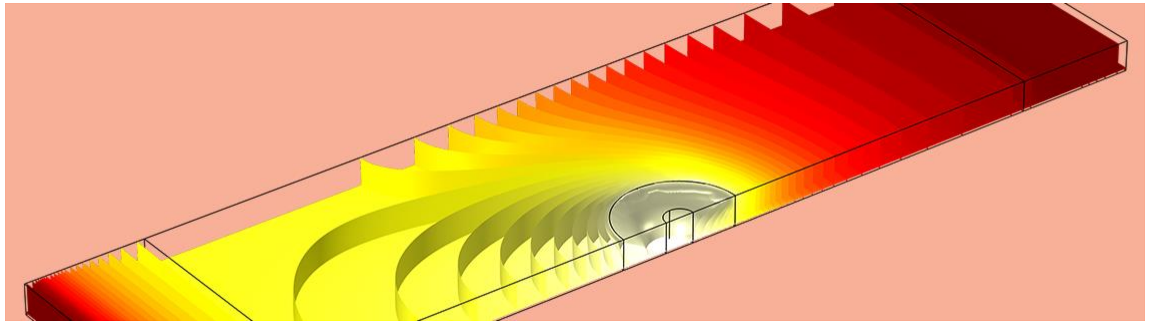
FSW Weld Zone

- Translational movement of the tool causes mixing of the plasticized material
- Complex material movement results in a non-homogenous weld zone
  - Strain, strain rate, and temperature gradients
  - Advancing and retreating side macrostructures very different
- Intense plastic deformation and elevated temperatures result in a fully recrystallized fine grain microstructure
  - Excellent mechanical and fatigue properties
- Resulted in new nomenclature



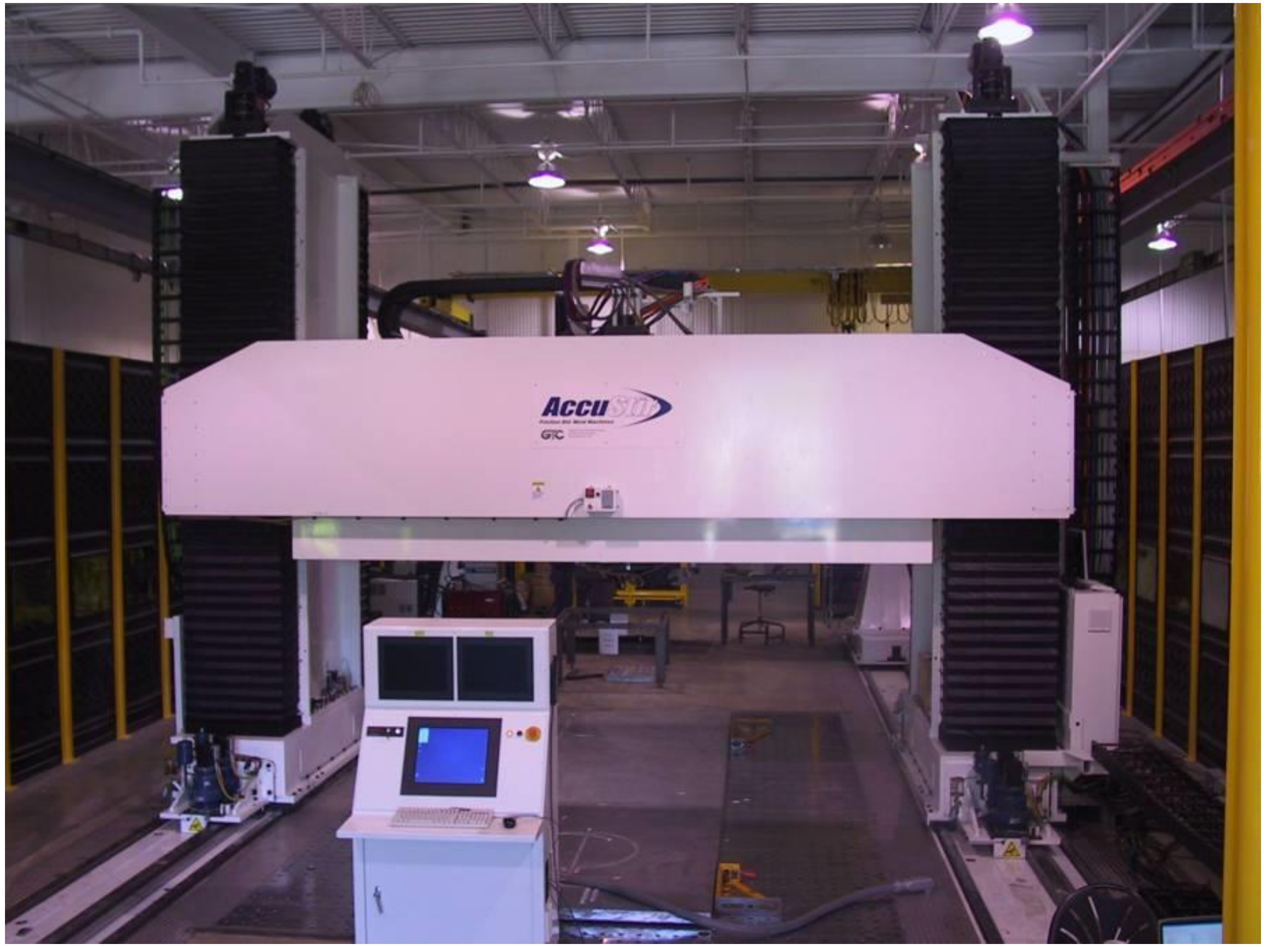
FSW Heat Generation

- Heat is generated from two primary sources
  - Friction and plastic deformation
- Heat input is affected by
  - Tool geometry, weld parameters, and tool material/substrate interactions
- Asymmetric temperature field
  - Higher temperatures on the retreating side and near the shoulder
- Various weld temperature approximations
  - Aluminum: 400-500°C
  - Copper: 800-900°C
  - Ferrous: 800-1300°C
- Experimentally measured with thermocouples and interpreted through mathematical models



FSW Large Production Scale

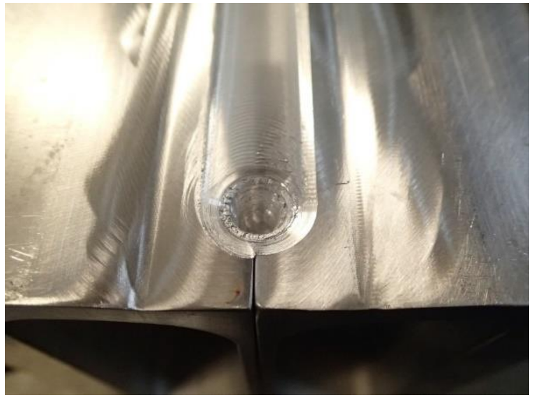
- 2.2 kW spindle drive
- 21 Nm spindle torque
- 11 kN force capacity
- 3,300 RPM maximum
- 10 mm stroke
- 5.7 mm/sec travel speed
- Weight = 65 kg

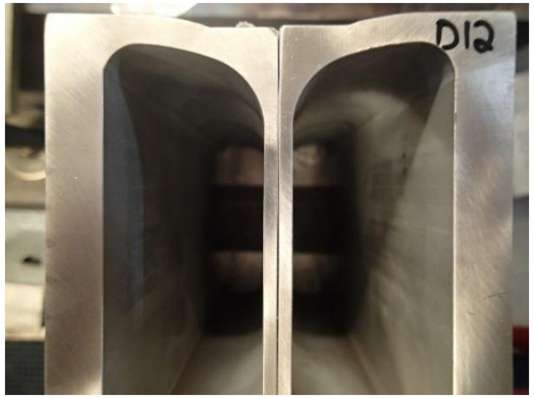


Friction Stir Welding Advantages and Disadvantages

- Advantages
  - Considered a green technology
    - Low energy consumption, no hazardous fumes
  - Solid-state joining process
    - Excellent weld properties, no solidification cracking, dissimilar material joints, low post-weld distortion
  - Capable of multiple joint positions
  - Highly automated and repeatable
  - Can join all commercial aluminum alloys
  - Desirable and anodization-friendly surface finish

- Disadvantages
  - Tight joint fit-up
  - High capital costs (machine and fixture)
  - Slower travel speeds for thicker materials
    - Typically, below 10-ipm above 0.5-in thickness





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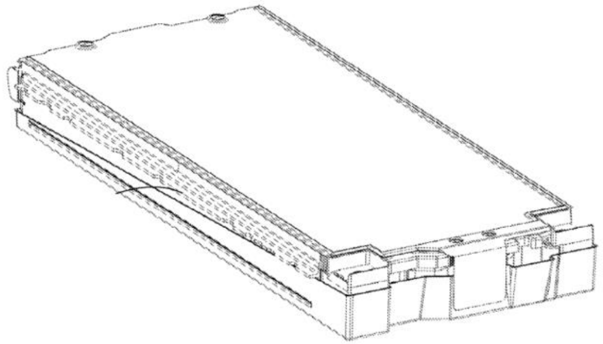
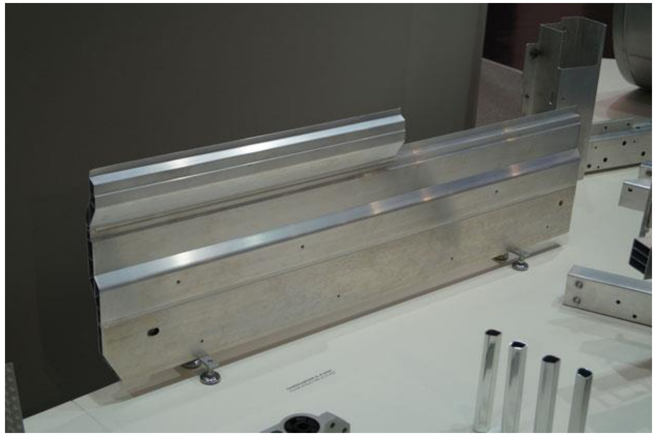
Aluminum FSW Joint Efficiencies

0.25” Plate Butt Weld Joint Strengths

Alloy	Parent Metal UTS	Friction Stir Weld UTS	Joint Efficiency
AFC458-T8	79.0	52.5	66%
2014-T651	70.0	49.0	70%
2024-T351	70.0	63.0	90%
2219-T87	69.0	45.0	65%
2195-T8	86.0	59.0	69%
5083-O	42.0	43.0	102%
6061-T6	47.0	31.5	67%
7050-T7451	79.0	64.0	81%
7075-T7351	68.5	66.0	96%

*Not for design purposes





[1]

Table I- Comparison of Fusion Welds and FSJ Strengths [29]

Base Alloy and Temper	Parent Material [30]	Gas-Shielded Arc Welded Butt Joint		Friction Stir Welding	
	Tensile strength (MPa)	Tensile strength (MPa)	% of Parent	Tensile strength (MPa)	% of Parent
2024-T3	485	Non-weldable	-	432 [32]	89
6061-T6	415	207 [35]	50	252 [34]	61
6N01-T5	260	165 [31]	63	200 [31]	77
7075-T6	585	Non-weldable	-	468 [33]	80

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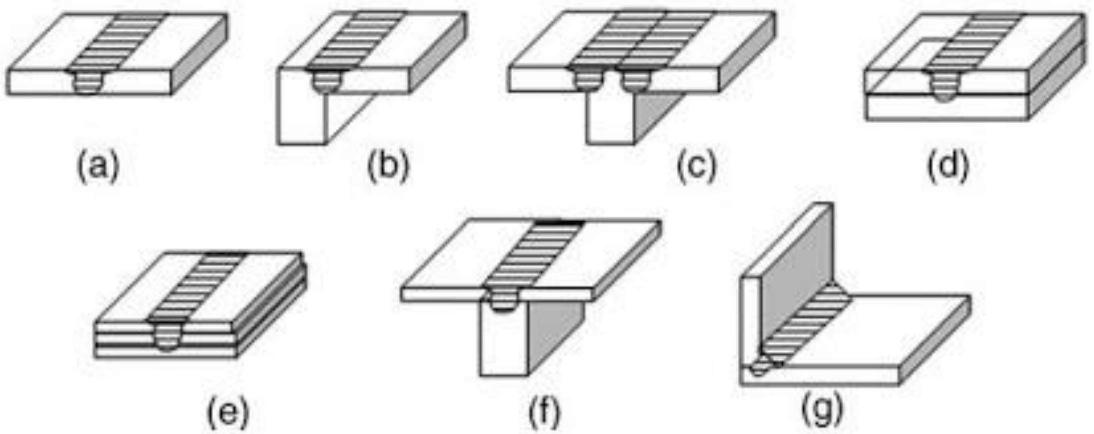
[1] “FSW: Automotive Industry,” *AluStir - Stephan Kallee*. https://www.alustir.com/english/fsw-automotive-industry/ (accessed Oct. 20, 2022).

Friction Stir Welding - Economic Incentives

- FSW of Aluminum
  - 15% reduction in man-hour per ton rate in aluminum panel fabrication – Hydro Aluminum
  - Total fabrication savings of 10% in shipbuilding - Fjellstrand
  - 60% cost savings on Delta II and IV rockets – Boeing
  - 400% improvement in cycle time for fabricating 25-mm-thick plates – General Dynamics Land Systems
- FSW of Steel
  - Estimated cost savings
    - Onshore construction, 7%
    - Offshore construction (J-Lay), 25%

[1]



[1] Kallee, S. W. (2010). Industrial Applications of Friction Stir Welding. In D. Lohwasser, & Z. Chen, *Friction Stir Welding From Basics to Applications* (pp. 118-163). Boca Raton: CRC Press.
Kumar, A., Fairchild, D. P., Macia, M., Anderson, T. D., Jin, H. W., Ayer, R., . . . Mueller, R. R. (2011). Evaluation of Economic Incentives and Weld Properties for Welding Steel Pipelines Using Friction Stir Welding. *Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference* (pp. 460-467). Maui: ISOPE.

Resistance Welding

Using current to join metal

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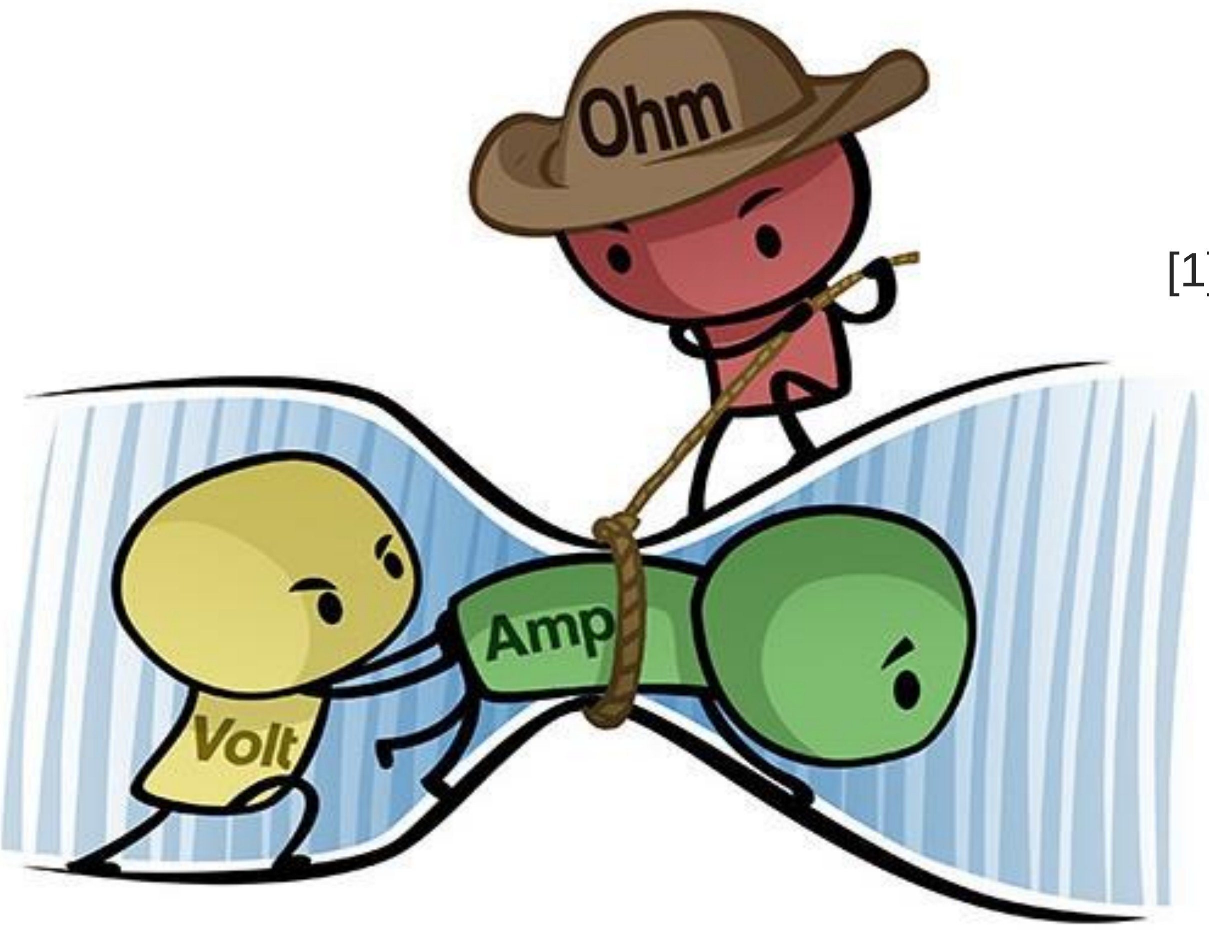
Resistance Welding Overview

- Resistance welding refers to a family of welding processes that generate heat as a result of the electrical resistance of the parts being welded to current that is passed

- Variables to consider for heat balance
  - Materials to be welded
  - Thicknesses
  - Pressure
  - Contact resistance

- Common processes
  - Spot welding
  - Projection welding
  - Seam welding
  - Flash welding

What is Voltage?



[1]

$$R = \frac{V}{I}$$

R = Resistance
V = Voltage
I = Current

[1] Ø. N. Dahl, “What You Need to Know About Current, Voltage and Resistance,” *Build Electronic Circuits*, Sep. 18, 2014. https://www.build-electronic-circuits.com/current-voltage-resistance/ (accessed Oct. 20, 2022).

What is Electrical Resistance?

- Just Like Water Flowing in Pipes, Fewer Electrons can Flow in Smaller “Conductors” or “Clogged” Conductors at the Same Pressure
- Resistance is the Ratio of Electrical Pressure (Voltage) to the Number of Electrons (Current) that Flow Through the Pipe (Circuit)

[1]

$$R = \rho \frac{\ell}{A}$$

R = Resistance
A = Contact Area
ρ = Density
ℓ = length

[1] seowerkz, “Types Of Steel And Other Metal Types Used In Piping | Wasatch Steel,” Feb. 28, 2020. https://www.wasatchsteel.com/types-of-steel-and-other-metal-types-used-in-piping/ (accessed Oct. 20, 2022).

Resistive (Joule) Heat

- Electrical Resistance Heating
  - Generates Heat Due to Electrical “Friction” Between the Electrons and the Conductor
  - Voltage Drop (Loss of Electrical Pressure)

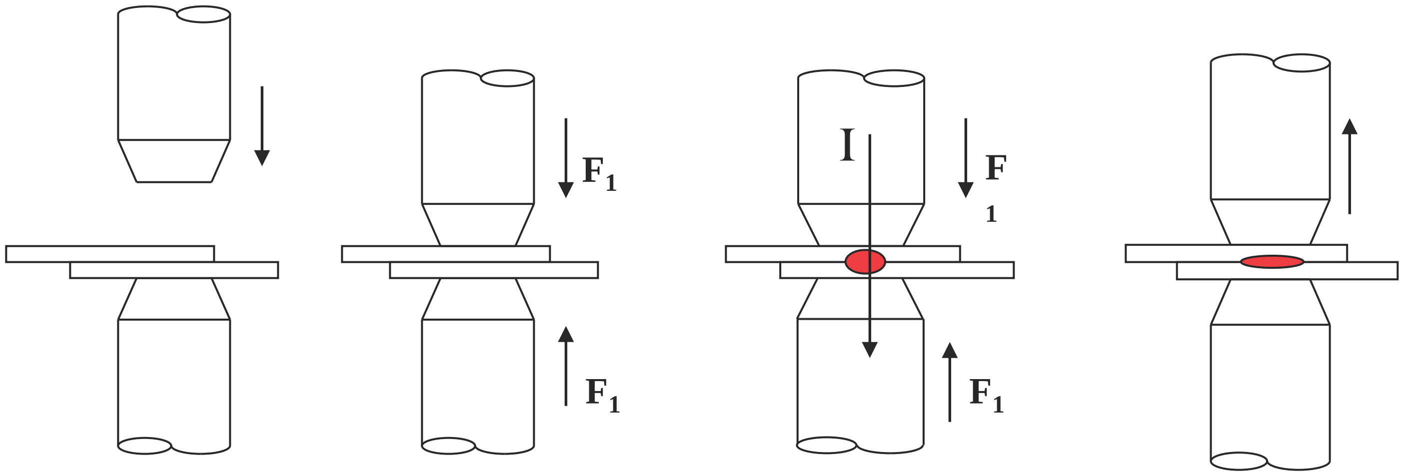
$$Heat = I^2 R t$$

R = Resistance
I = Current
t = time

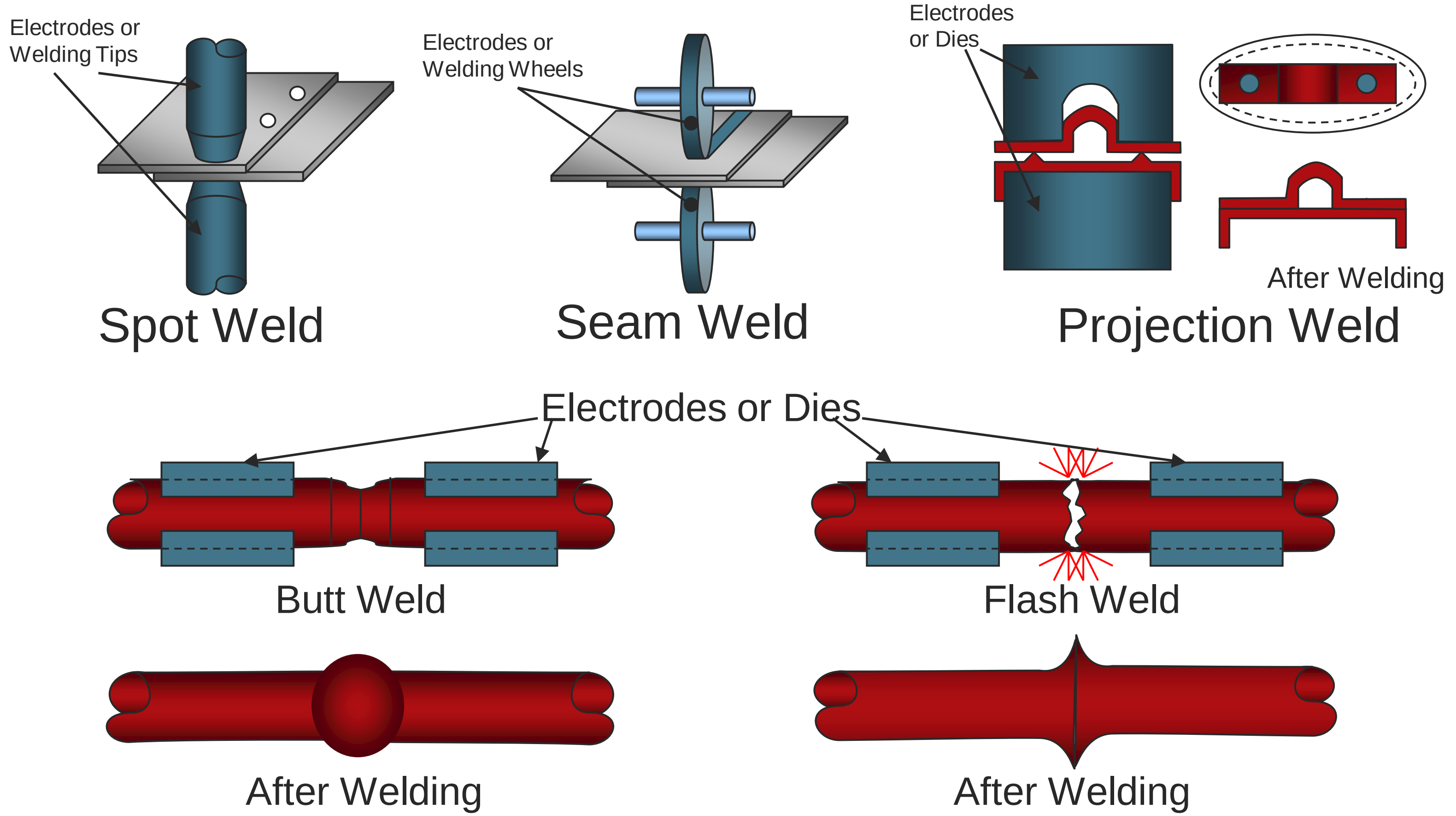
- Resistance welding uses electrical resistance of materials to produce the heat needed to either melt the interface between the substrates or soften the metal and enable a forge-type joint

Steps in Resistance Spot Welding

- The steps in making a resistance weld include:
  - Closing the electrodes during the squeeze time
  - Application of electrode force
  - Conduction of current
  - Solidification of weld metal
  - Release of force and reposition sheet or welder



Principle Types of Resistance Welds

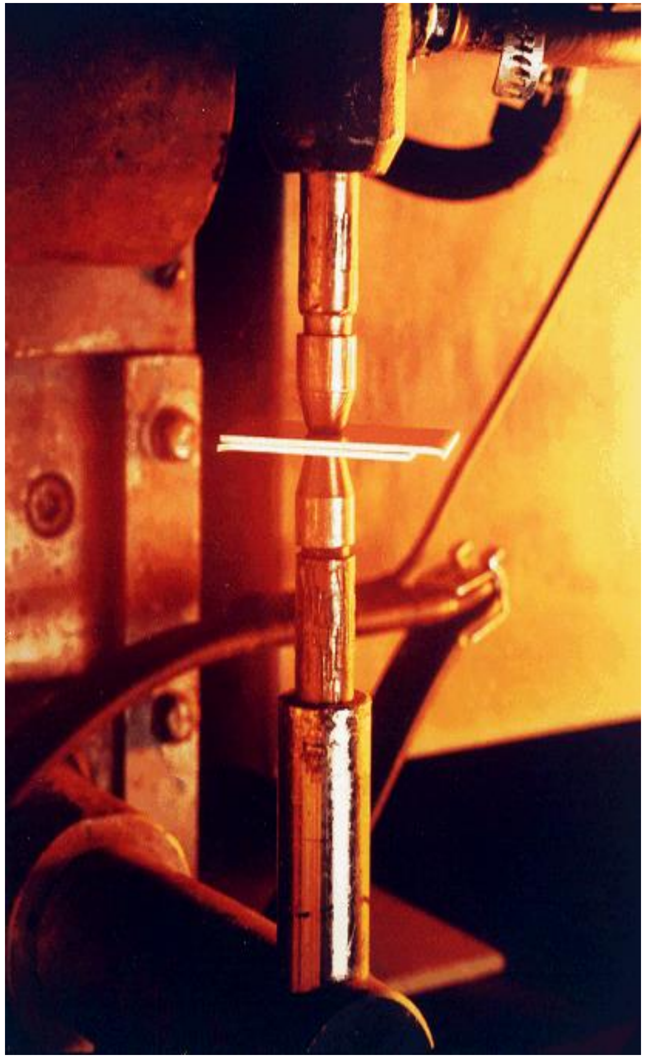


Power Supplies

Power Supply	Typical Cycle Time	Typical Bond Type	Advantages	Limitations
AC	> 8 msec	Fusion, Re-flow	Rugged and inexpensive	Poor control at short cycle times
Linear DC	0.1 - 50 msec	Solid State	Suitable for amorphous materials, thin foils, fine wires. Excellent control and repeatability	Limited current capacity
HF Inverter	1-1000 msec	Fusion, Solid State, Re-flow	Excellent control and repeatability, High current capacity	Three-phase AC required
Capacitor Discharge	1-5 msec	Solid State	Rugged and inexpensive, Suitable for highly conductive materials	Poor feedback, discharge "self-regulating"

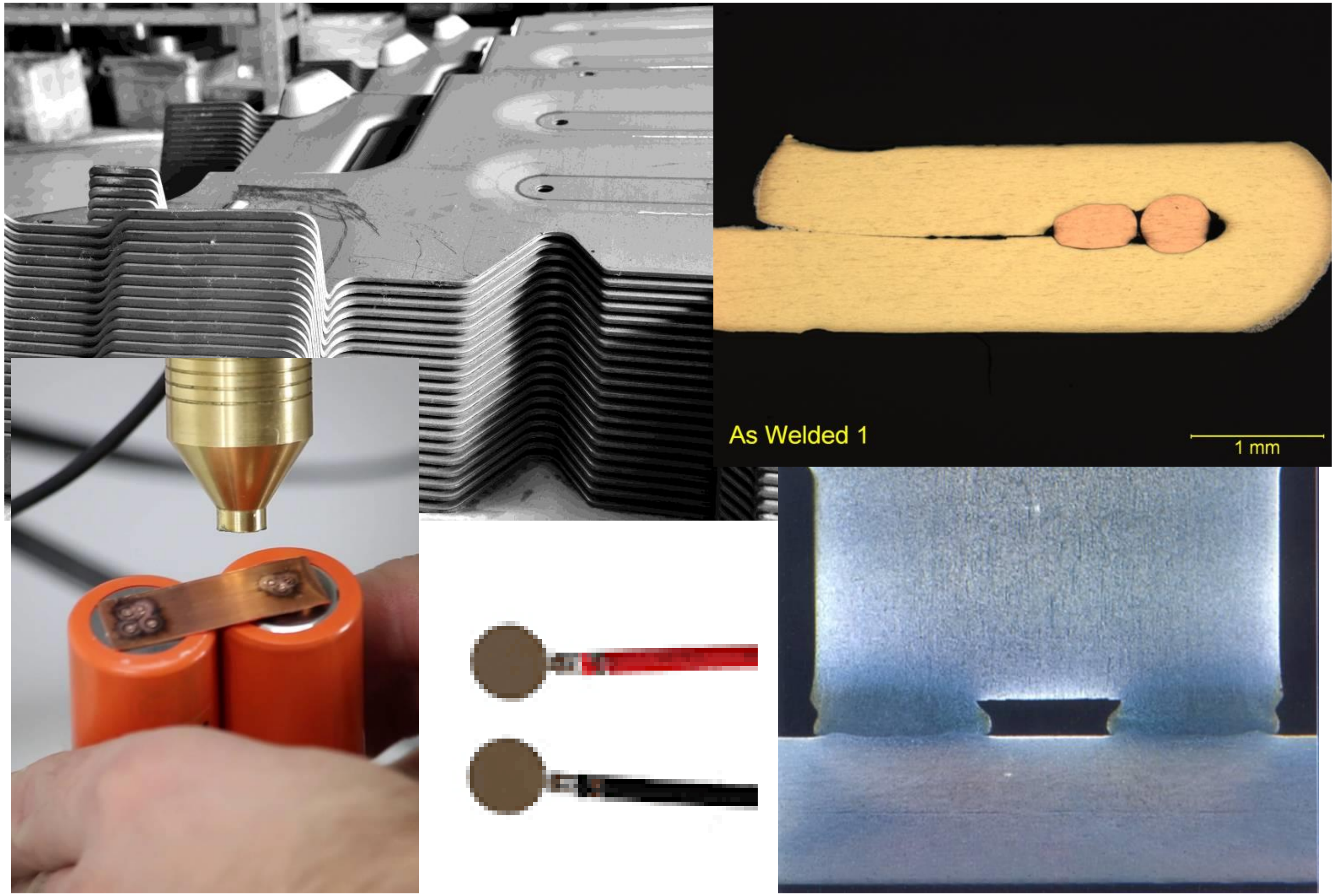
Resistance Spot Welding

- Advantages
  - Ideal for high-speed production
  - Easy to automate
  - Self-clamping
  - No filler materials required
  - “Aesthetics” of surface condition
- Disadvantages
  - Overlapping joint adds weight
  - Need for sufficient joint access
  - Hidden weld location – quality control is difficult, highly dependent on lobe curves
  - Poor mechanical properties due to notches and uneven loading
  - Expensive equipment
  - Weld repair difficult
  - Extreme power line demands



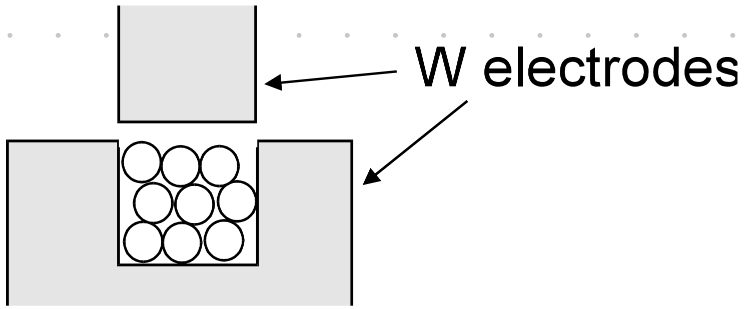
Resistance Welding for Batteries

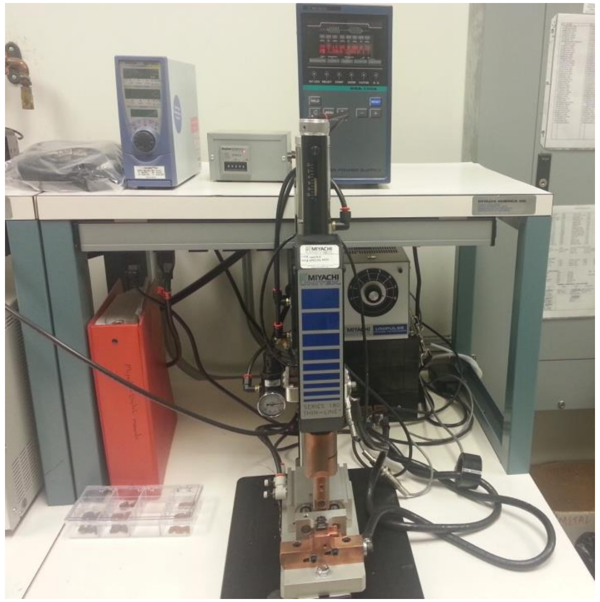
- Seam welding for cooling blocks
- Spot welding for battery bands
- Spot welding for tabs
- Capacitance welding for wires to tabs
- Projection welding for can closures



Wire Consolidation

- Overlap welding of solid & stranded wires
- Pre-consolidation of stranded wires for resistance or ultrasonic welding
- Works best on plain copper or tin-plated copper wire
- Not for aluminum wires (use ultrasonic instead)



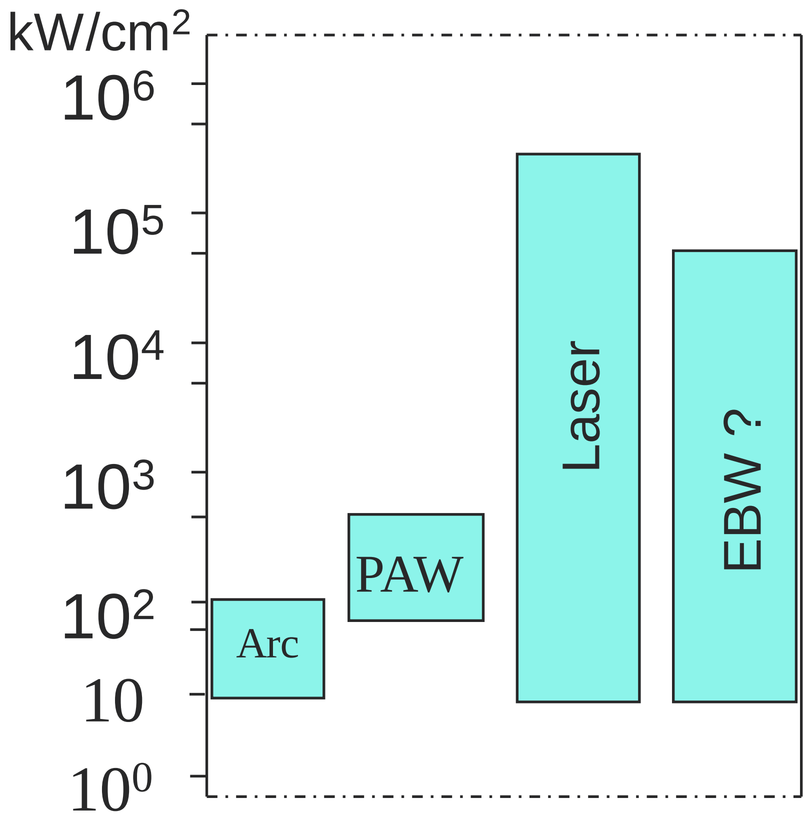


Laser Welding

Using light to join metal

HED Welding: High Energy Density Welding

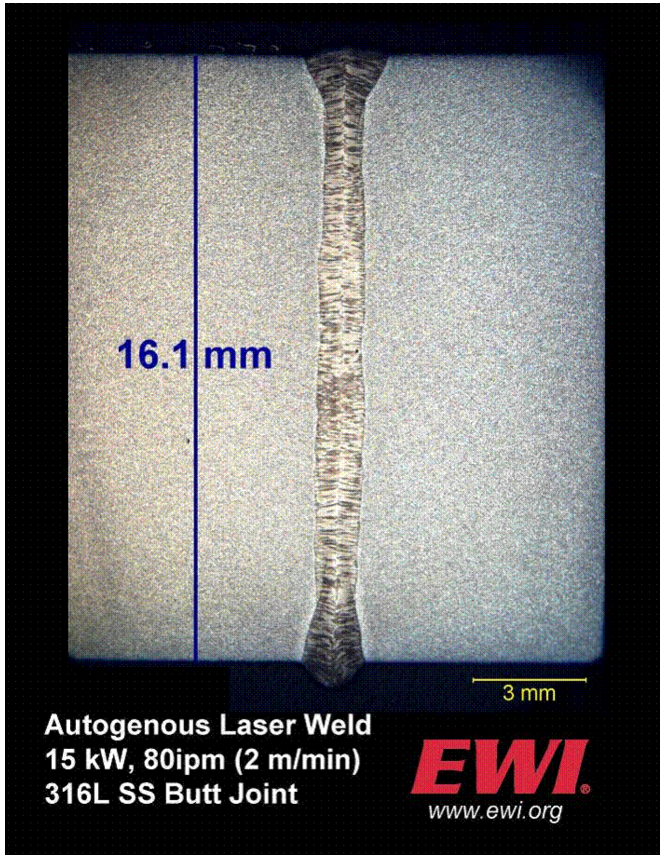
- HED processes include laser beam welding (LBW), electron beam welding (EBW), and sometimes plasma arc welding (PAW)
- Focused to small spot sizes
- Melt and/or vaporize materials
- Metals and alloys, plastics and composites, ceramics, etc.
- Power density (power/area) is significantly higher than common arc welding processes
  - Greater than 5×10^2 kW/cm^2

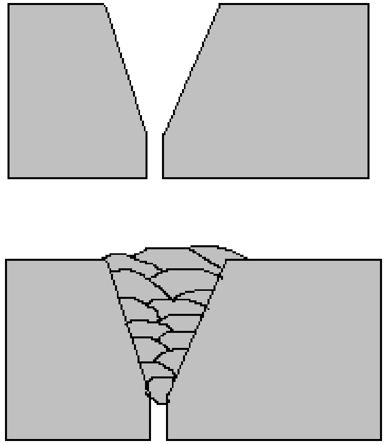


Electron Beam vs. Laser Beam (electrons vs. photons)

5.75-in.-Deep EB Weld

~1mm/kW @ 2m/min*





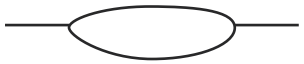
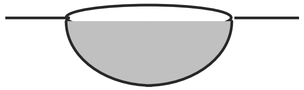
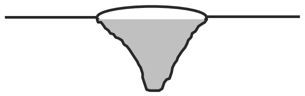
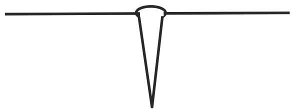
Multi-Pass Arc Welding Above

*Laser in low vacuum can achieve comparable penetration depths as EB

LASER

Laser is an acronym:

- Light
- Amplification by
- Stimulated
- Emission of
- Radiation

Flux cored arc welding	**0.5 - 50 kW/cm^2**	
Gas metal arc welding	**0.5 - 50 kW/cm^2**	
Plasma arc welding	**50 - 5×10^3 kW/cm^2**	
Laser or electron beam welding	**5×10^3 - 5×10^5 kW/cm^2**	

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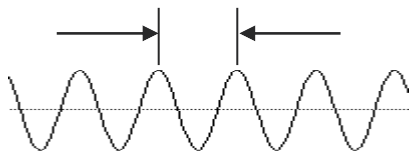
What is Light?

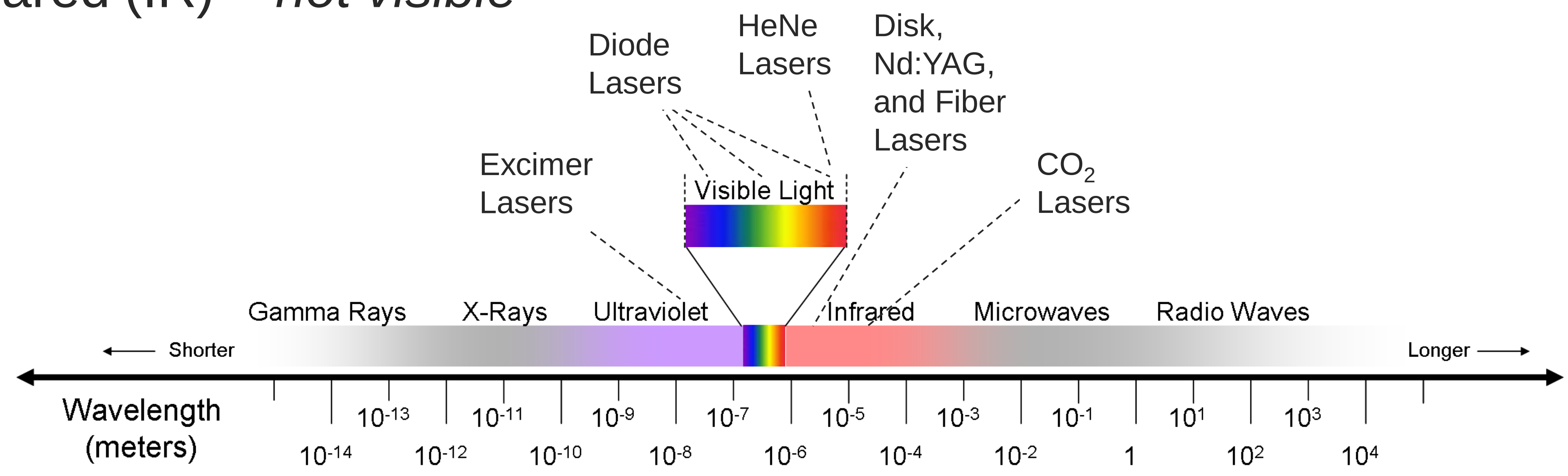
- Radiation within a certain portion of the electromagnetic spectrum
- Defined by its wavelength (λ – “lambda”)
- Form of energy created by the acceleration and deceleration of electrons
    - The nature of the acceleration/deceleration of electrons influences the wavelength
- Wavelength of the light influences what it can do during materials processing
- Exhibits particle and wave behavior
- Has a magnetic and electric field component
- A “packet” of light is called a photon

Electromagnetic Radiation (Different Lasers)

- Different lasers produce different wavelengths of light
- (Explains visible, UV, and IR)
  - Visible (ROYGBIV)
  - Ultraviolet (UV) – *not visible*
  - Infrared (IR) – *not visible*

Wavelength = λ





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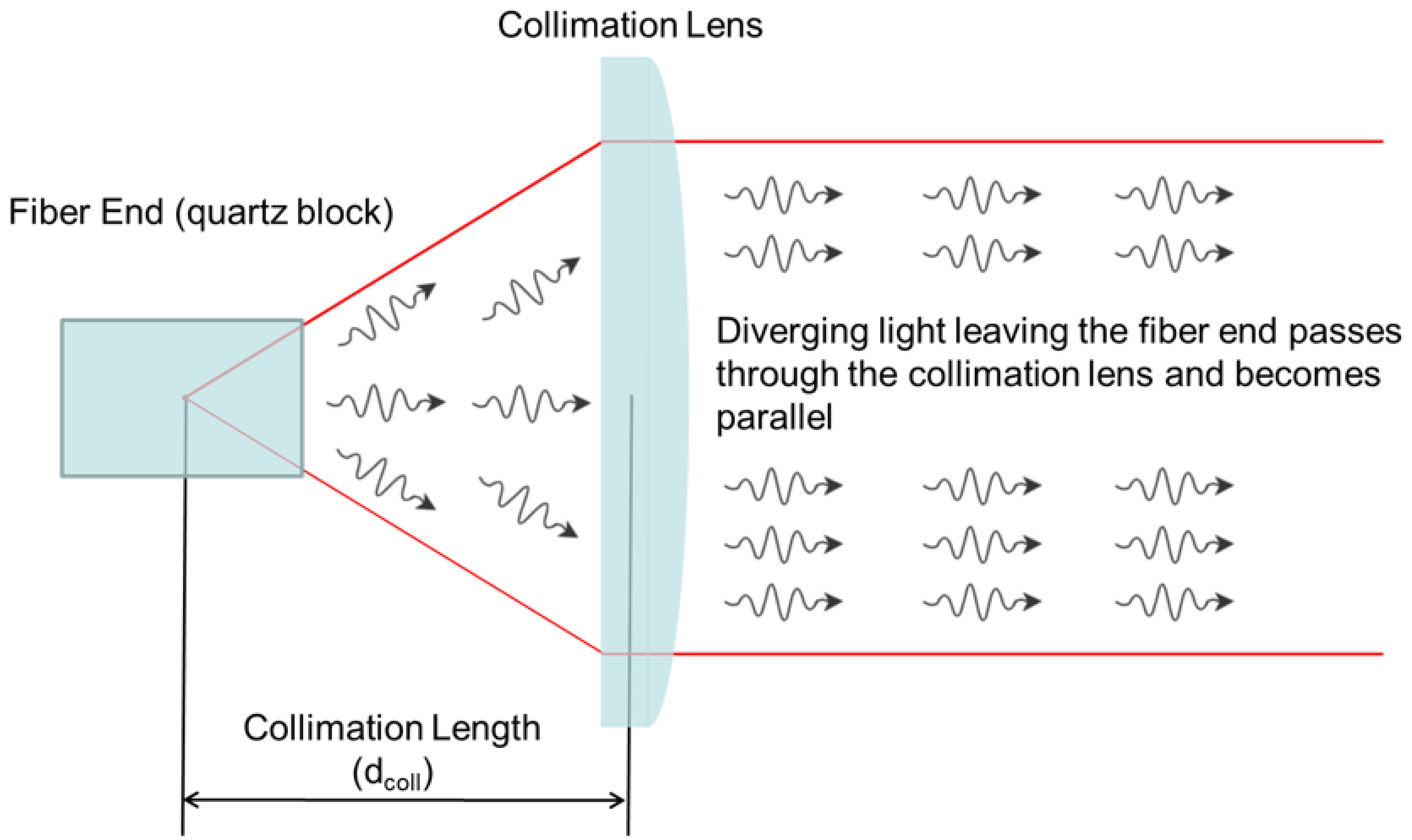
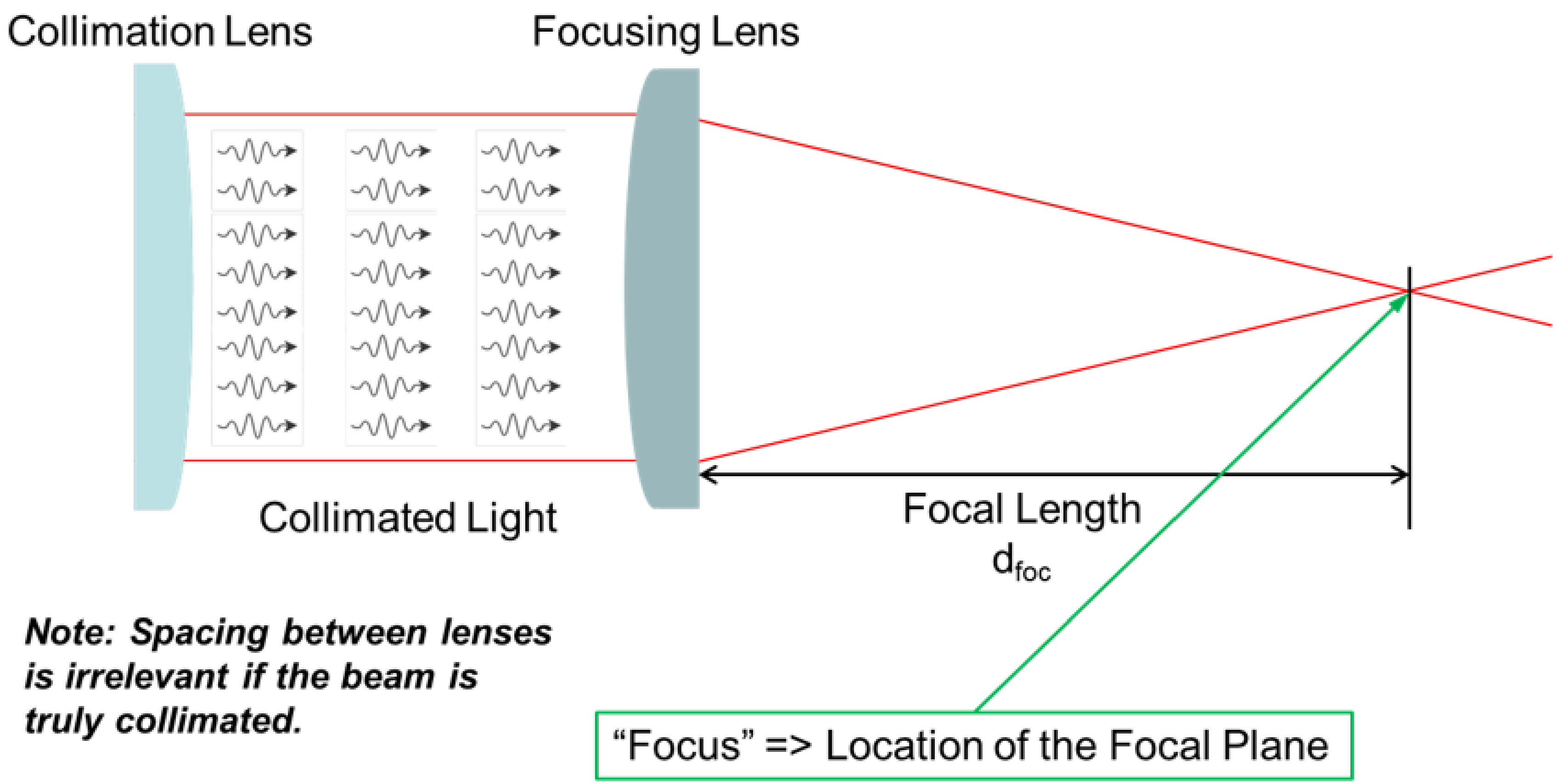
Collimation of Light

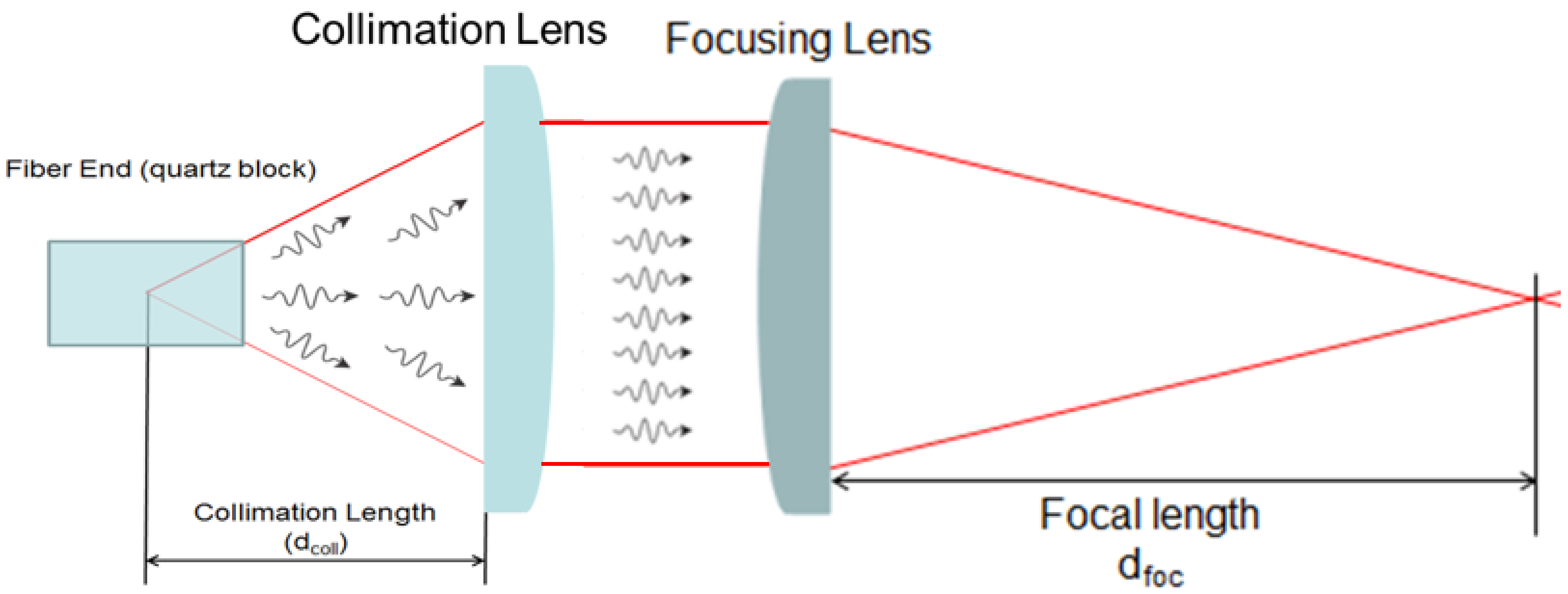


Focused Light



Note: Spacing between lenses is irrelevant if the beam is truly collimated.

Magnification



$$Magnification = \frac{Focal\ Length}{Collimation\ Length} = \frac{d_{foc}}{d_{coll}}$$

Theoretical Spot Size

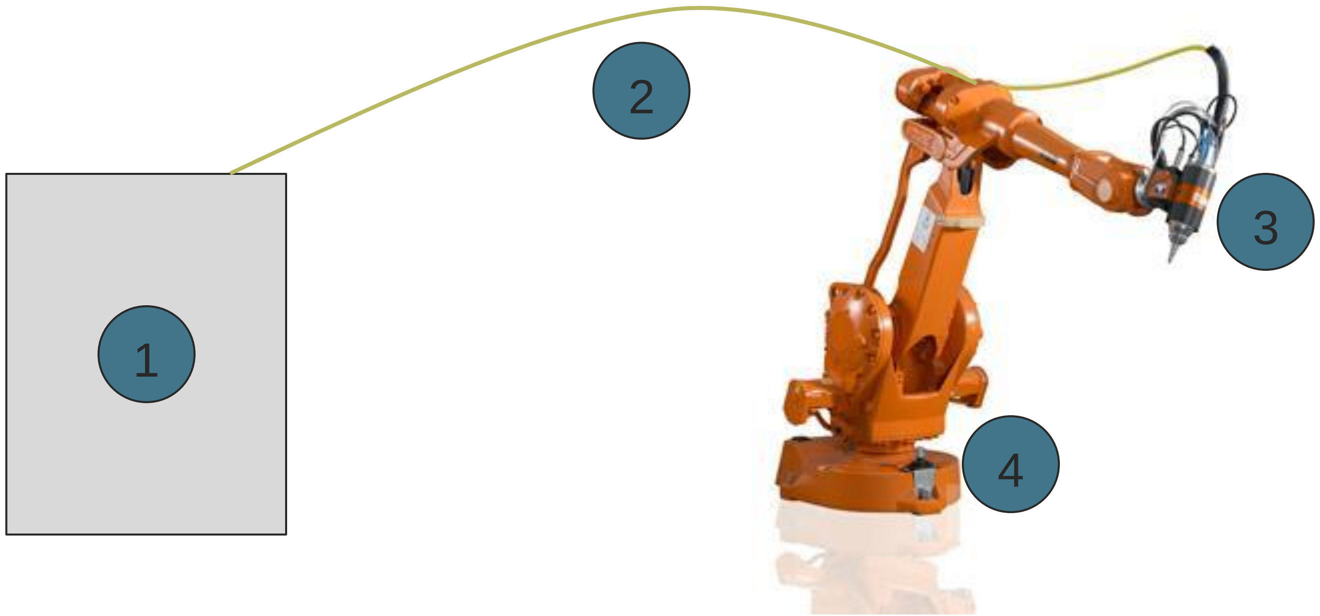
$$D_{Spot} = Magnification \times Fiber\ Diameter\ = \frac{d_{foc}}{d_{coll}} \times d_{fiber}$$

- Step 1: Calculate the magnification by dividing the focal length by the collimation length.
- Step 2: Multiply the magnification by the fiber diameter (d_{fiber}) to calculate the theoretical spot size.

Components of a Laser System

Primary components of a laser system include:

1. Laser Power Source
2. Beam Path/Fiber
3. Laser Processing Head (optics)
4. Motion System
5. Safety enclosure (not pictured)



Laser for Welding

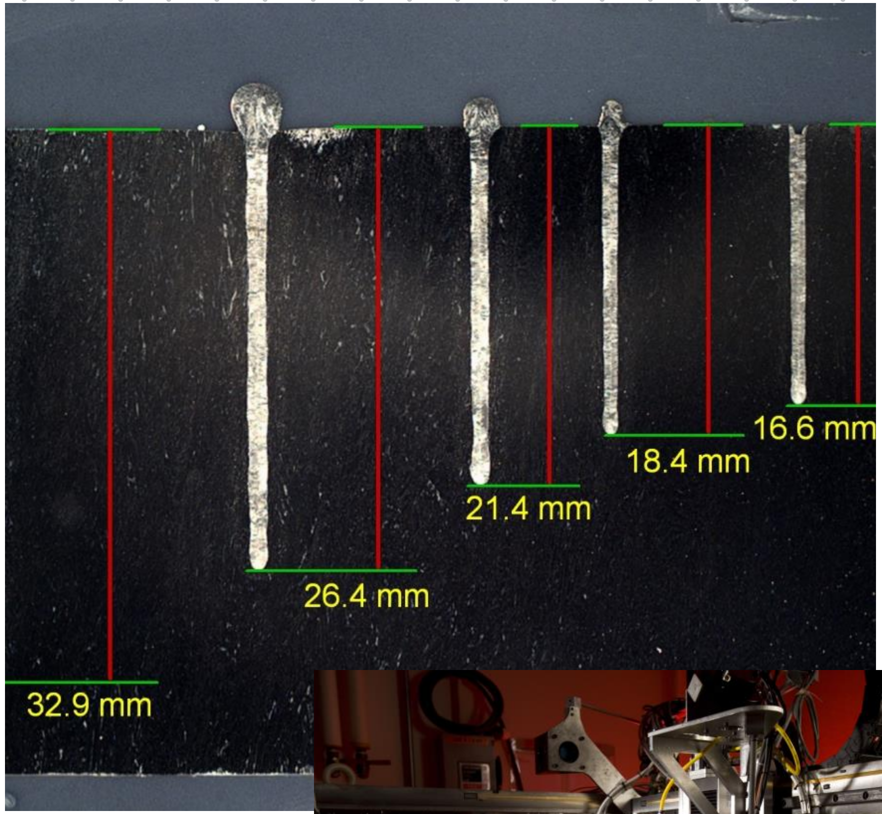
- Five common laser types used in welding
  - Gas (CO_2) – 10.6µm wavelength
  - Solid-state lasers – ~1µm wavelength
    - Nd:YAG
    - Fiber
    - Disk
    - Diode
- Solid-state lasers can be fiber optically delivered while CO_2 requires hard beam paths (mirrors and tubes).
  - Wavelength is the determining factor for fiber deliverability.
- Power levels >100kW available, but <10kW are most common.

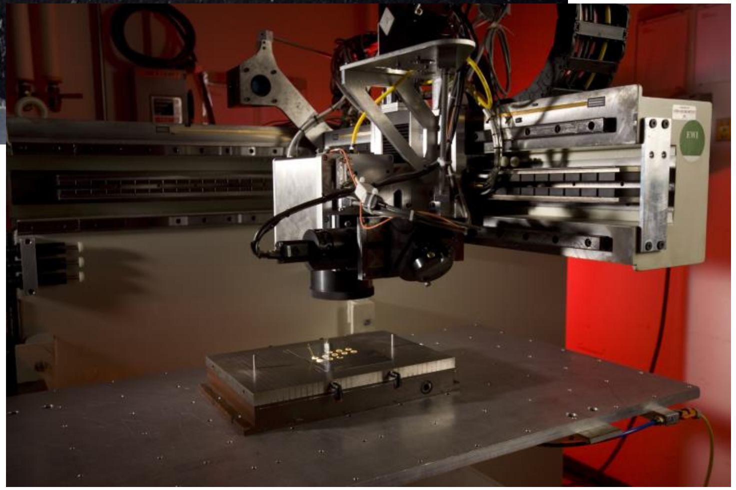
HED Advantages and Disadvantages

- Advantages compared to arc welding processes
  - Low overall heat input results in lower distortion and a small heat affected zone (HAZ)
    - Less detrimental effects to material properties
  - Fast single-pass weld speeds possible
    - Up to 10 m/min: Multi-mode fiber laser
    - Up to 1 m/s: Single-mode fiber laser
  - Non-contact processes, no tool or electrode wear
  - No filler metal required with accurate fit-up and joint positioning
- Potential disadvantages
  - Accurate joint positioning and fit-up required
  - High equipment cost
  - Must be automated or semi-automated
  - Safety concerns

Laser Beam Welding for Batteries

- High-speed welding
  - High-power density allows for high speed
- High cooling rate
  - Metallurgical effects: In crack-susceptible materials and dissimilar metals, high cooling rates can minimize or eliminate the formation of brittle intermetallics
- Small spot sizes
  - Precise Cutting Ability
  - Very directed energy input
- Widely used
  - Medical implantable devices
  - Electronics





Arc Welding

Using plasma to join metal

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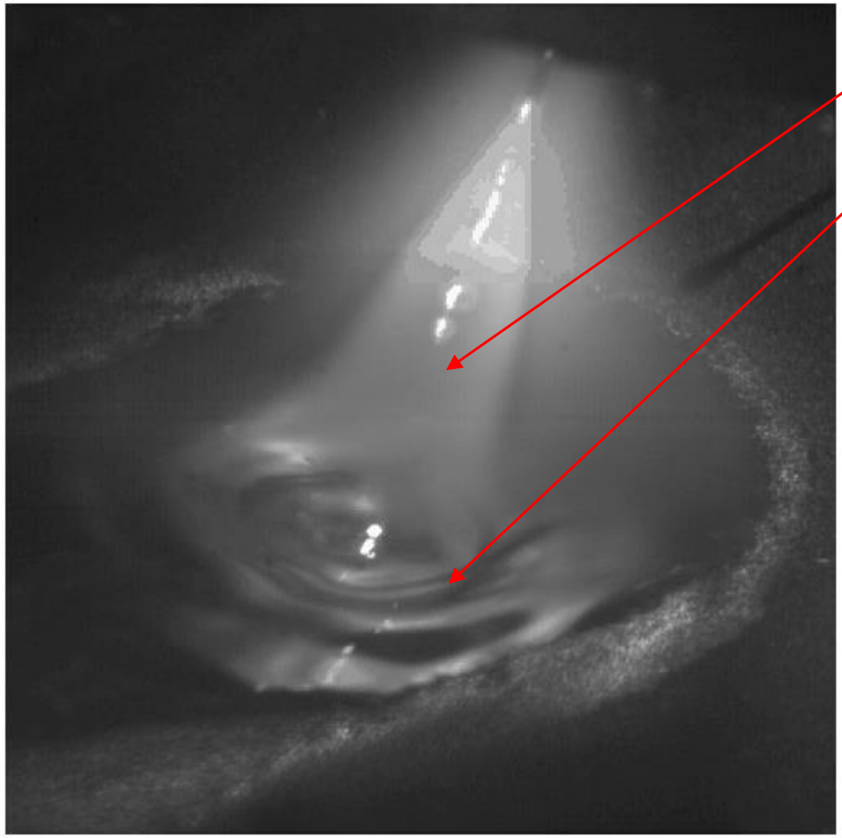
Non-High Energy Density Welding

GMAW Spray Mode



- Arc plasma can exceed 15,000 K
- The base metal and filler wire will reach basically only the melting point of that metal
- The energy of the plasma is spread out over a large area
- High Energy Density processes focus their energy to small points and can create boiling and vaporization of the metal

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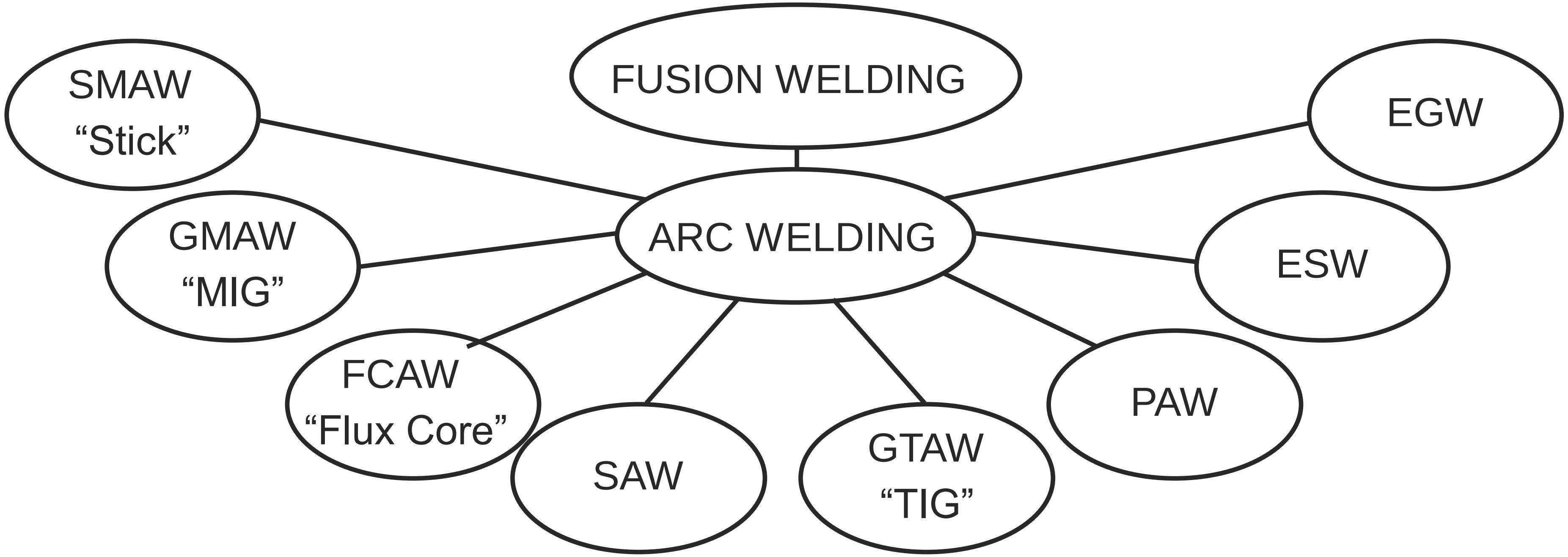
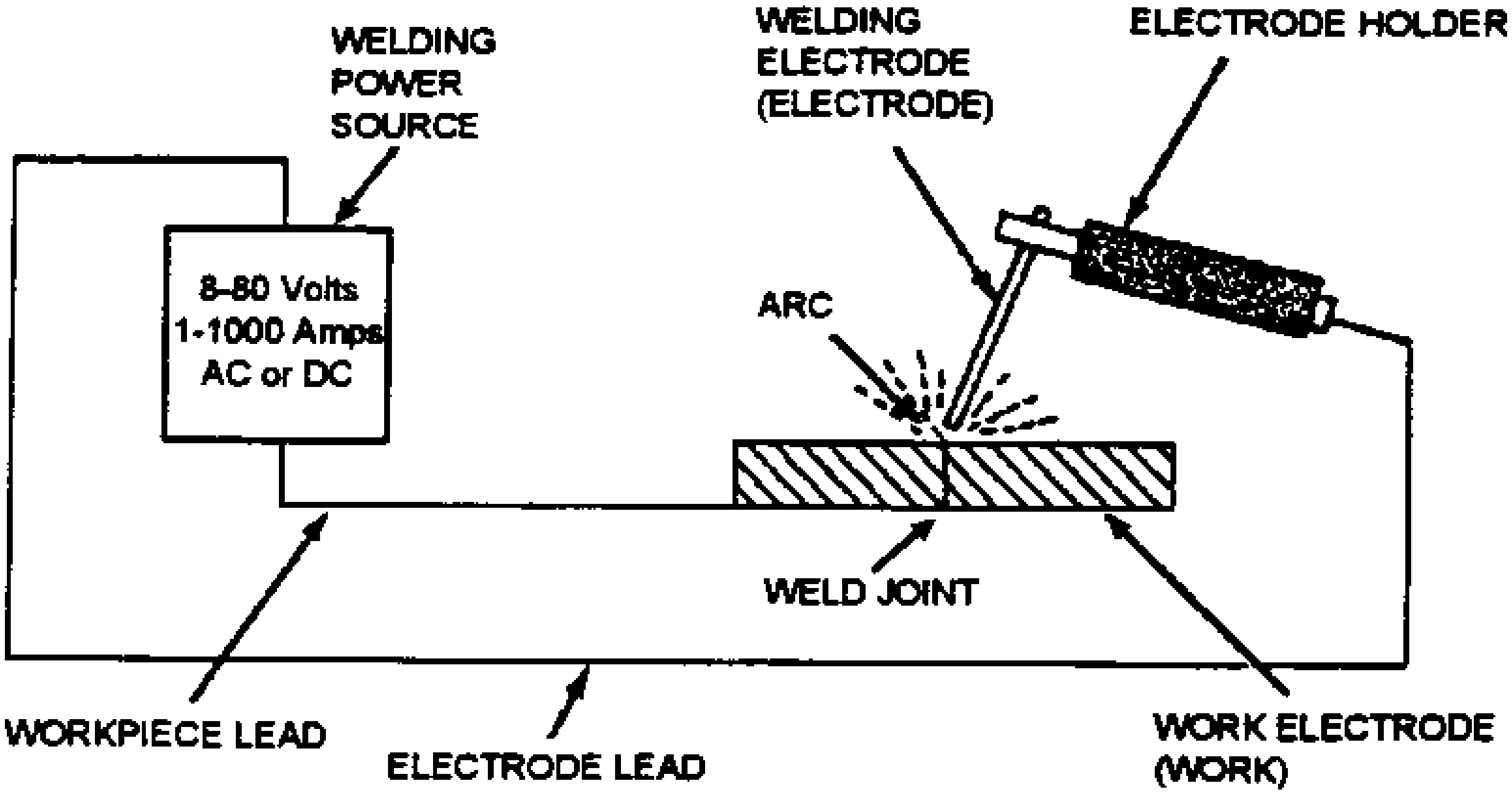
Process Definition

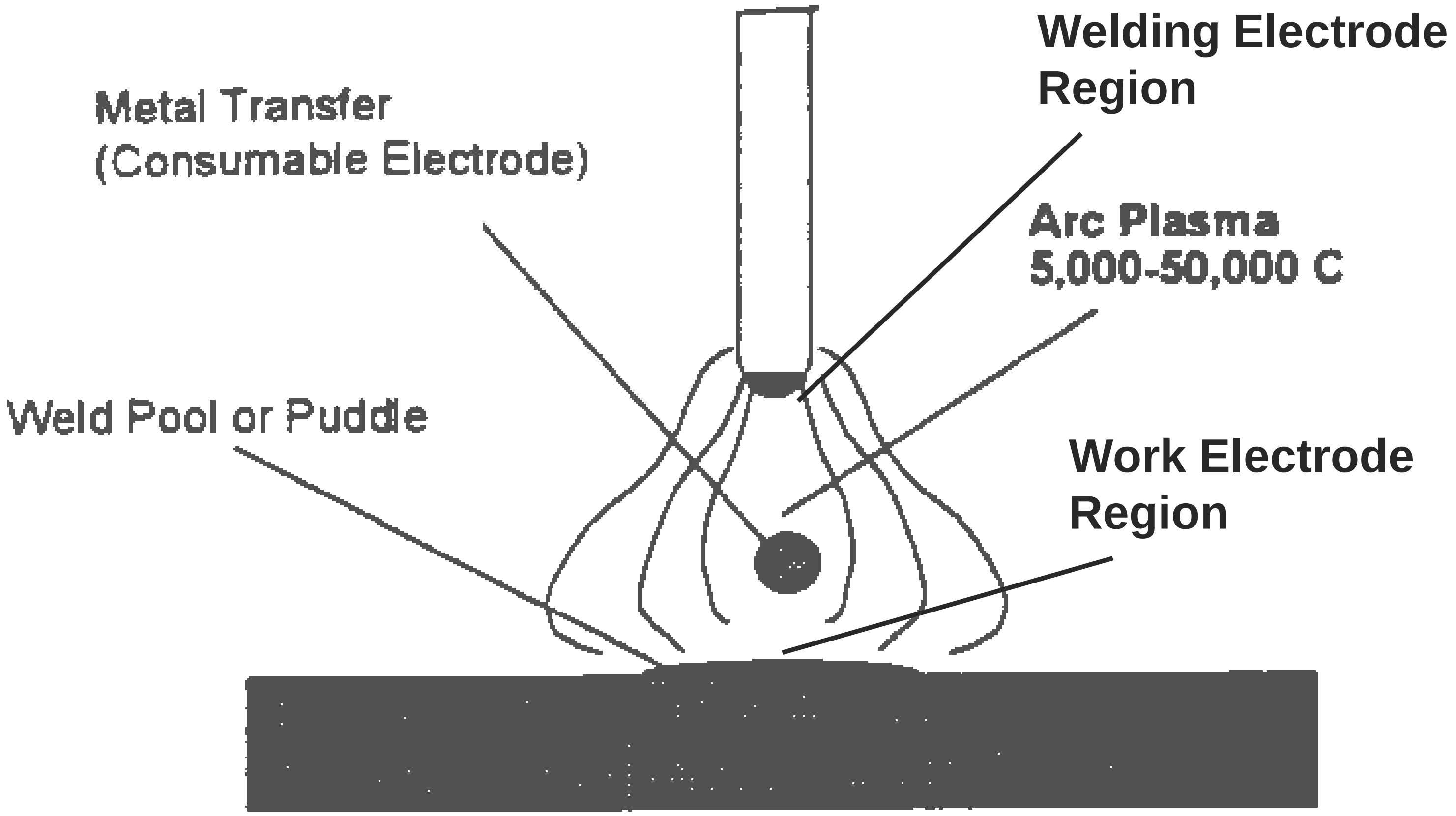


- Upper: Standard terminology - AWS
- Lower: Commonly used trade names

Basic Arc Welding Circuit



Welding Arc


Welding Electrode
Region
Metal Transfer
(Consumable Electrode)
Arc Plasma
5,000-50,000 C
Weld Pool or Puddle
Work Electrode
Region

Arc Voltage

- Affects concentration of arc heat
  - Shorter arc, more heat concentration
  - Longer arc, less heat concentration
- Voltage can be regulated to control arc length
  - Low voltage levels result in a short arc length
  - High voltage levels result in a long arc length
- Varies little with arc current and welding speed
  - Has little effect on energy input and amount of melting
- Typical arc voltages: 8 to 40 V

[1]

[1] “Arc welding,” *Wikipedia*. May 20, 2022. Accessed: Oct. 23, 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Arc_welding&oldid=1088790273c

Arc Current

- Mainly affects amount of arc heat
- Determines electrode melting rate (consumable)
- Directly affects energy input to work and melting
  - More current, more melting
  - Less current, less melting
- Often regulated to control arc and energy input
- Arc currents: 1 to 1000 A
  - More typically, 50 to 500 A

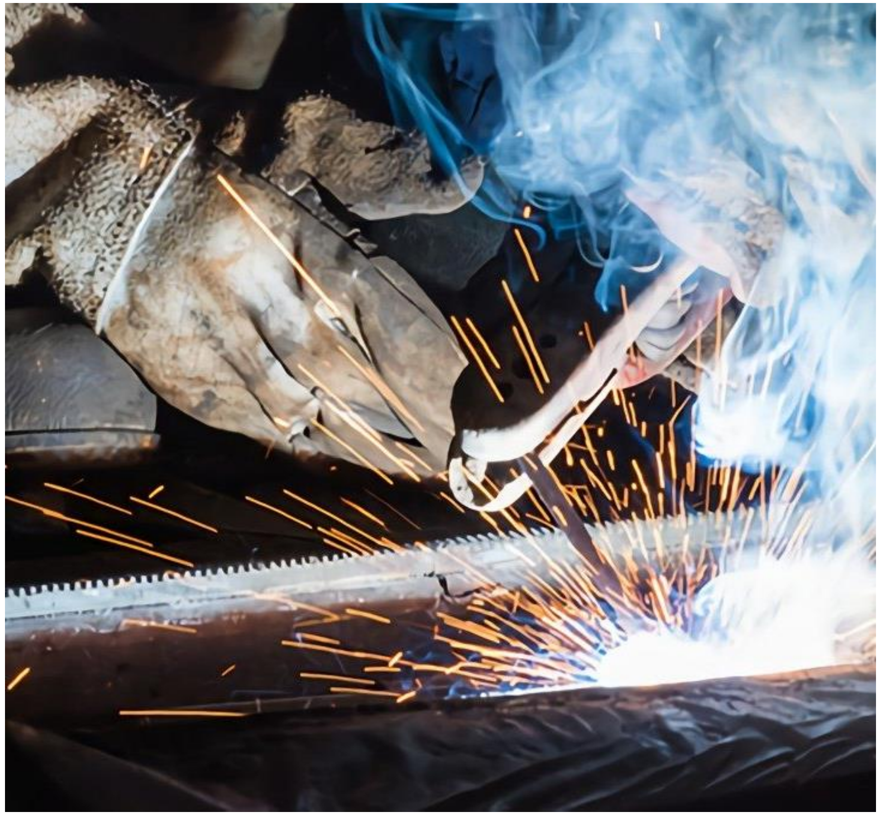
[1]

[1] “Arc welding,” *Wikipedia*. May 20, 2022. Accessed: Oct. 23, 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Arc_welding&oldid=1088790273c

Electrode Feed Rate

- Applies to wire fed welding processes
- Directly determines amount of metal deposited
- Closely related to current
  - Current must provide equal melt-off rate
- May be supplied manually or via an automatic feed system
- Typically, 10s to 100s ipm

[1]

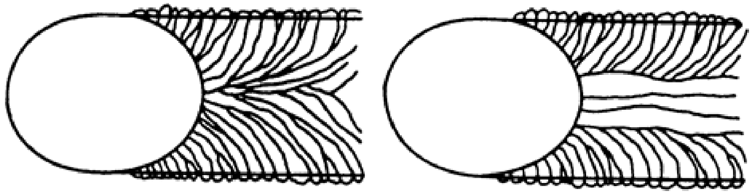


[1] O. Nguyen, "Different Types of Arc Welding," *Tulsa Welding School*, Oct. 10, 2017. https://www.tws.edu/blog/welding/different-types-of-arc-welding/ (accessed Oct. 23, 2022).

Welding Travel Speed

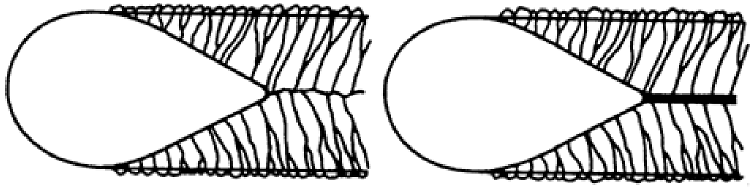
- Has little effect on arc and electrode melting
- Directly affects metal deposition per length of weld
- Mainly affects energy input to work
  - Faster travel, less energy input and base metal melting
  - Slower travel, more energy input and base metal melting
- Important productivity parameter
- May be provided manually or mechanized
- Typical range is 5 to 100 ipm

Elliptical pools



- High heat input, low travel speeds and 3-D heat flow conditions.
- Materials with high thermal conductivity, such as Al & Cu, form elliptical weld pools over a wide range of conditions.

Teardrop pool



- Rapid travel speed, low thermal conductivity and 2-D heat flow
- Austenitic stainless steels and nickel-based alloys often exhibit teardrop shape pools when welded in thin sheet form at high travel speeds.

Pulse Welding

- Electric arc welding processes typically rely on a consistent current or voltage to maintain the arc and heat the metals. Current continuously fluctuates from low to high.
- Pulse TIG welding
  - Operator controls the amperage output with a foot pedal
  - Torch pulsed waveform instead of a steady stream of electrical current.
- Pulse MIG welding,
  - Quick, high-current pulses at the work
  - Filler metal is transferred from the electrode to the weld puddle without contact
  - One droplet of molten metal is formed per each pulse

Pulse Welding Advantages and Disadvantages

- Advantages:
  - Pulse welding on thin metals reduces the risk of burn through
  - Lower the overall heat generated while working
  - Higher control in tight spaces
- Disadvantages
  - Melting cause recrystallization and microstructure change
  - Produces most heat out of all the process
  - Requires filler materials and often shielding gas

Micro TIG Welding for Batteries

[1]

- Very new technique
- Tabs and busbars to the cylindrical cells and tabs from prismatic batteries.
- Copper-to-nickel plated steel and nickel-to-nickel plated steel has shown promise
- Minimizes the HAZ and the risk for damage to the cell
- Good peel strength results
- Real promise in dissimilar materials joining were other techniques fail

[1] “Battery Copper Tabs,” *Sunstone Welders*. https://sunstonewelders.com/applications/battery/micro-welding-copper-battery-tabs/ (accessed Oct. 23, 2022).

New technology areas

See what's coming next

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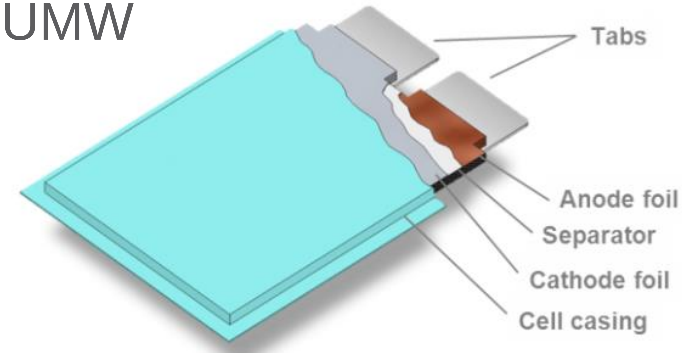
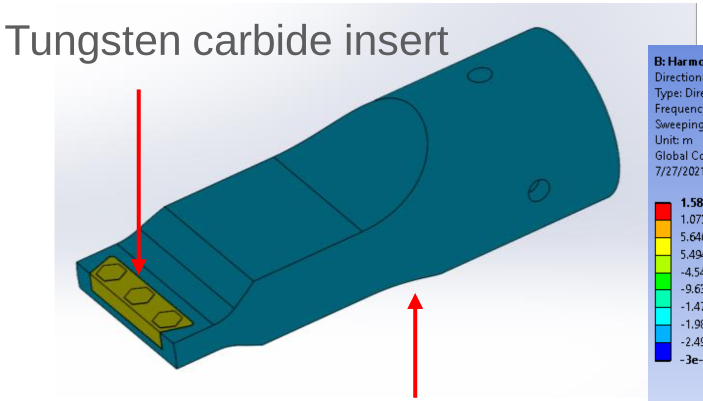
Development of Sonotrode with Replaceable Knurl Pad for use in Ultrasonic Metal Welding (UMW)

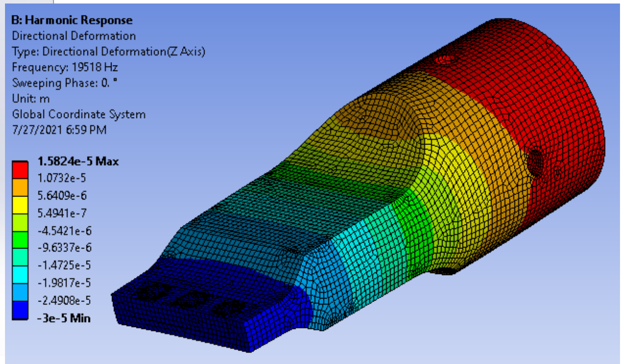
- One of the main welding process to manufacture lithium-ion batteries is UMW
- One of the challenges of UMW → Knurl pad wear
- EWI used FEA to develop sonotrodes with a replaceable knurl pad from wear resistant material which can:
  - Reduce tool cost and associated maintenance cost
  - Reduce machine downtime



Lithium-ion Pouch Style Cell Cutaway (Source: EWI)



Alloy Steel Sonotrode



Finite Element Analysis

Manufactured Sonotrode

Sonotrode Characterization and Testing

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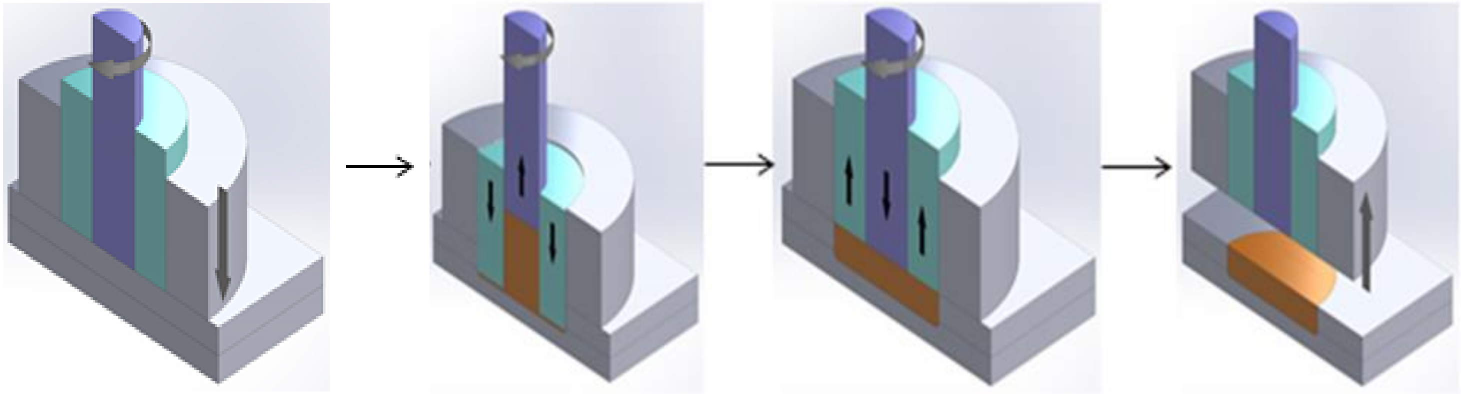
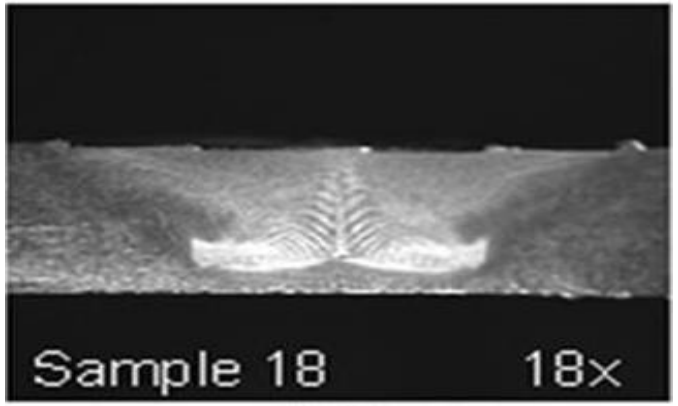
Refill FSW Process Overview

- Refill friction stir spot welding still uses a pin and shoulder, but they move independently.
- This allows the tool to displace, stir, and then replace the material, leaving a perfectly flush surface
- If the shoulder is plunged first, this also leaves a bigger weld cross section (better mechanical properties)
- The entire stir zone contributes toward the strength of the weld.

Friction Stir Refill Spot Weld

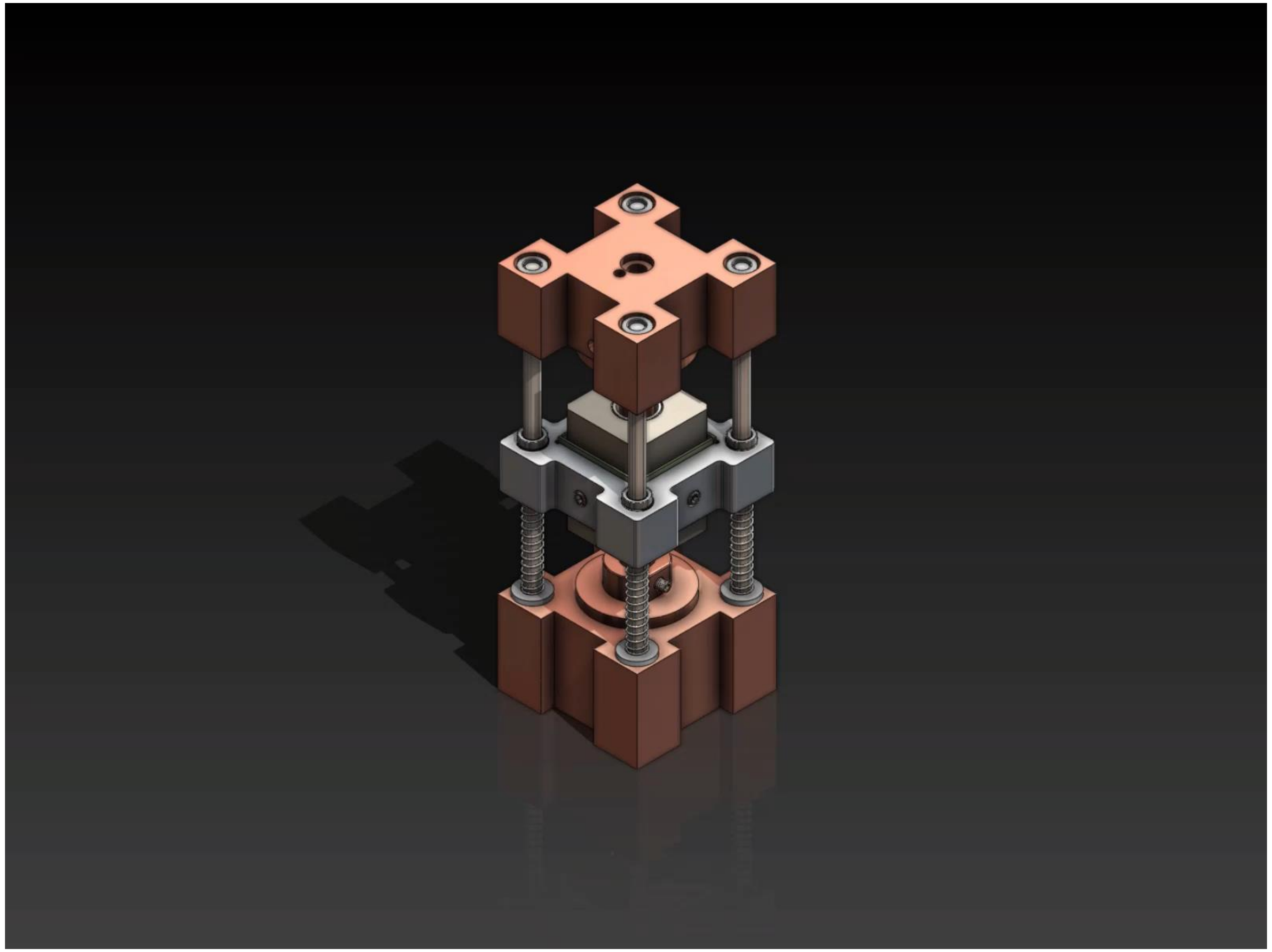




Images Courtesy of SDSMT

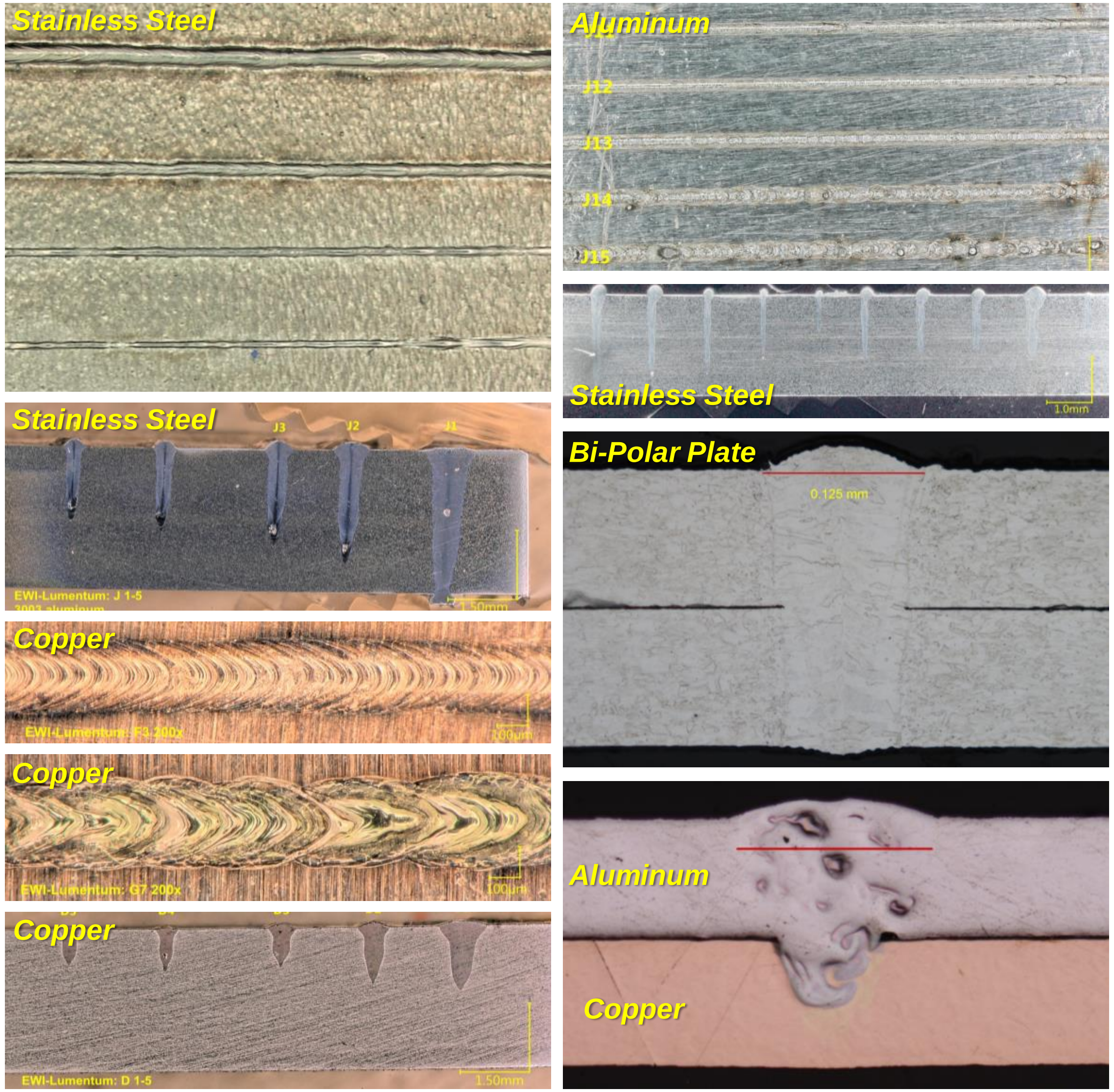
Resistance-Based Sintering

- Combining precision sintering with automotive speed
- Based on the idea of resistance heating and particle to particle projection welding
- Each powder particle acts like a projection and concentrates the current to create heat
- Allows sintering in less the 5 sec
- Success in Ti, Al, Cu and more to come



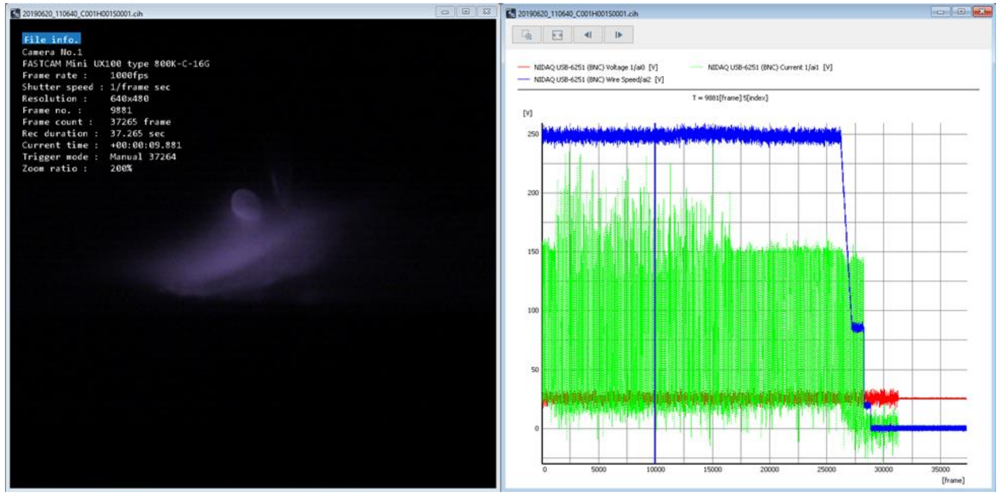
Emerging Laser Sources for Electrification Applications

- **Dissimilar metals:**
  - Creates metallurgical issues
  - Fatigue
  - Corrosion issues
- **Objective:** Use new, emerging laser sources to conduct experimental laser welding trials in order to establish baseline process parameters, evaluate weld quality, and leverage results for future applications.
- laser sources for sheet welding in electrification applications.
- Project was successful in proving lasers were capable of achieving all the alleged benefits and advantages for welding:
  - Reduced spatter
  - Smoother bead surfaces
  - Higher travel speeds
  - Enhanced performance on reflective materials
  - Freedom from some forms of welding solidification defects



EWI's Synchronized High-Speed Video and Data Acquisition System

- EWI has added to it's weld monitoring capabilities with a synchronized high-speed video and data acquisition system for advanced weld process monitoring and waveform analysis
  - The system utilizes a Photron FastCam Mini UX 100 camera integrated with a Cavitar Cavilux HF laser for process illumination capable of recording at 200,000 frames per second
  - The system is also integrated with a Texas Instruments data acquisition unit which records process amperage, voltage and wire feed speed



Questions?

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