Joining II

Processes and Types

Importance of Assembly and Joining

Why focus on Assembly?

parts: 1 4

Approximate Number of Parts in Products

Common pencil	4
Rotary lawn mower	300
Grand piano	12,000
Automobile	15,000
Boeing 747–400	6,000,000

Assemblies actually do things customers want

Get it Right the First Time…

TABLE 1.5

Relative Cost of Repair at Various Stages of Product Development and Sale

Stage	Relative cost of repair
When the part is being made	1
Subassembly of the product	10
Assembly of the product	100
Product at the dealership	1000
Product at the customer	10,000

"The Multiplier" According to Ford and GM or: Why Is DFM/DFA Important?

- For every product part, there are about 1000 manufacturing equipment parts*
- Or, for every toleranced dimension or feature on a product part, there are about 1000 toleranced dimensions or features on manufacturing equipment
- Such "equipment" includes fixtures, transporters, dies, clamps, robots, machine tool elements, etc

*Note: Ford's estimate is 1000, GM's is 1800. Both are informal estimates.

MIT Prof. Daniel Whitney

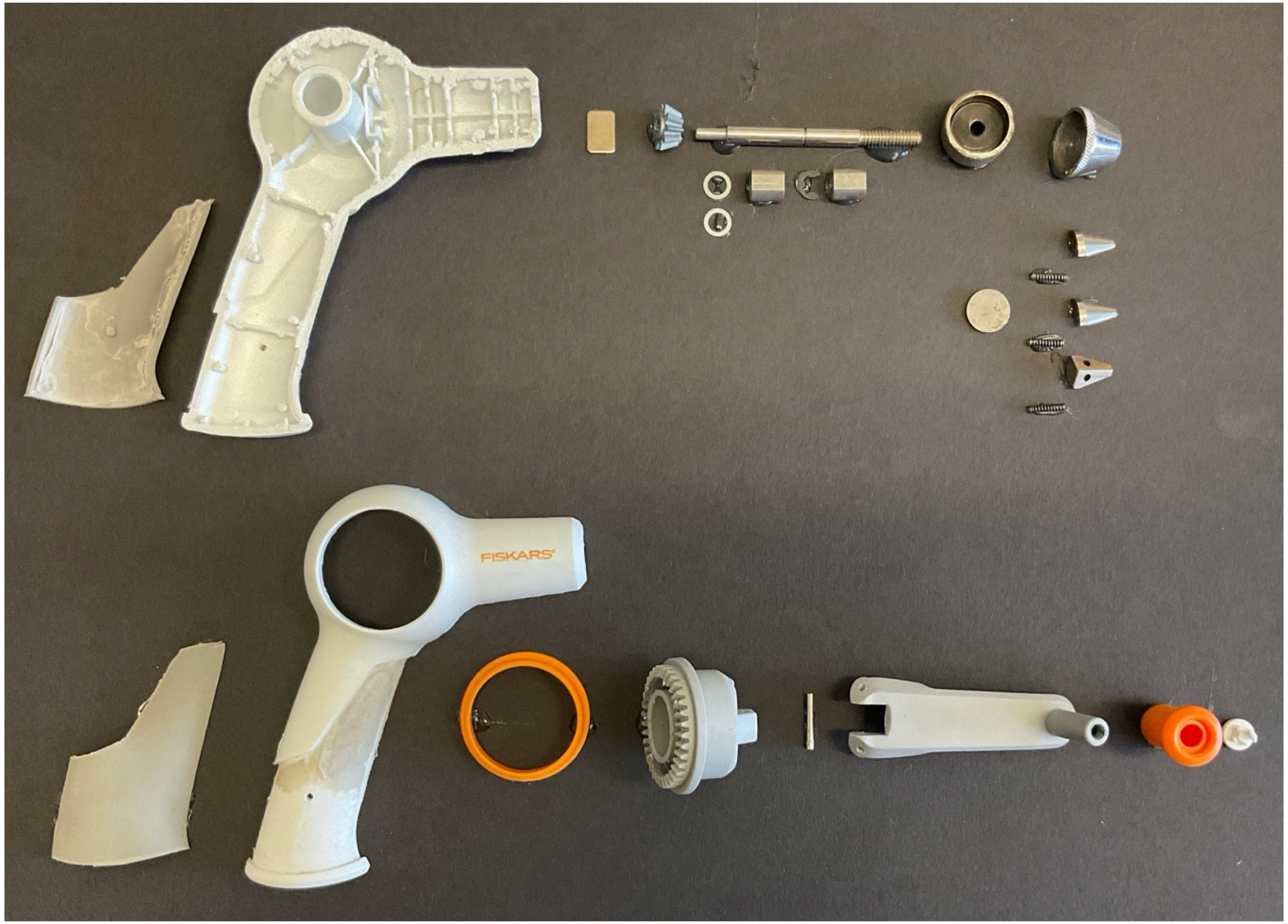
DFA: Design for Assembly

1. Reduce the Part Count

- relative motion
- material properties
- otherwise impossible
- maybe disassembly: for recycling

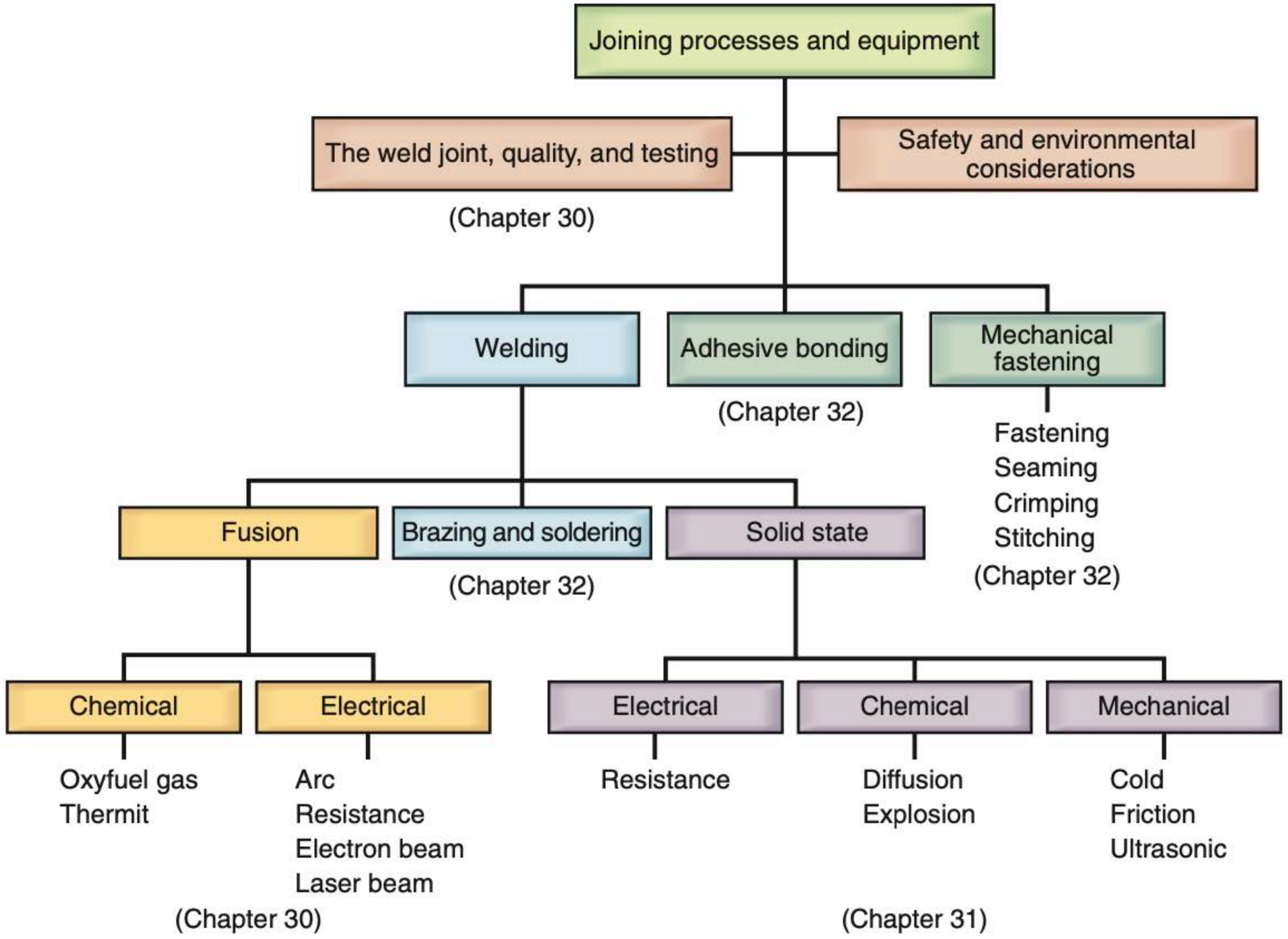
2. Make Each Part Easier to Assemble

Note: parts still need to be manufacturable (DFM still applies: DFMA)



Process Planning: Your “Well Orchestrated Dance” Plan

which manufacturing methods + joining methods (plus all of the logistical details to make it happen)



Selection Criteria

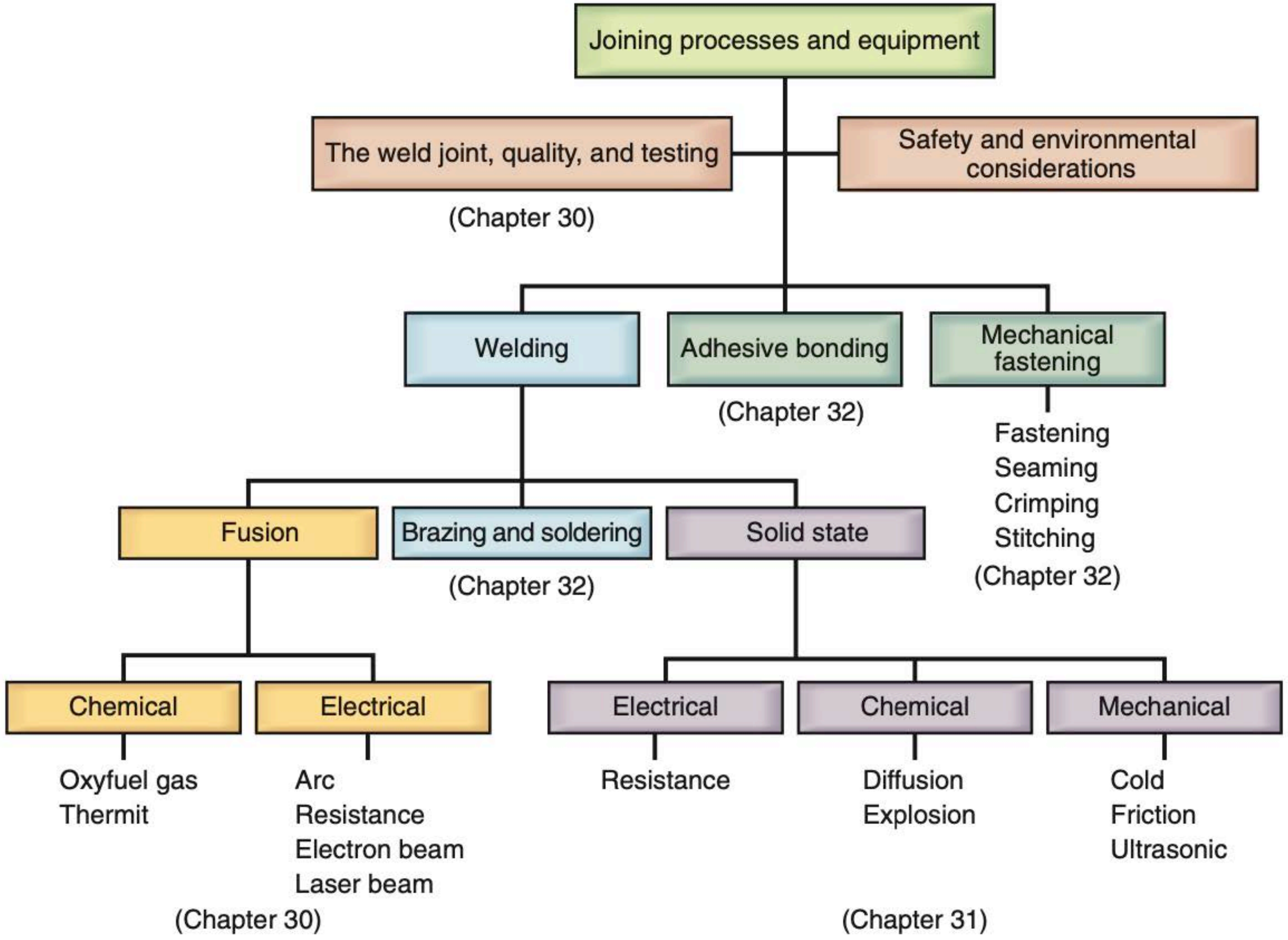
- geometry (sheet example)
- material type
- size of production run
- value of end product

car: $40k for 4,000lbs: ~$10/lb

airplane: $1,000/lb (sensitive to weight increase)

satellite: $10,000/lb

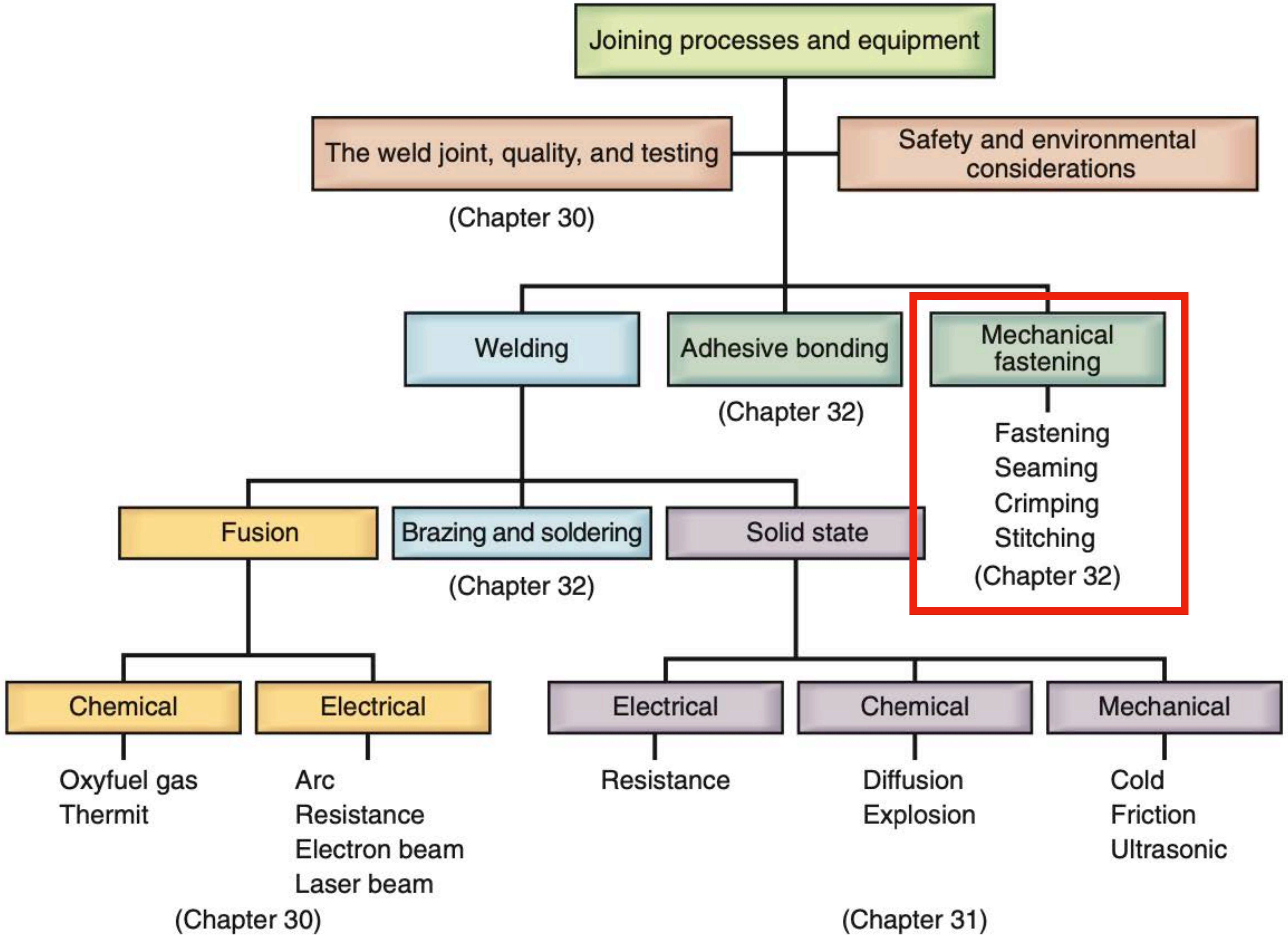
Joining Processes



Design for Joining

- design parts with that joining method in mind
- ease of locating/aligning (self-location, self-alignment)

Joining Processes



Mechanical Fastening

Mechanical Fastening

Type of Fasteners

- bolts/screws
  - disassembly/reassembly
  - cross threading
- rivets
  - when disassembly not required
- dowel pins
- cotter pins
- snap fits

Mechanical Fastening

Considerations

- any shape and material
- semi-permanent
- least expensive for low volume
- limited strength and sealing
- increases part count
- assembly can be challenging
- loosen over time

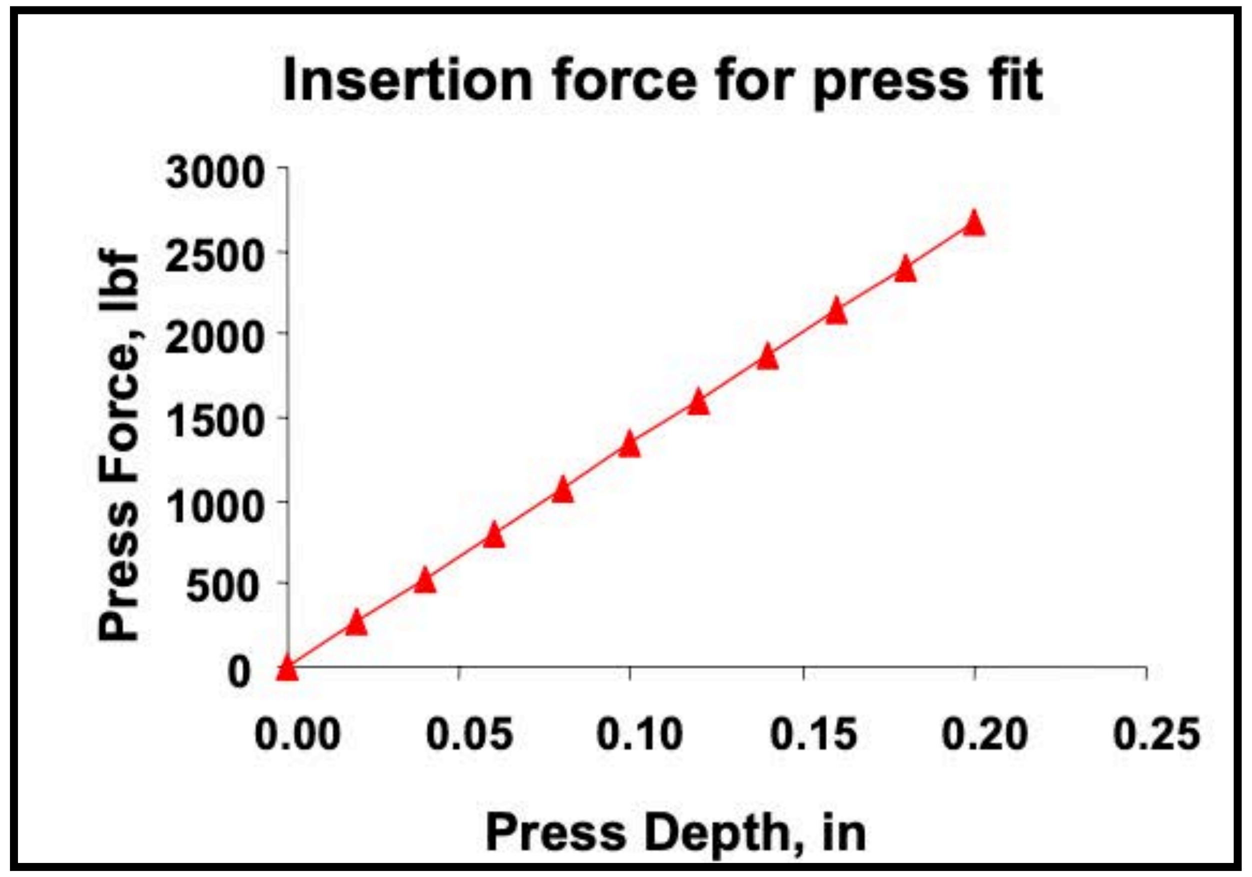
Joining II

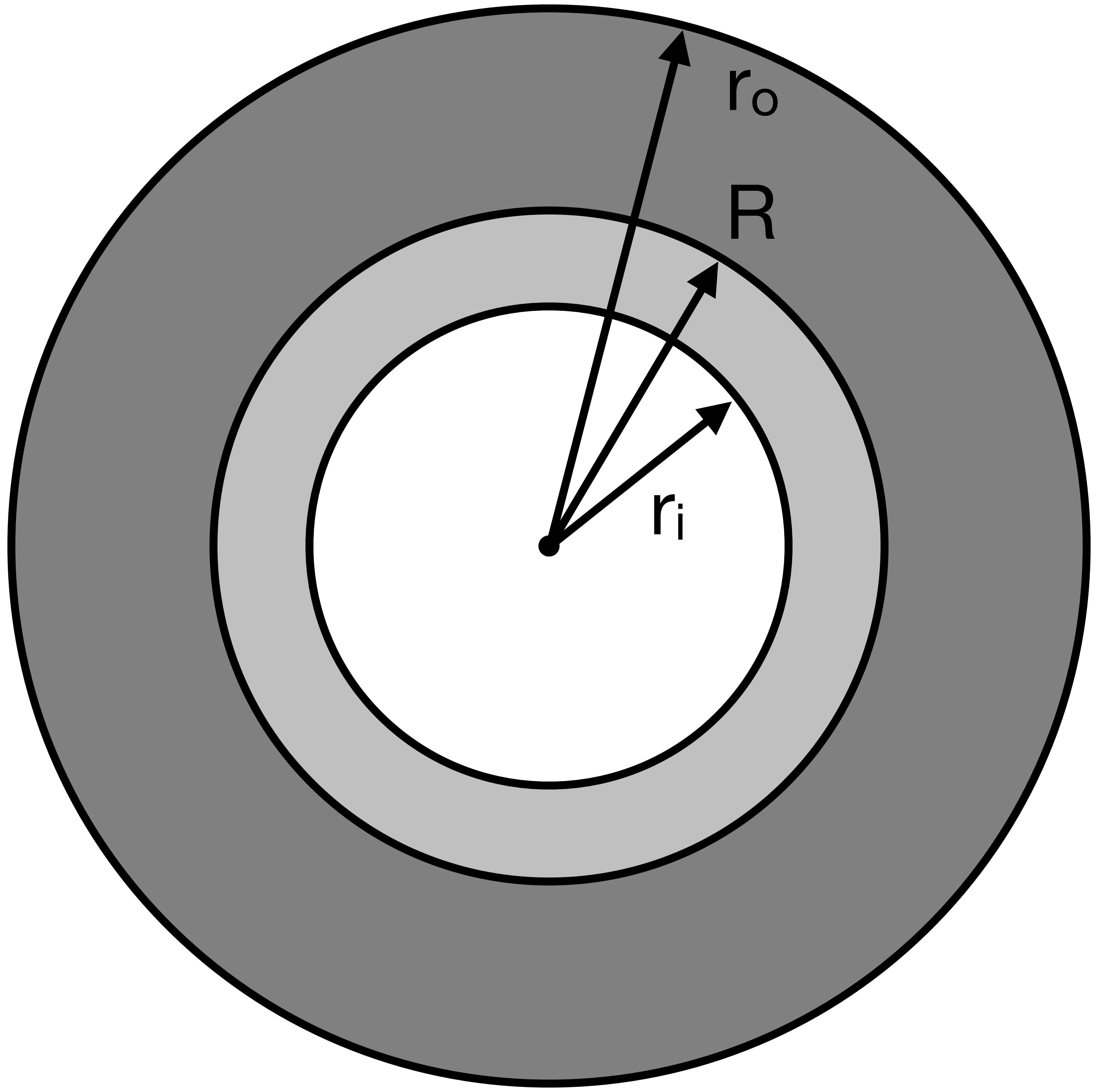
Processes and Types

Mechanical Fastening: Press/Shrink Fits

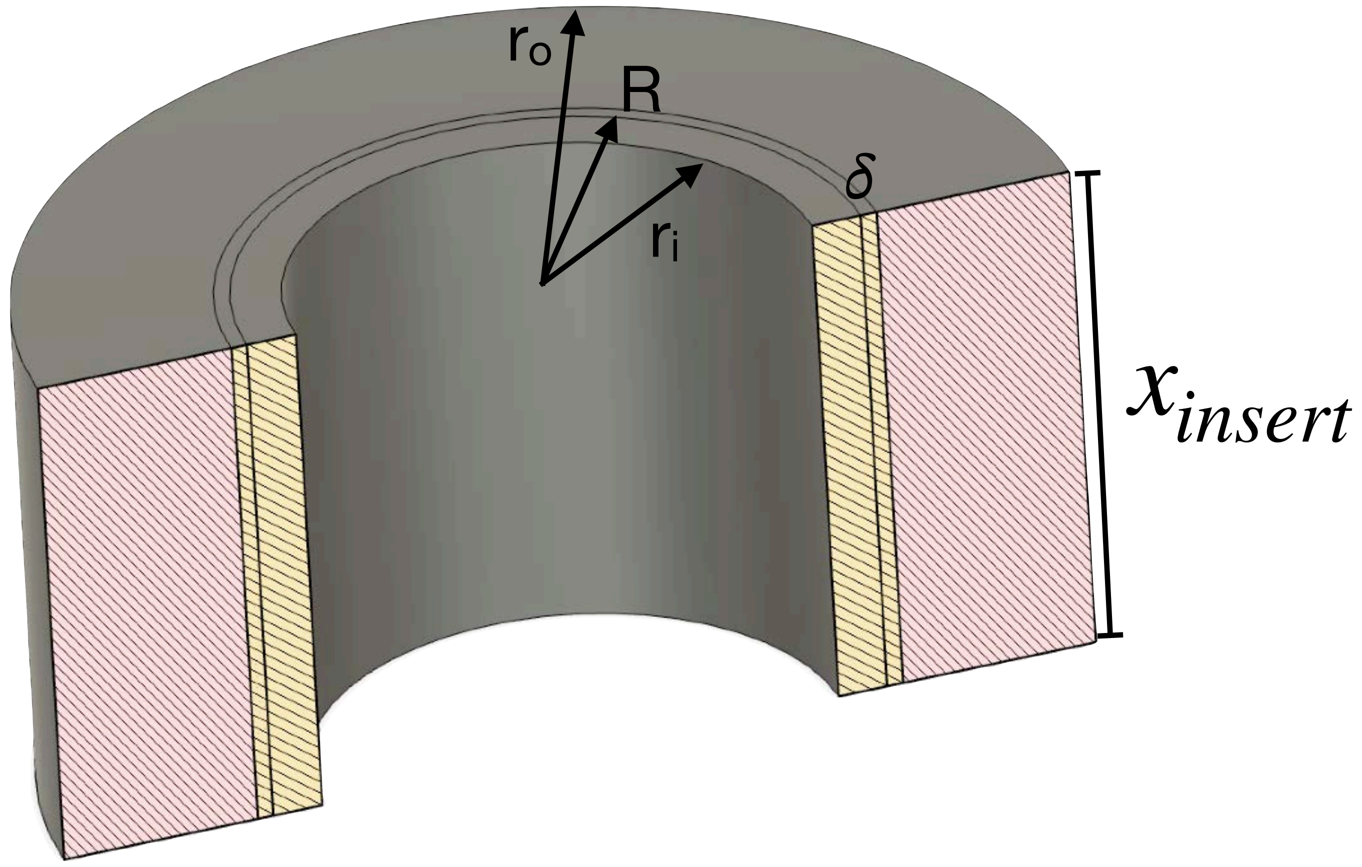
two cylinders of the same length pressed to interfere

or, one body is heated to expand, and then allowed to cool over the other part





$$p = \frac{E}{R}\delta\left(\frac{\left(r_0^2 - R^2\right)\left(R^2 - r_i^2\right)}{2R^2\left(r_0^2 - r_i^2\right)}\right) \rightarrow F_{insert} = \mu p 2\pi R x_{insert}$$



$$\delta_{thermal} = \alpha R \Delta T$$

p: interface pressure, [Pa] or [psi]

E: Young's Modulus, [Pa] or [psi]

δ: radial interference [m] or [in]

α: coefficient of thermal expansion [deg^{-1}] ⚠️

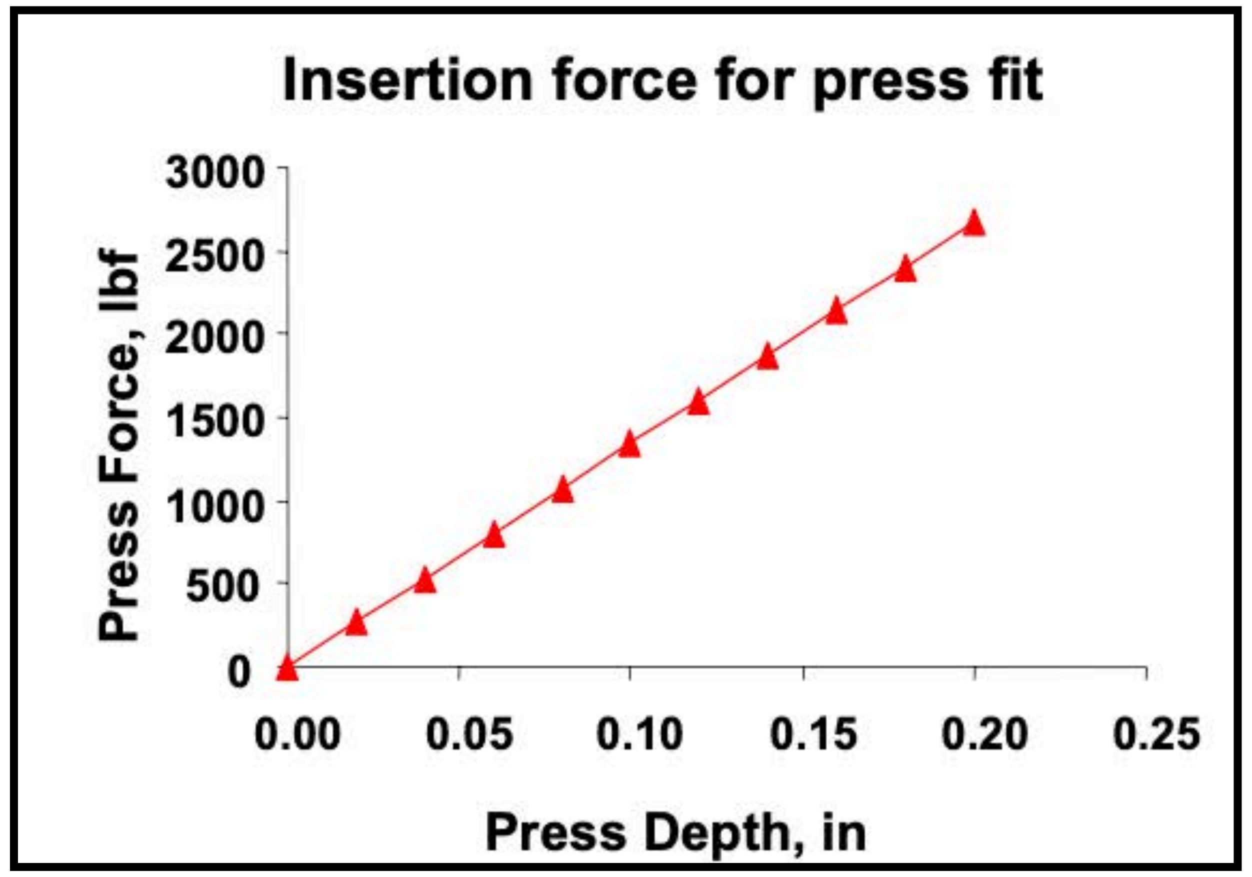
ΔT: temperature change [deg]

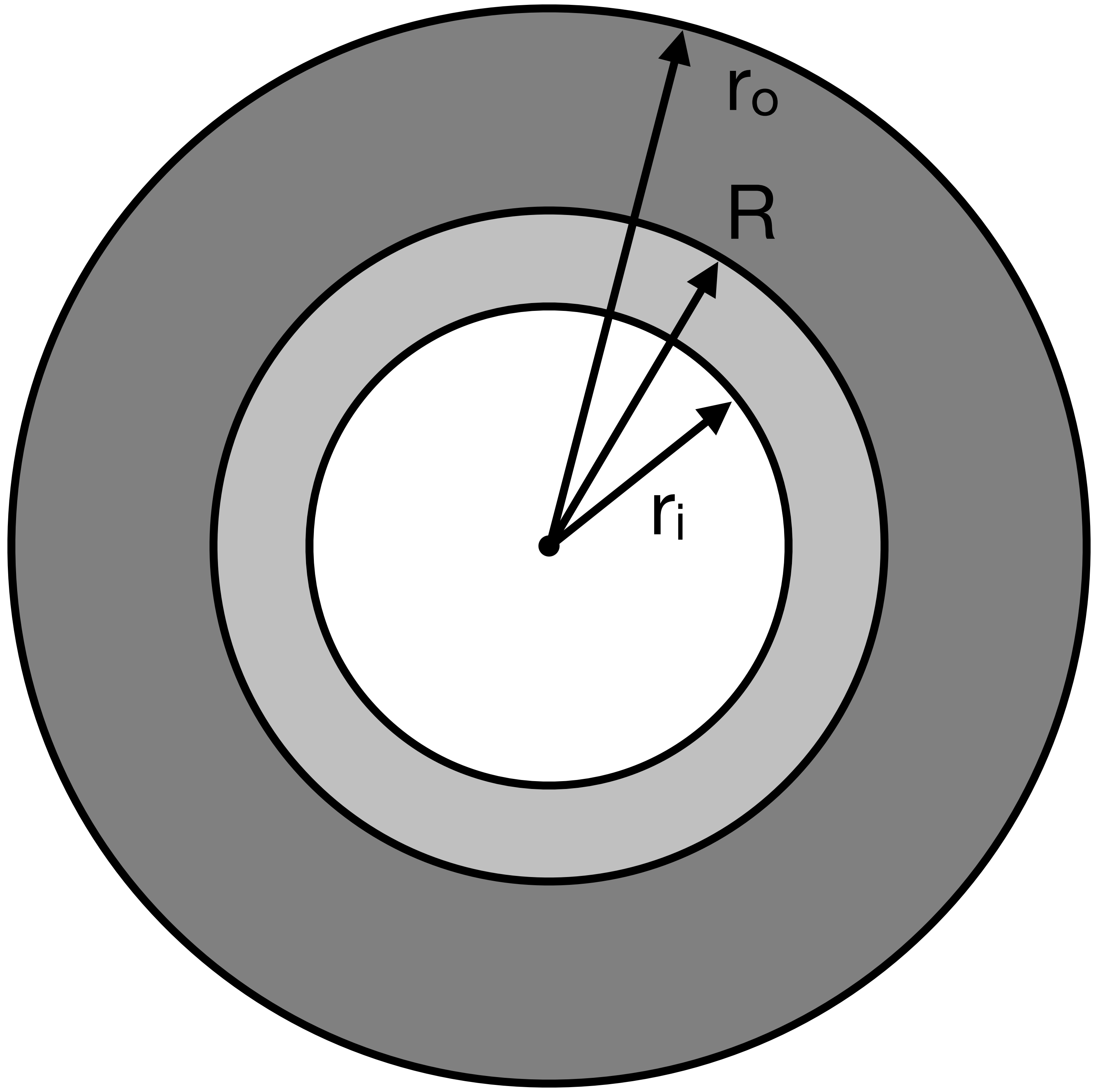
x_{insert}: length of engagement [m] or [in]

Mechanical Fastening: Press/Shrink Fits

two cylinders of the same length pressed to interfere

or, one body is heated to expand, and then allowed to cool over the other part





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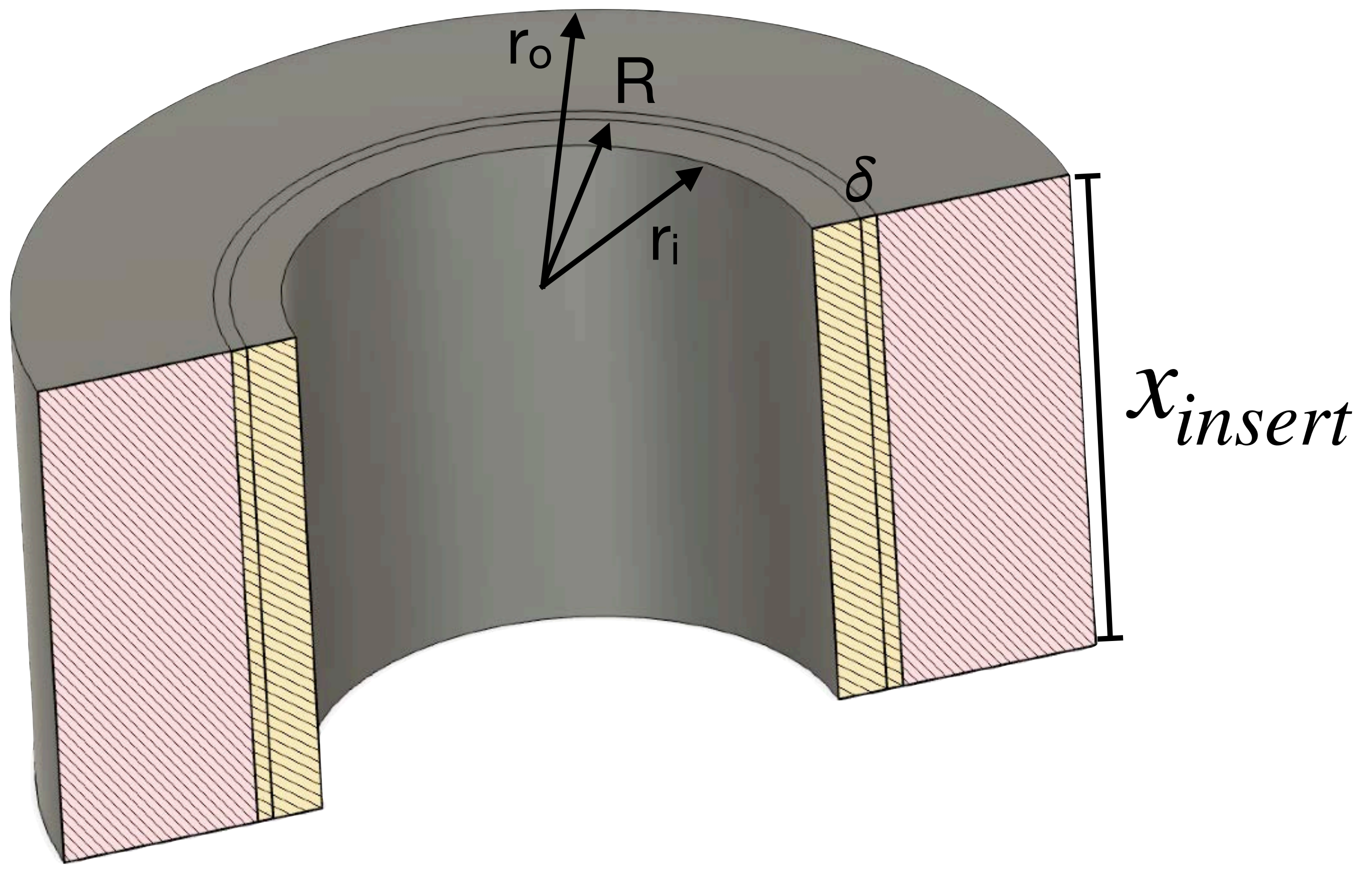
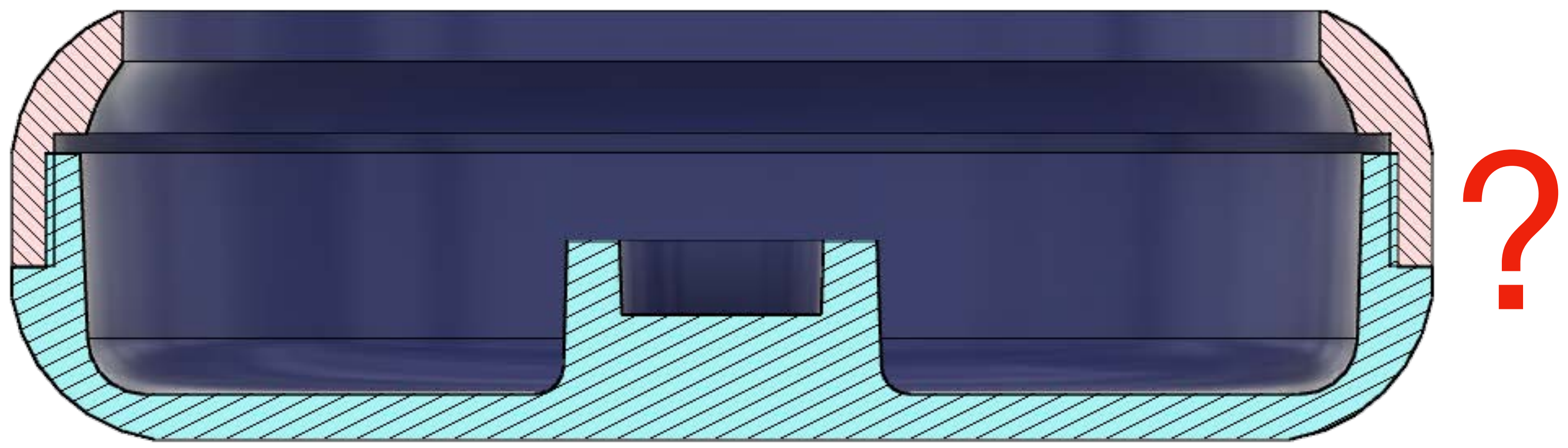
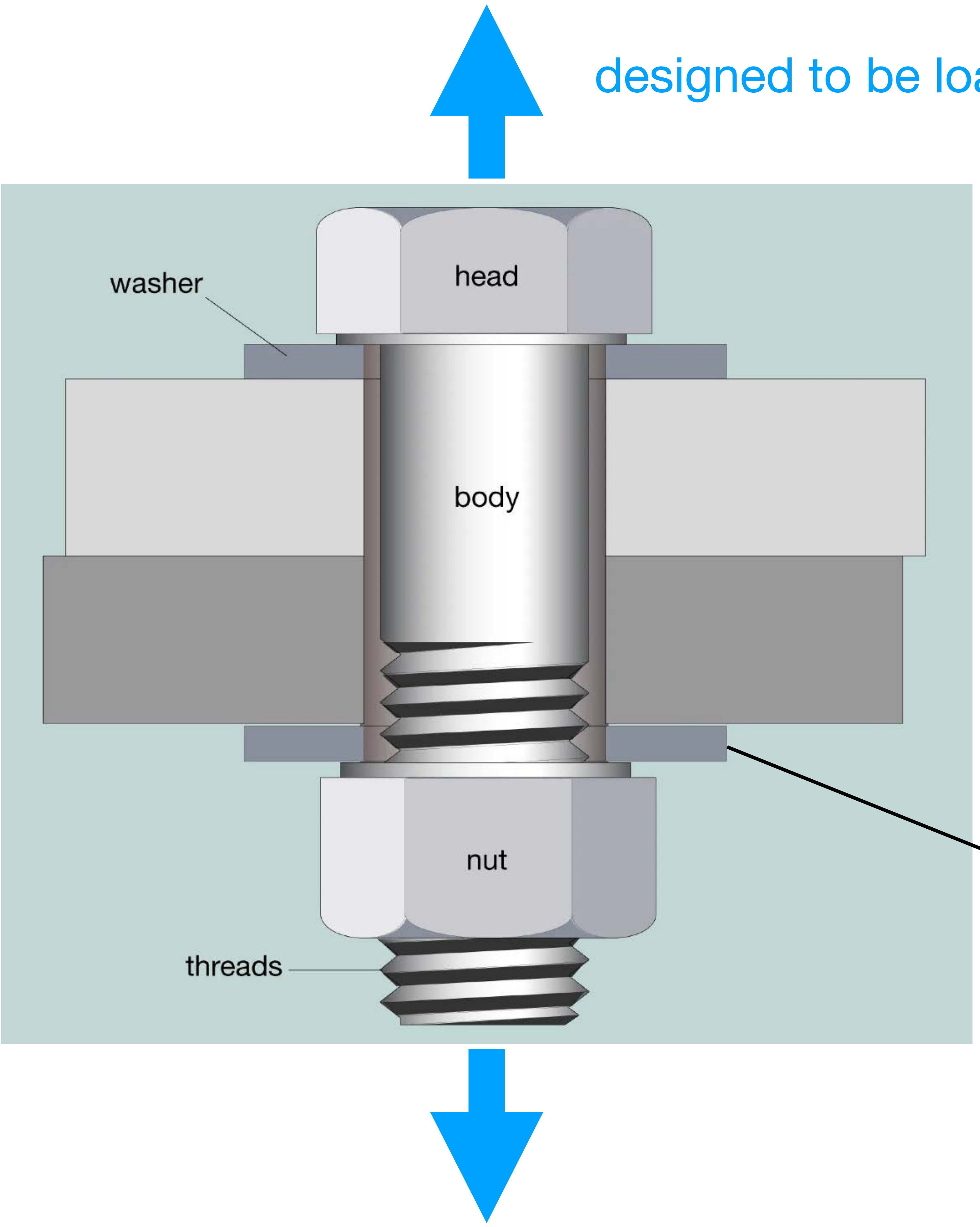




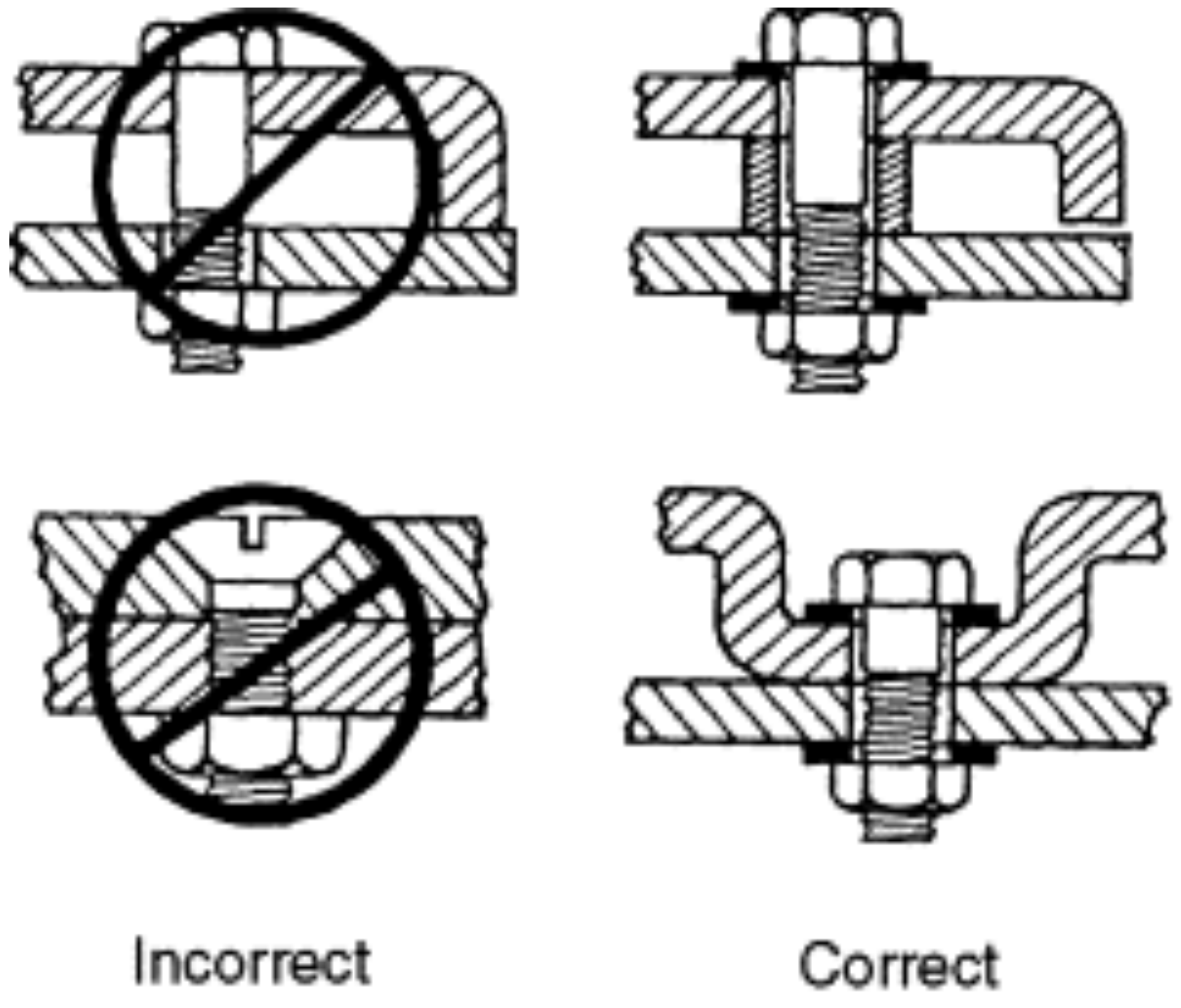
DF: Mechanical Joining

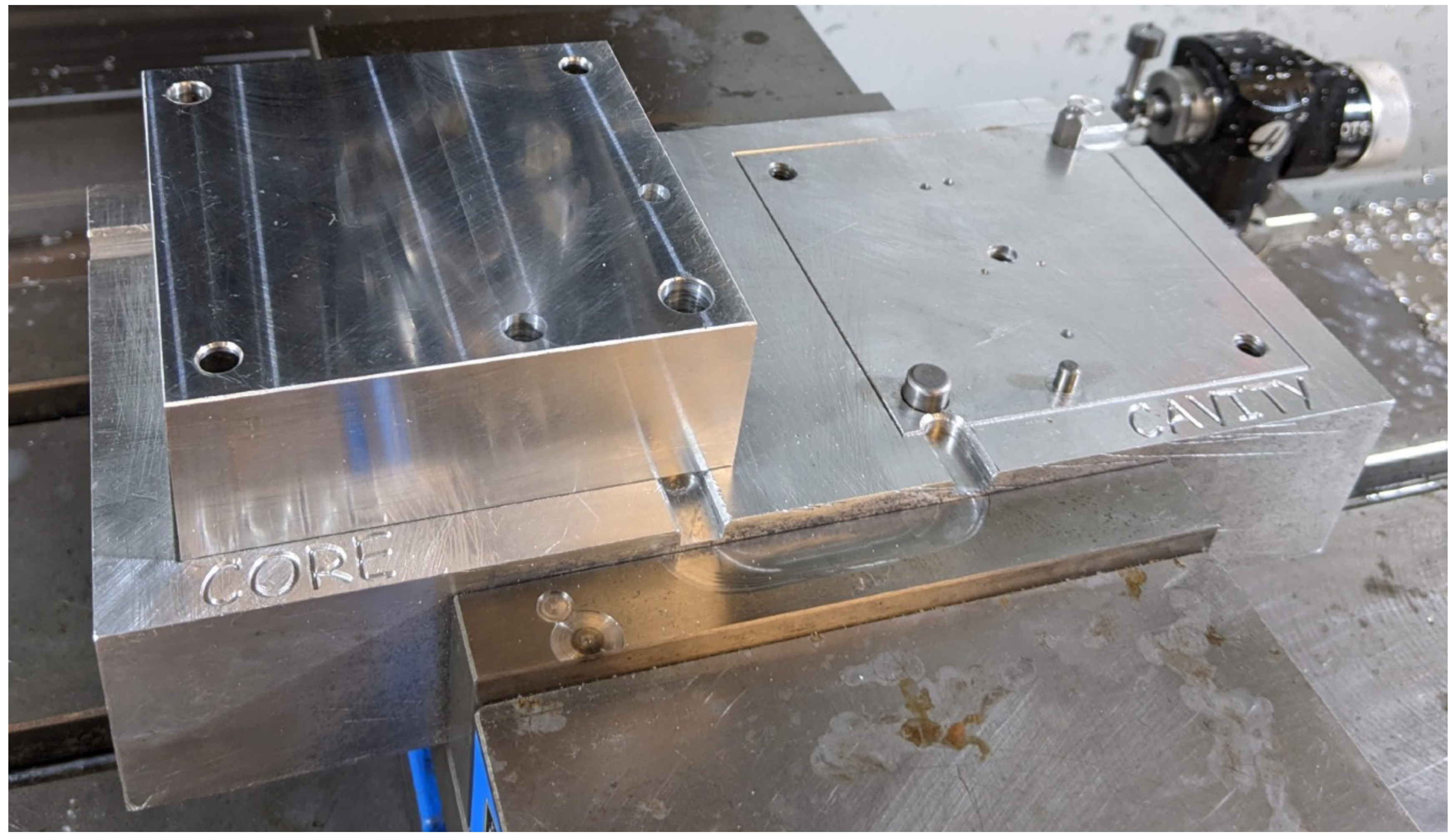
designed to be loaded in tension



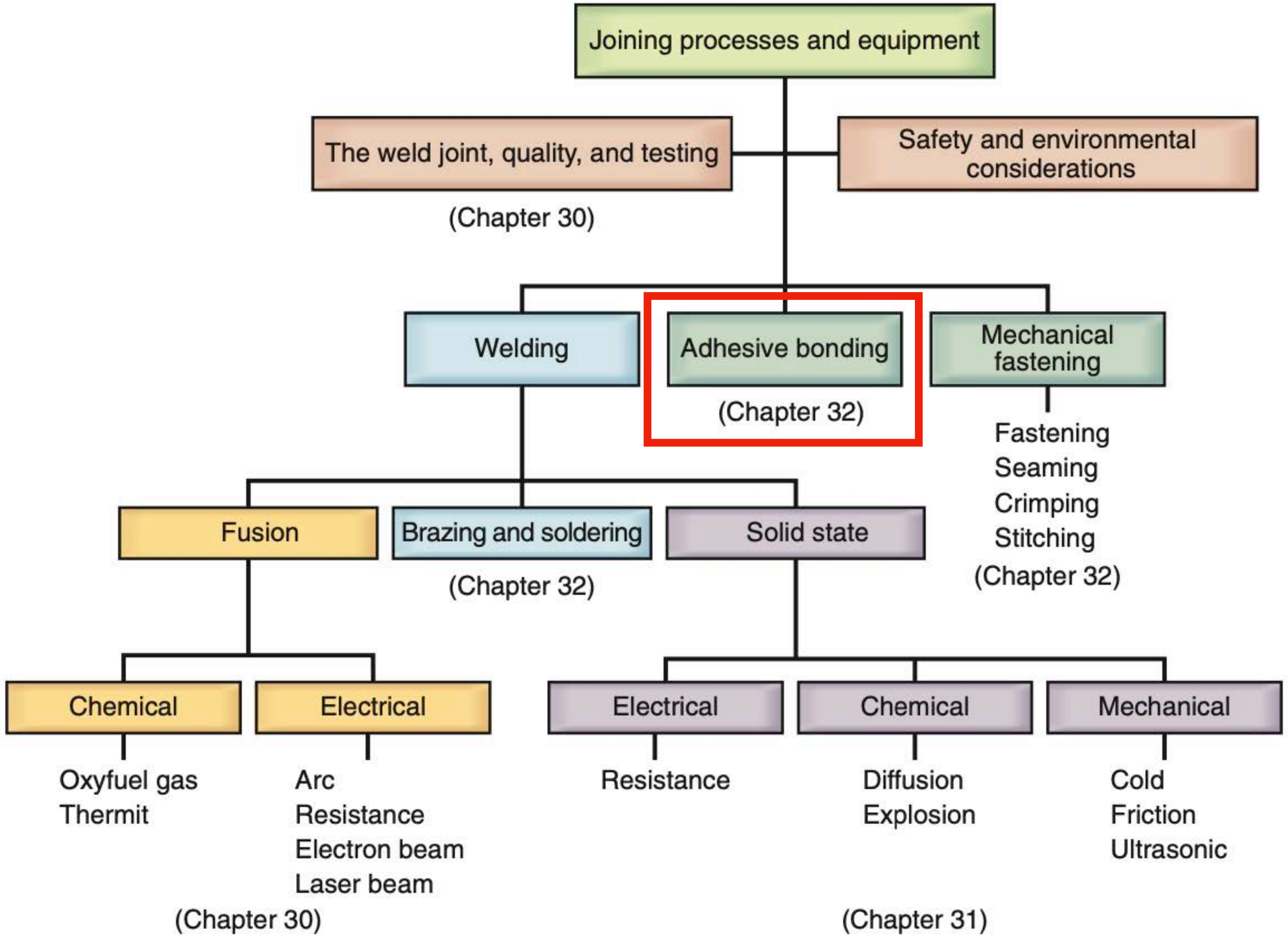
washers: distribute load (can provide locking/preload)

consider how the material is loaded



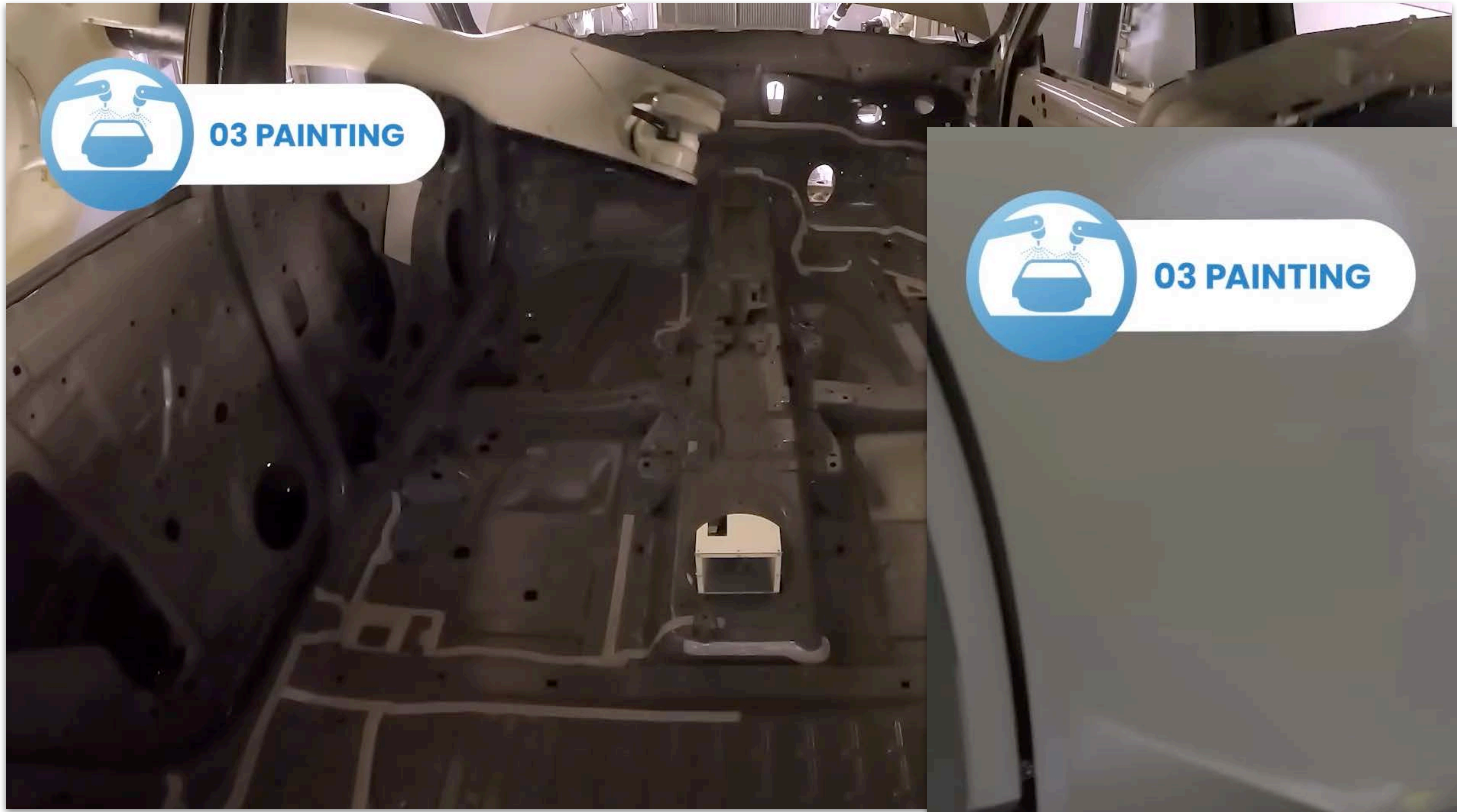


Joining Processes



Adhesive Joining

Adhesive Joining



Adhesive Joining

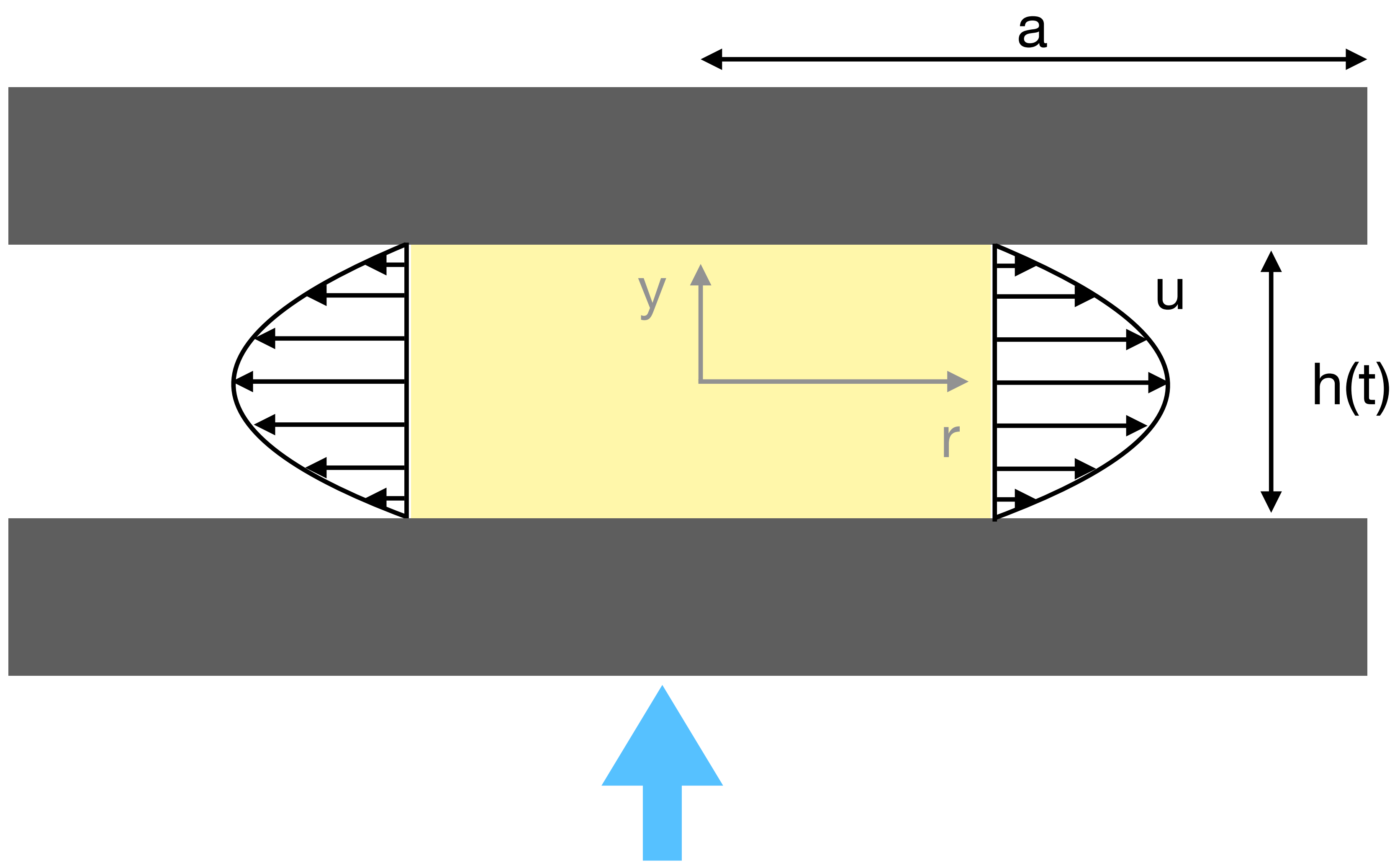
Considerations

- different materials
- easily automated
- inexpensive
- curing time limitations
- surface prep
- chemical compatibility
- strength, porosity

Adhesive Joining

adhesion physics: viscosity and separation forces (demo)

Stefan Equation: apply a force over time to induce parabolic flow



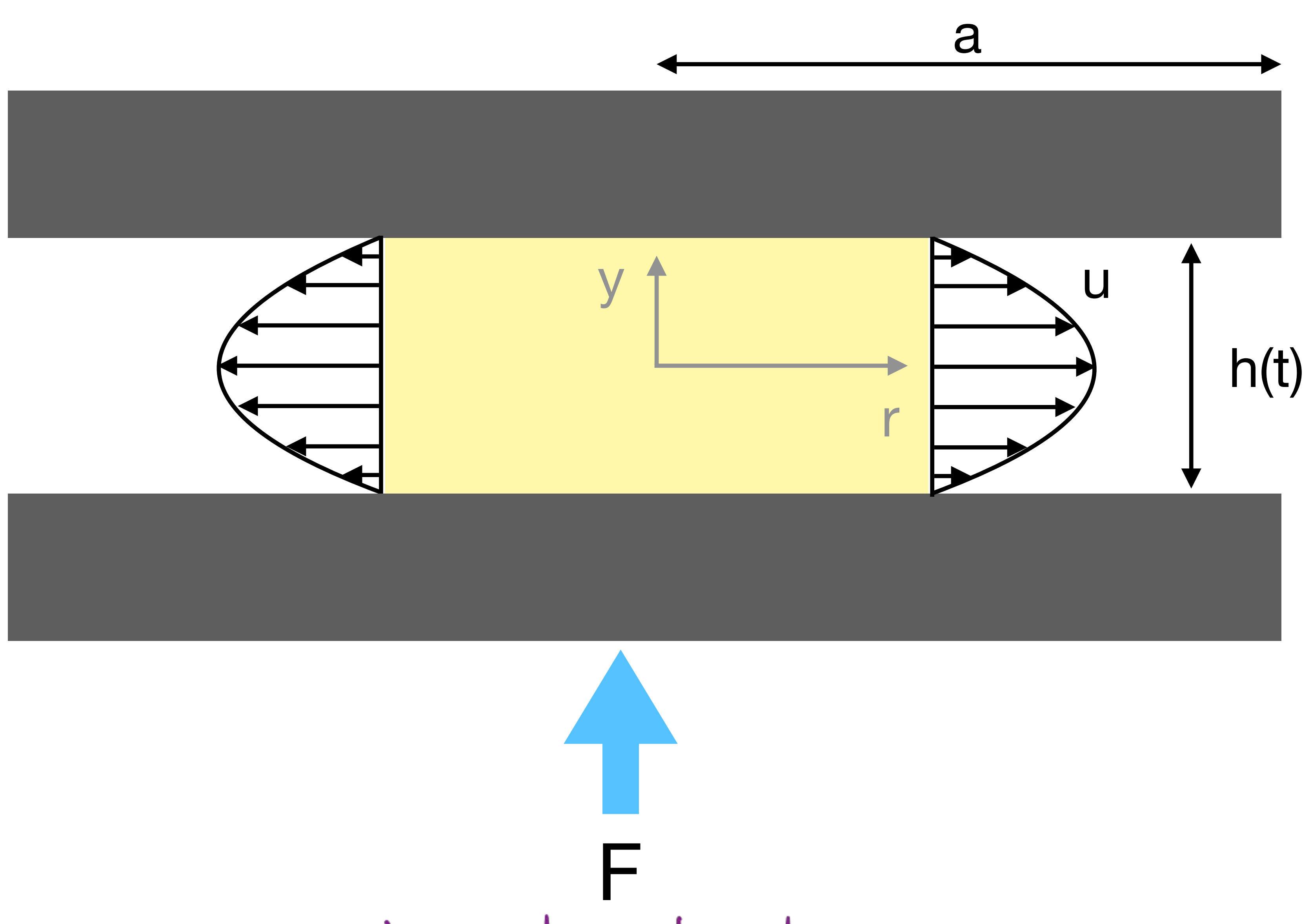
$$F t_{final} \approx \frac{3\mu\pi a^4}{4}\left(\frac{1}{h_f^2}\right)$$

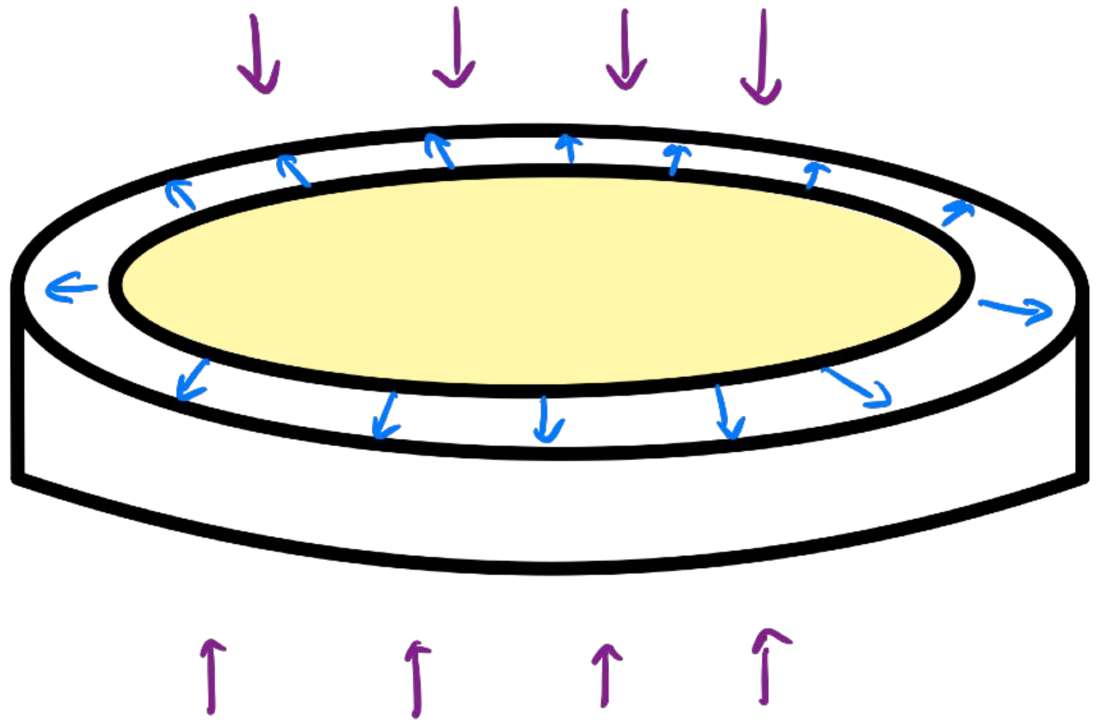
μ: increases with drying/solvent/curing

want a small gap (surface roughness/dirt can interfere)

- μ: viscosity, [Pa-s]
- h_i: initial gap [m]
- h_f: final gap [m]
- F: applied force [N]
- t: time [s]

Stefan Equation Derivation





Fluid Dynamics: $$u = \frac{1}{2\mu}\frac{dP}{dr}\left(y^2 - \frac{h^2}{4}\right)$$

Conservation of Mass: $$flow\ rate = \int_{-\frac{h}{2}}^{\frac{h}{2}} u2\pi r\, dy = -\pi r^2 \frac{dh}{dt}$$

substitute, integrate: $$P = \frac{3\mu}{h^3}\frac{dh}{dt}(r^2 - a^2) \rightarrow F = \int_0^a P2\pi r\, dr$$

integrate r, t, h:

$$Ft = \frac{3\mu\pi a^4}{4}\left(\frac{1}{h_f^2} - \frac{1}{h_i^2}\right)$$

μ: viscosity, [Pa-s]
u: velocity profile [m/s]
h: gap height [m]
F: applied force [N]
t: time [s]
a: radius of the disks [m]

Joining II

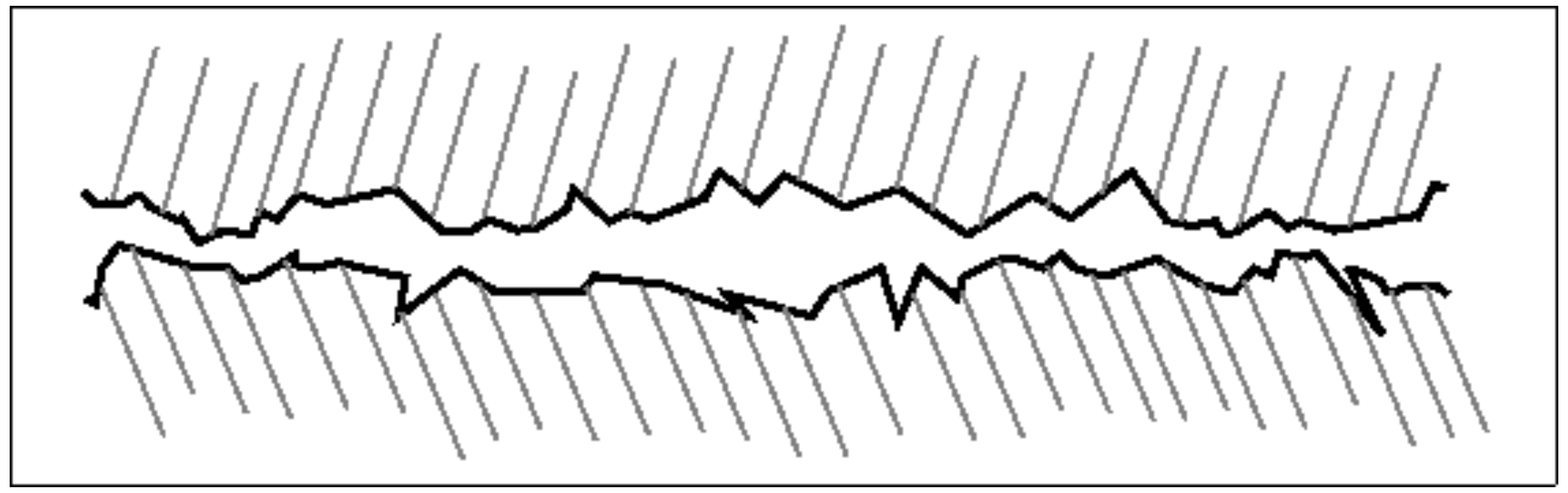
Processes and Types

Adhesive Joining

cohesion (like molecules) vs adhesion (different molecules)

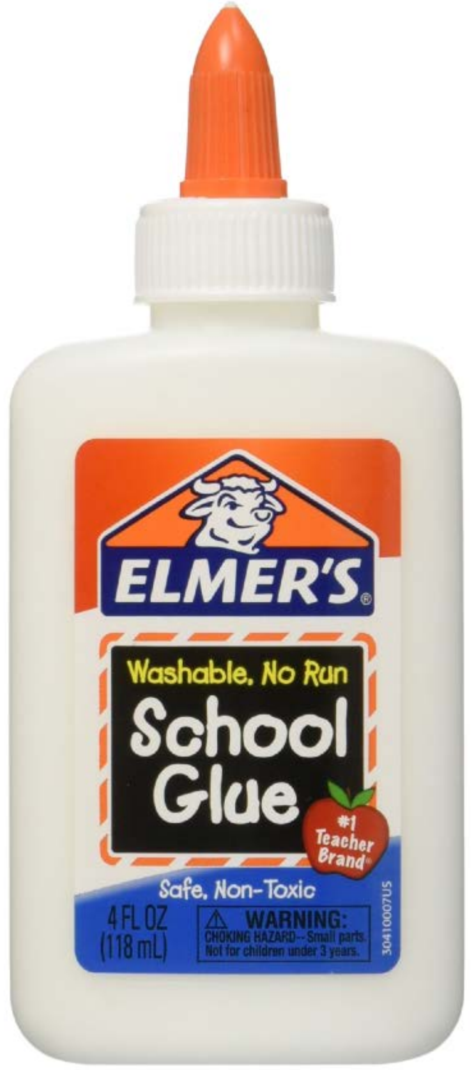
types of surface interactions

- mechanical
- chemical
- electrostatic (Van der Waal’s)
- diffusion



epoxies: thermoset polymers

that cross-link while curing



PVA (polyvinyl acetate) + water

(similar to wood glue)

latex (rubber) in a solvent

application with flexibility

cyanoacrylate reacts to moisture in air (org. medical)

Adhesive Joining

spray adhesive for fast, wide application

thermoset that also can react with moisture in air, inert sealer

(urethane glue also reacts to moisture or is two part)

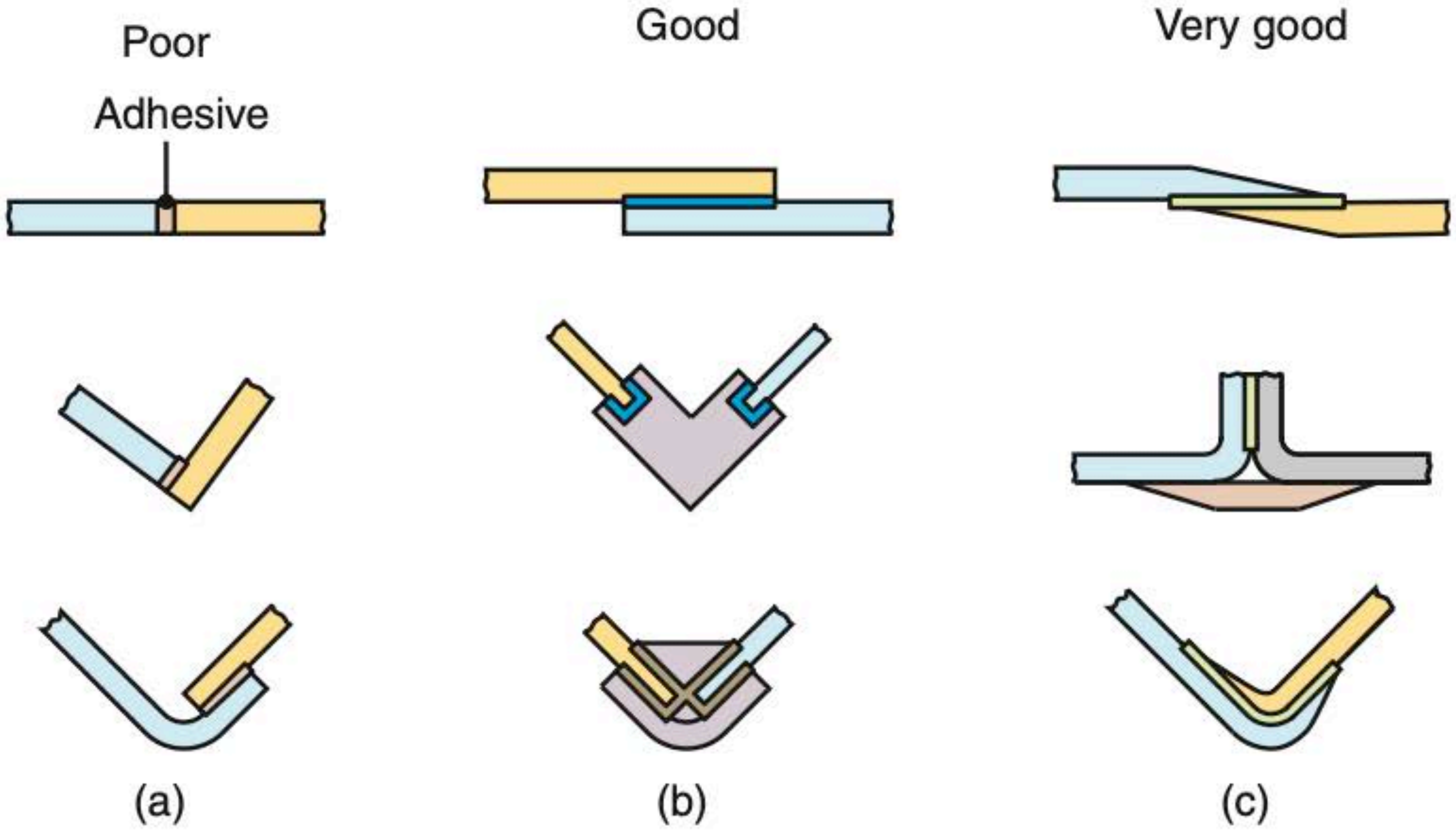
hot melt glue transitions with heat

solvent that chemically melts and reforms plastic, creating new molecular bonds

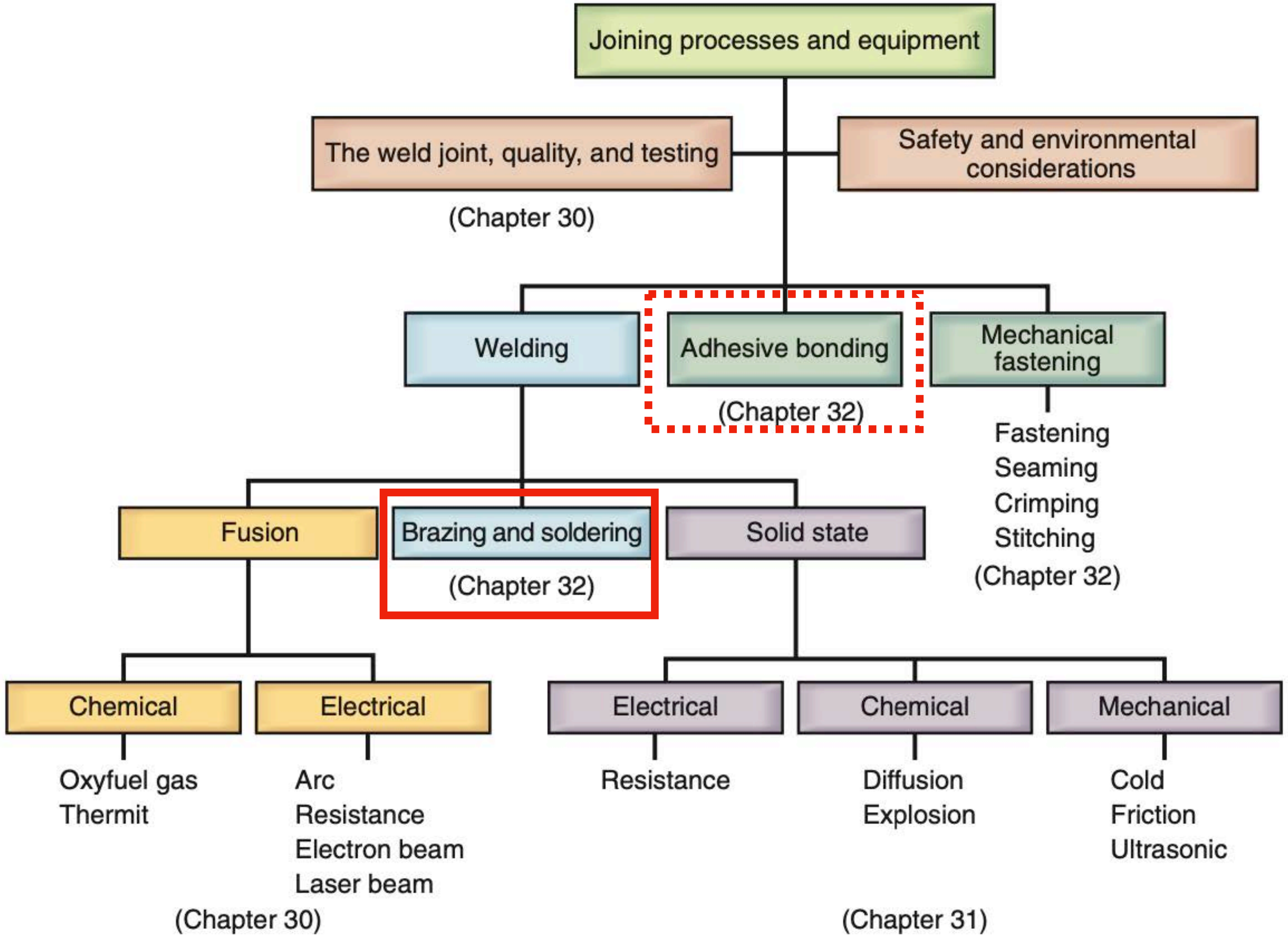
DF: Adhesive Joining

match loading type between design and adhesive choice

large contact area is best



Joining Processes



Brazing and Soldering

filler metals are melted and used to fill the gap

Brazing and Soldering

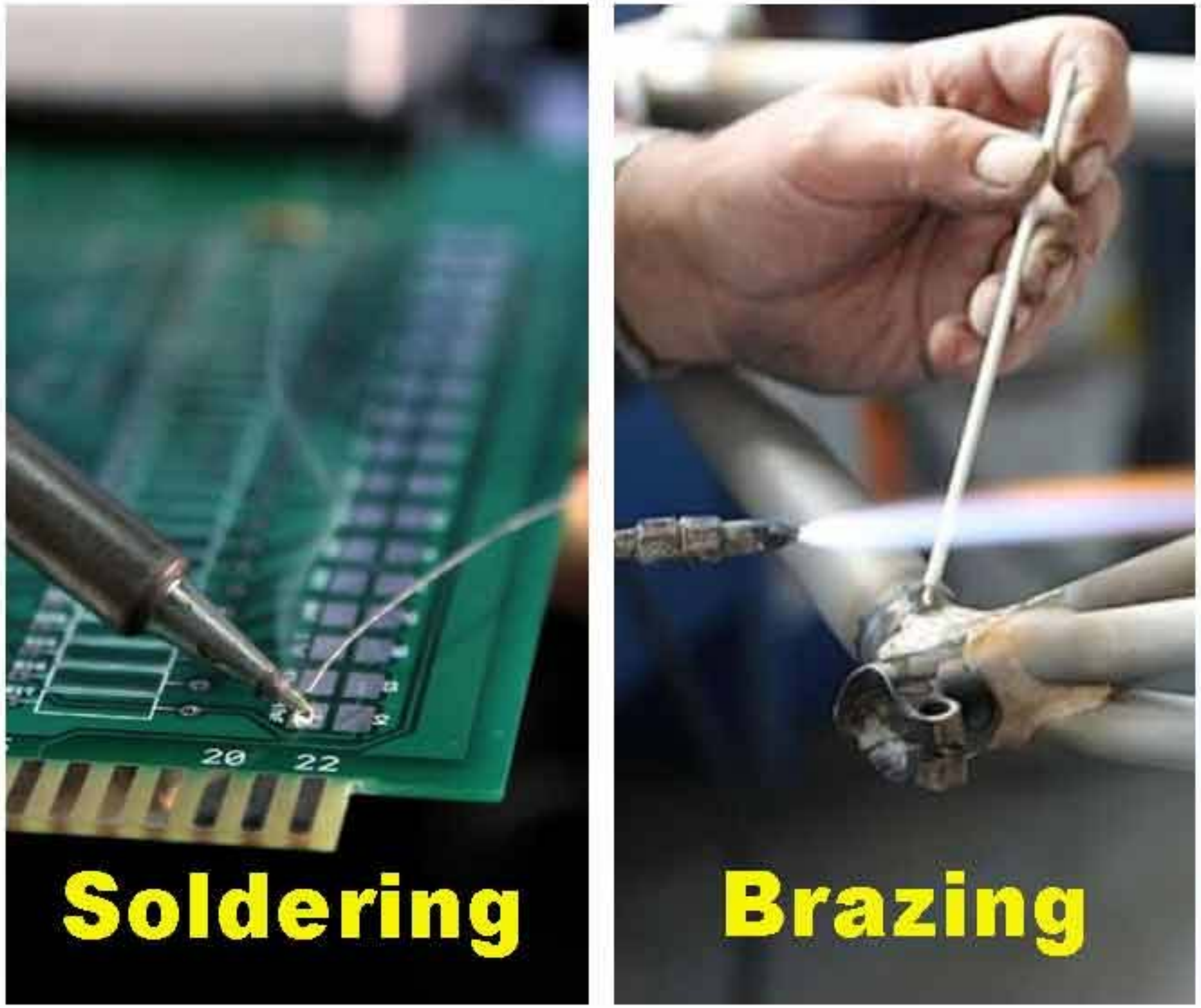
same process at different temperatures

electronics, plumbing, jewelry, structural

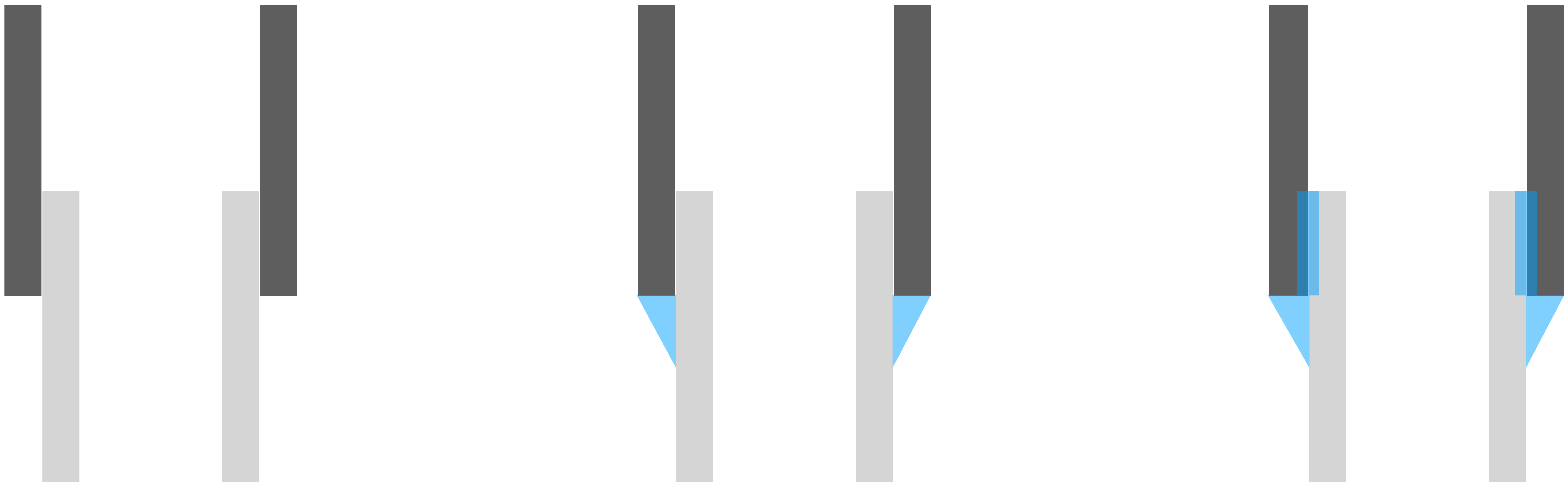
above 450°C (840°F) is brazing (e.g. Silver, Brass)

below is soldering (e.g. Tin/Lead)

liquid-solid-state bonding (+ dissimilar metals)



Brazing and Soldering: Capillary Forces



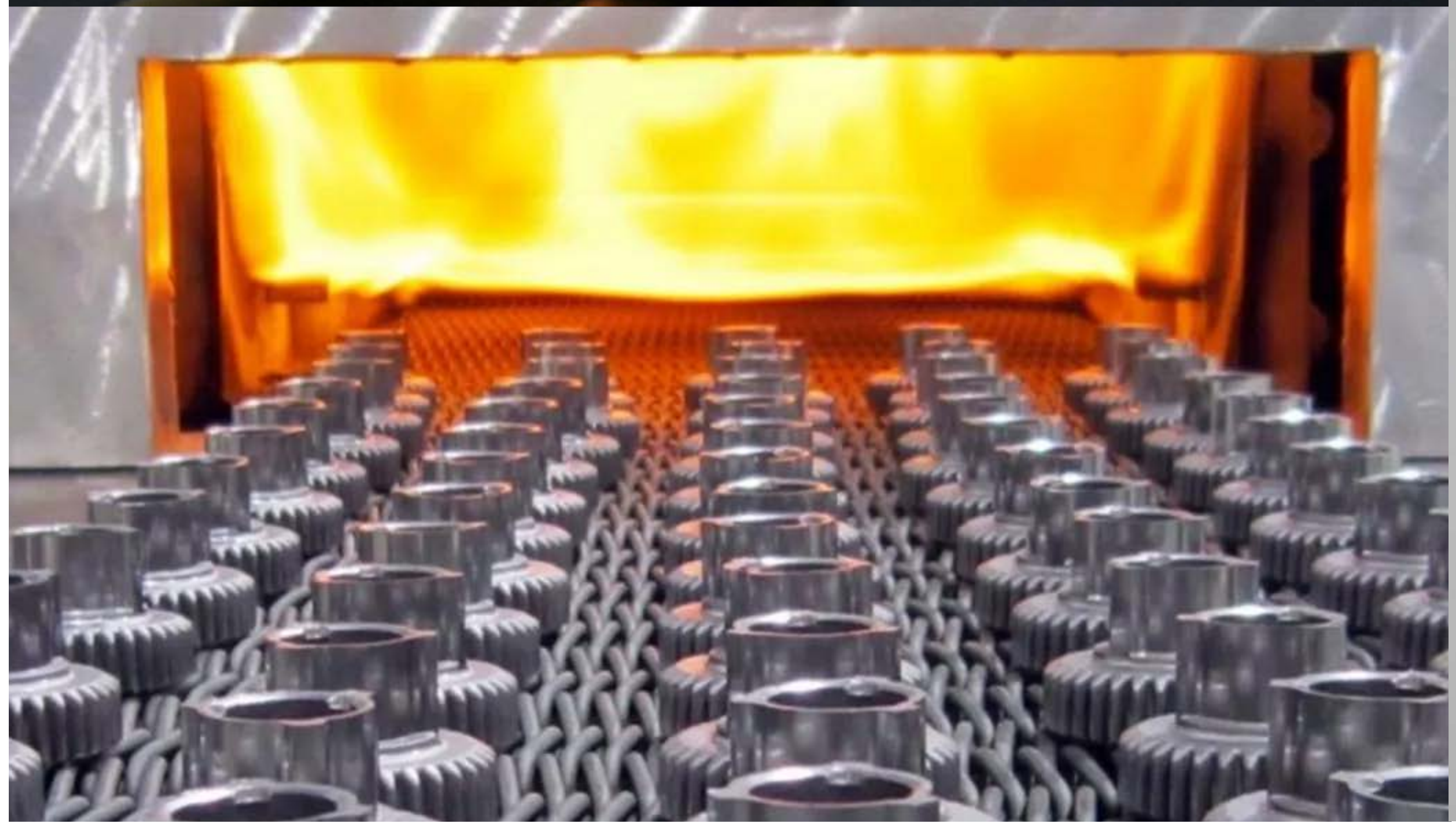
1. two pipes to be joined

2. introduce liquid filler

3. surfaces joined (strong in shear)

demo: surface preparation

Brazing and Soldering



Processes

- torch (oxyacetylene)
- furnace
- induction
- resistance

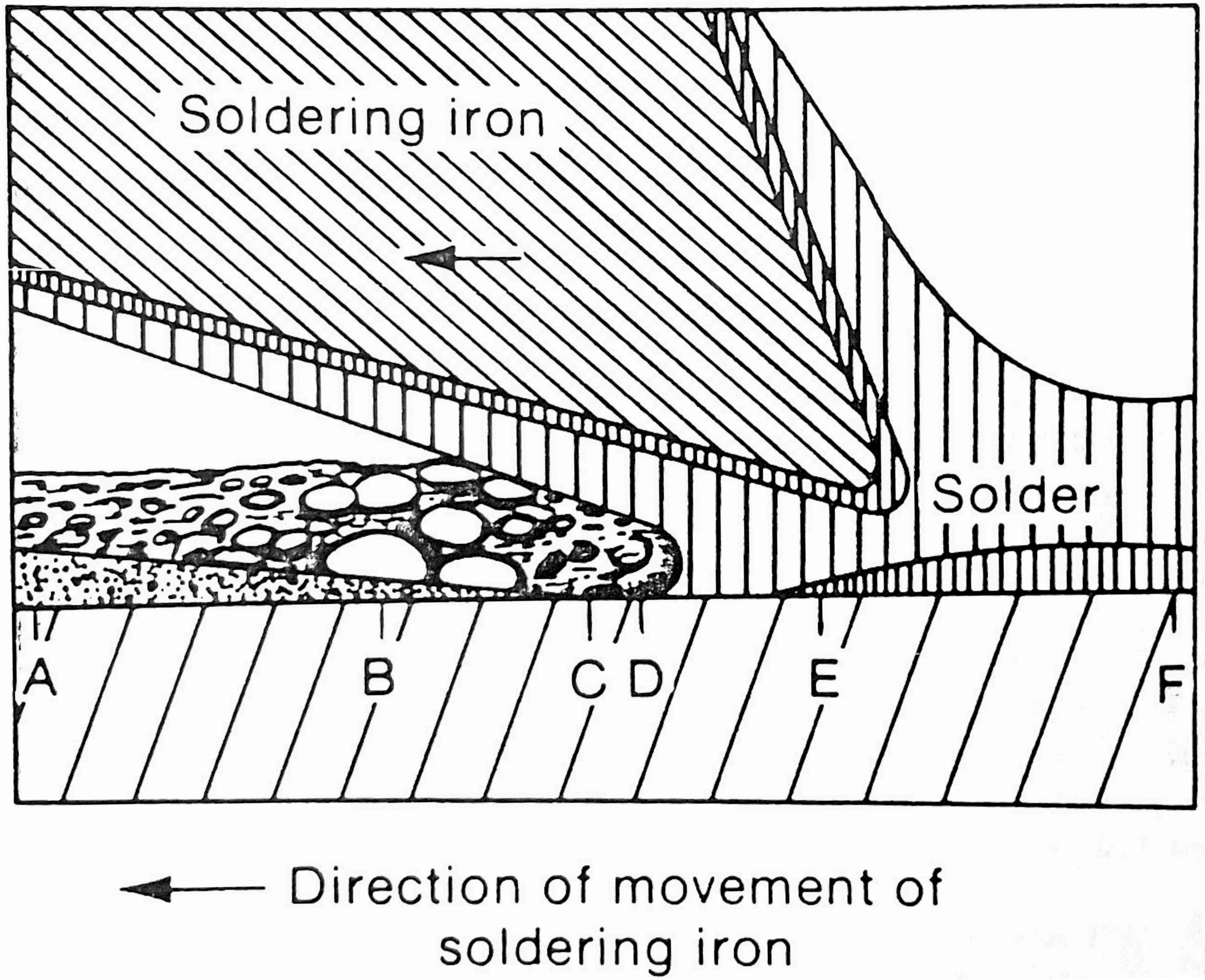
Brazing and Soldering

purpose of flux

- removes oxides (protects from oxidation)
- improves surface wetting

process

A. Flux on top of oxidized metal
B. boiling flux removes oxide
C. base metal in contact with molten flux
D. molten solder displaces molten flux
E. solder adheres to based metal
F. solder solidifies



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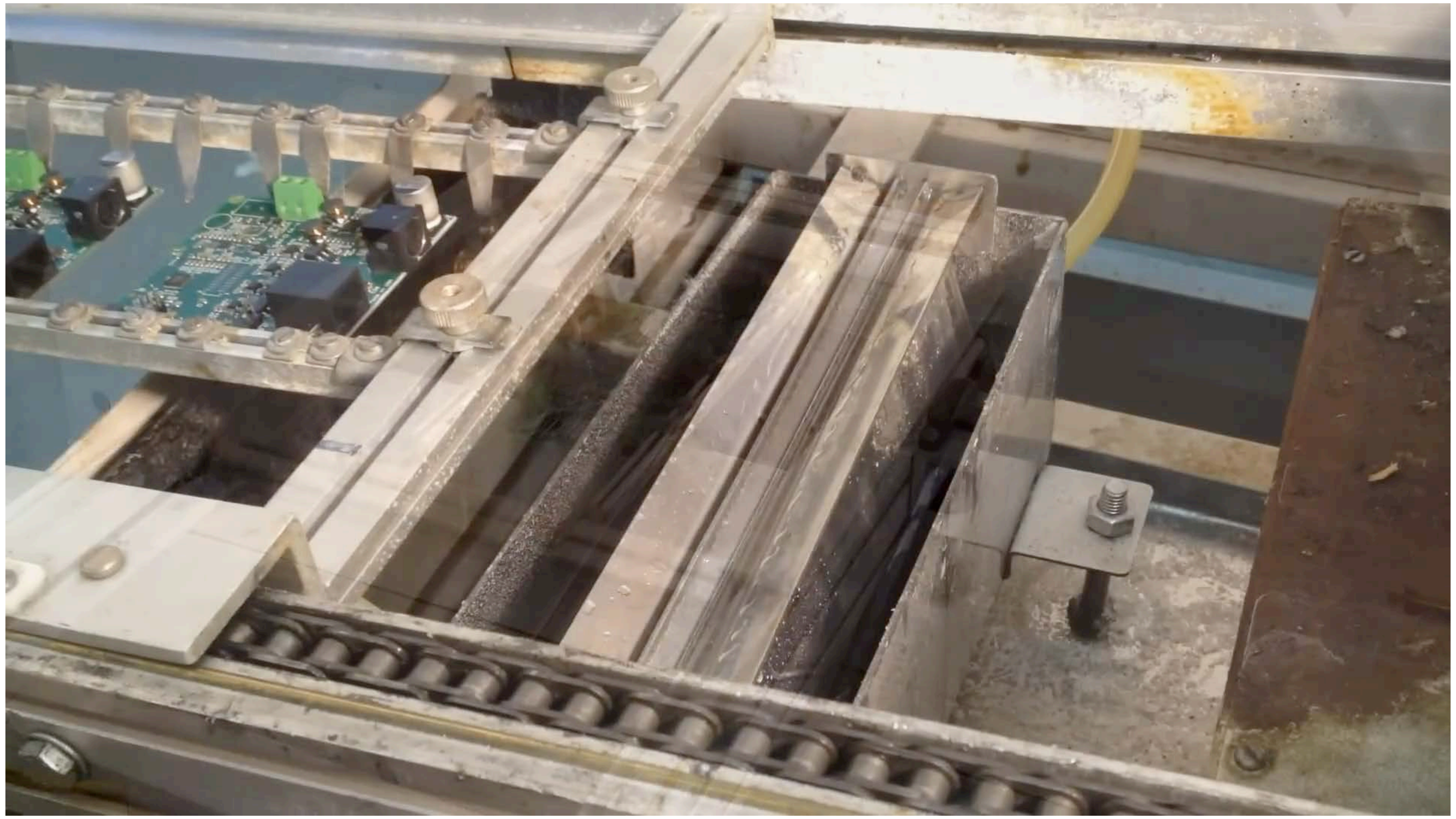


DF: Brazing and Soldering

filler metal should have good “wetting” characteristics

joined surfaces should not be smooth

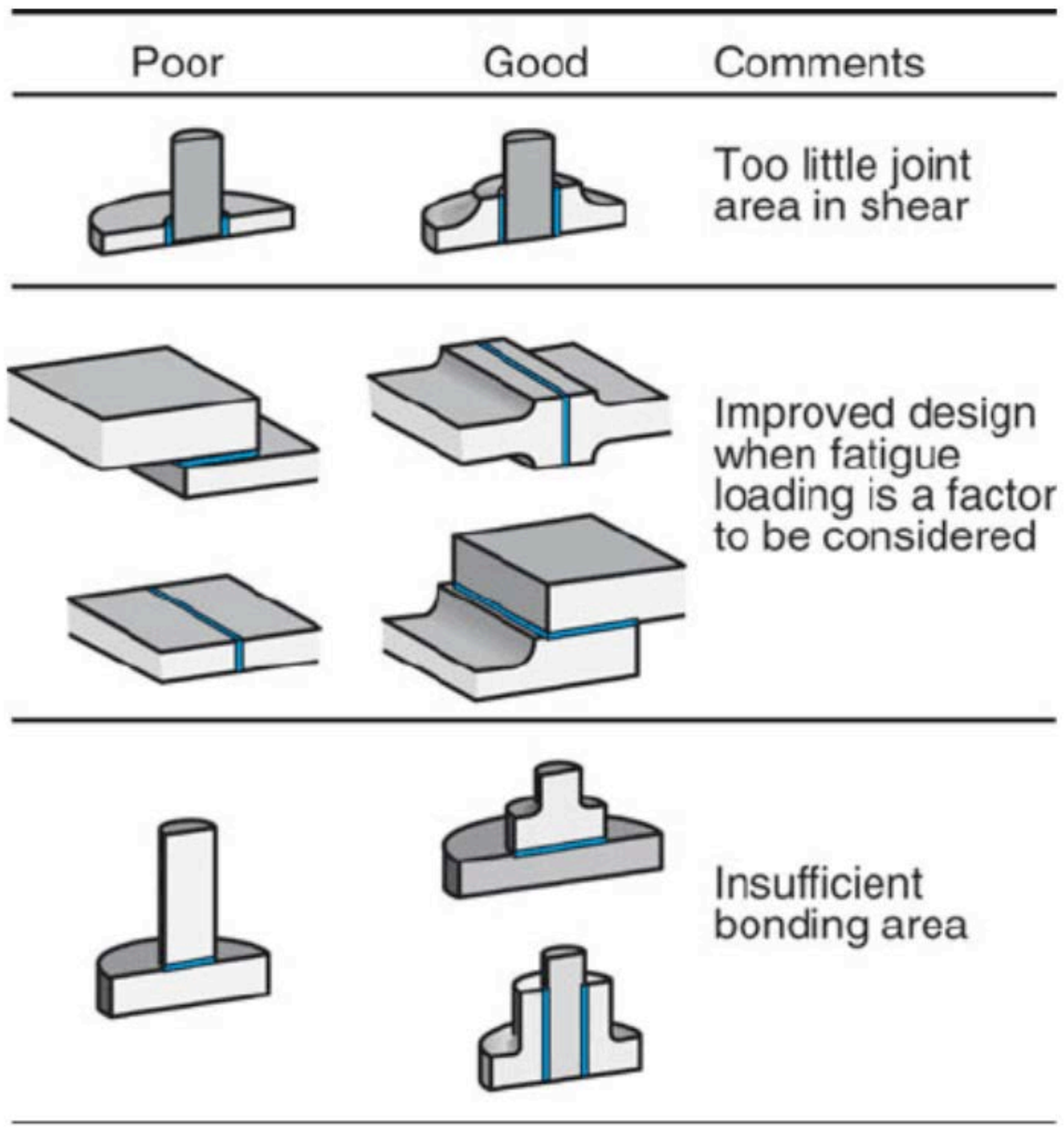
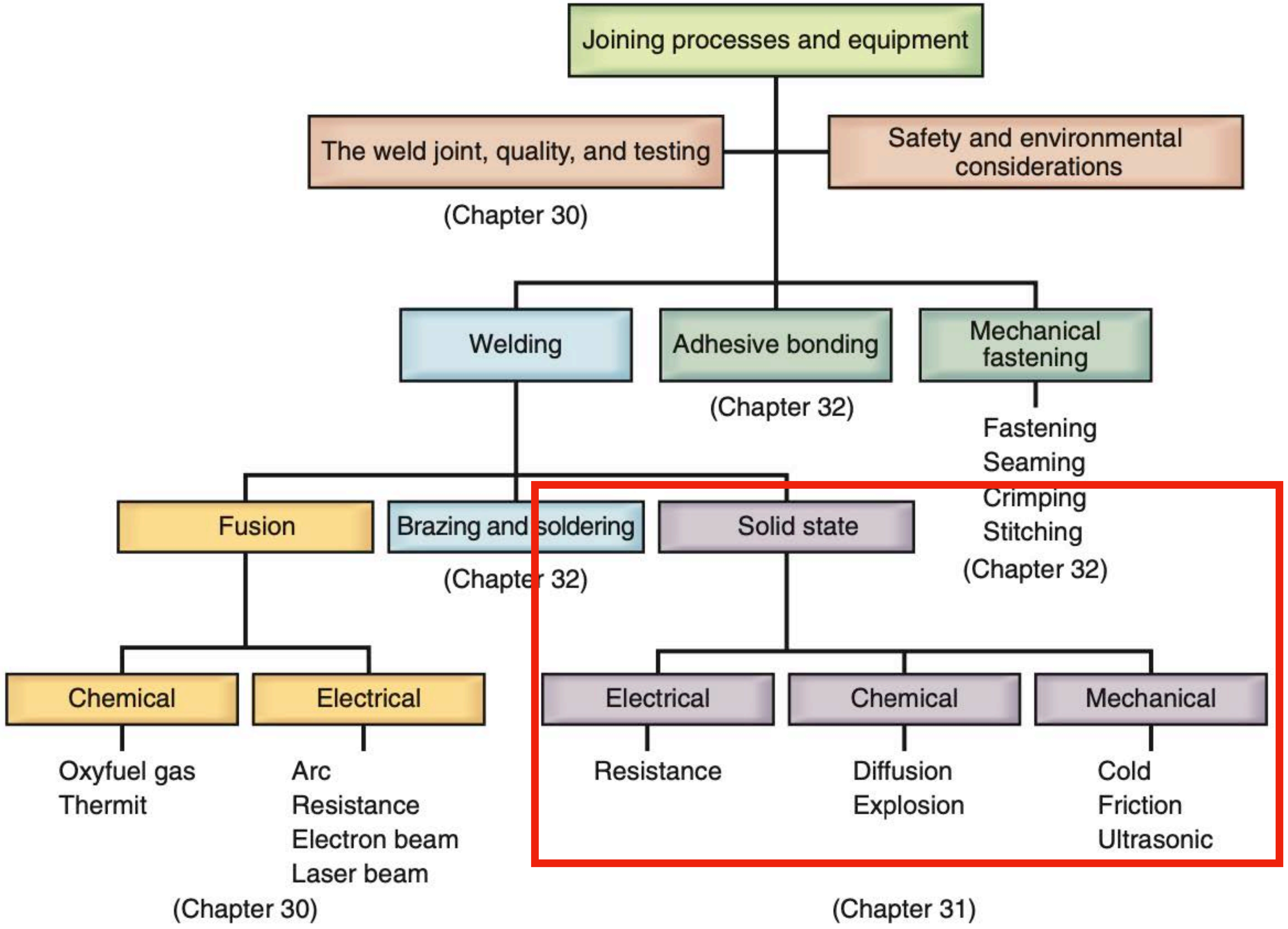


FIGURE 32.6 Examples of poor and good designs for brazing. *Source:* American Welding Society.

Joining Processes



Solid State (Interatomic) Processes

no third material: just bonding one material directly to another

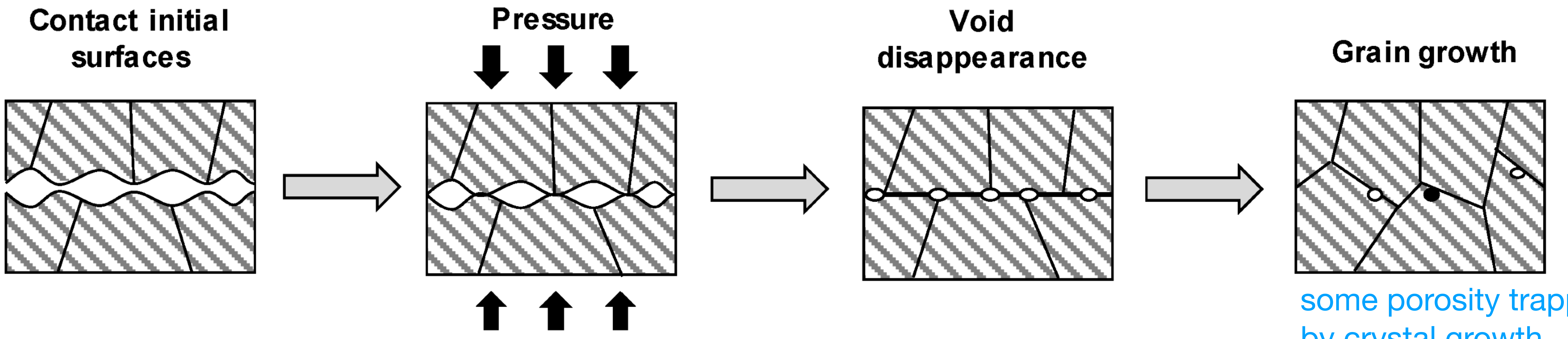
Diffusion Bonding

materials “grow across to each other”

typically at temperatures of 2/3*T_{melt}, pressures of 500 to 5,000 psi

expensive: aerospace, not automotive

surface quality/finish matters



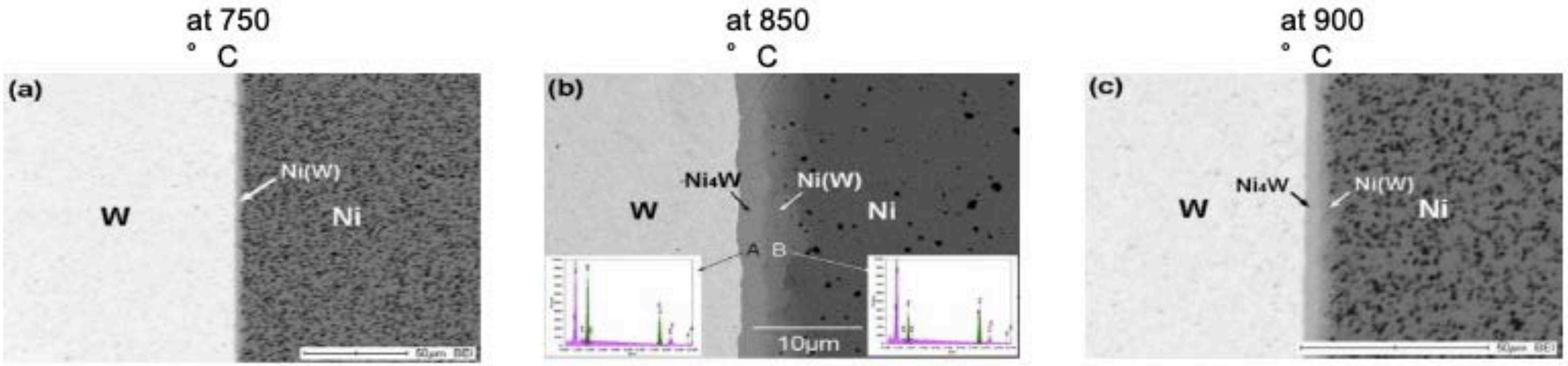
asperities + pressure ➡ decreased porosity

some porosity trapped by crystal growth

Diffusion Bonding

Nickel and Tungsten react to each other, otherwise you might need a film of another metal to facilitate bonding

gradient of material is formed



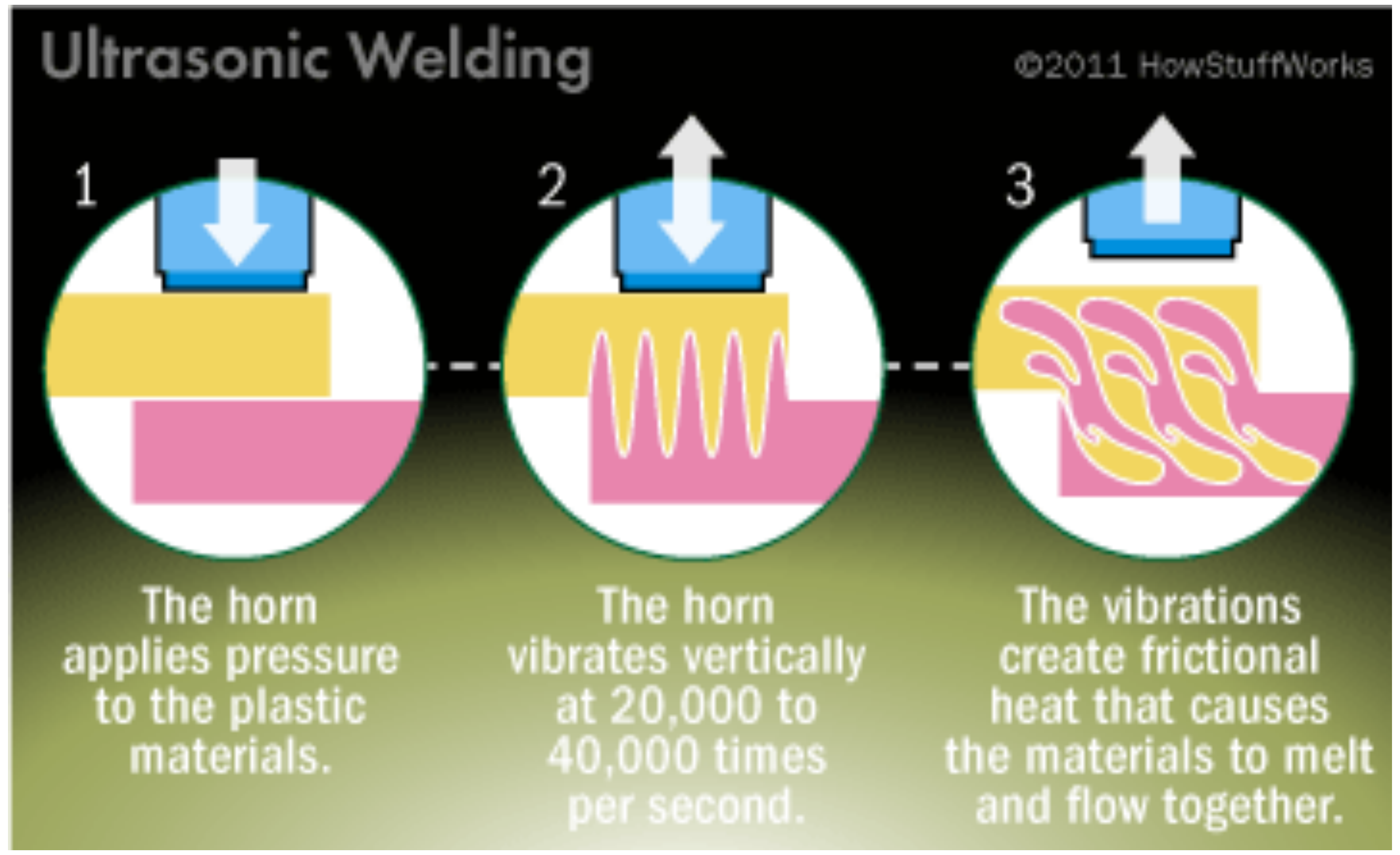
Back-scatter electron micrographs of W/Ni interfaces, diffusion bonded for 3 hours at different temperatures

Zhihong Zhong , Tatsuya Hinoki , Hun-Chea Jung , Yi-Hyun Park , Akira Kohyama, "Microstructure and mechanical properties of diffusion bonded SiC/steel joint using W/Ni interlayer," Msterials & Design, Vol. 31, 3, 2010, pp.1070-1076.

Other Solid State Processes

Ultrasonic Welding

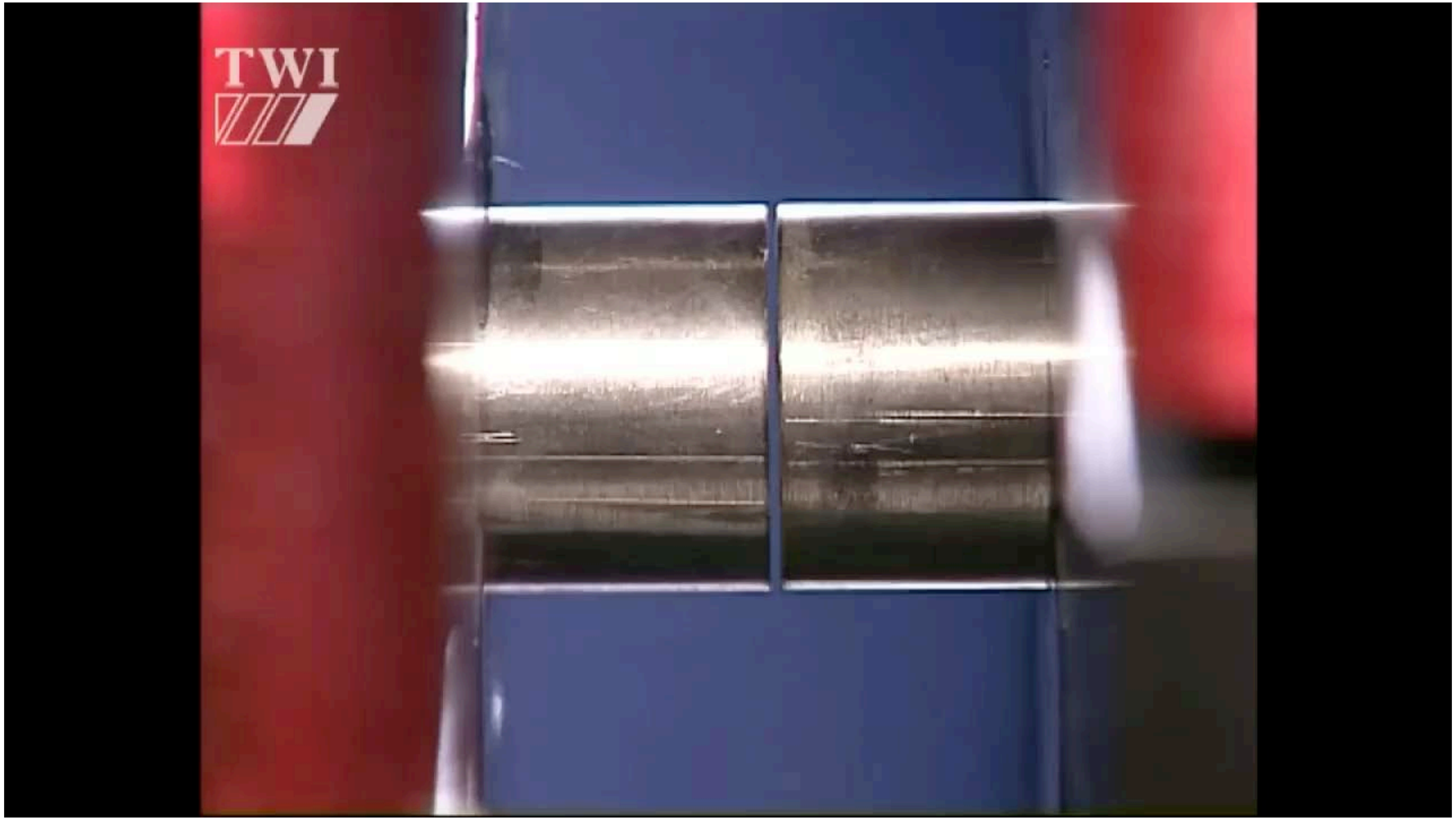
shear at 10-75 kHz vibration



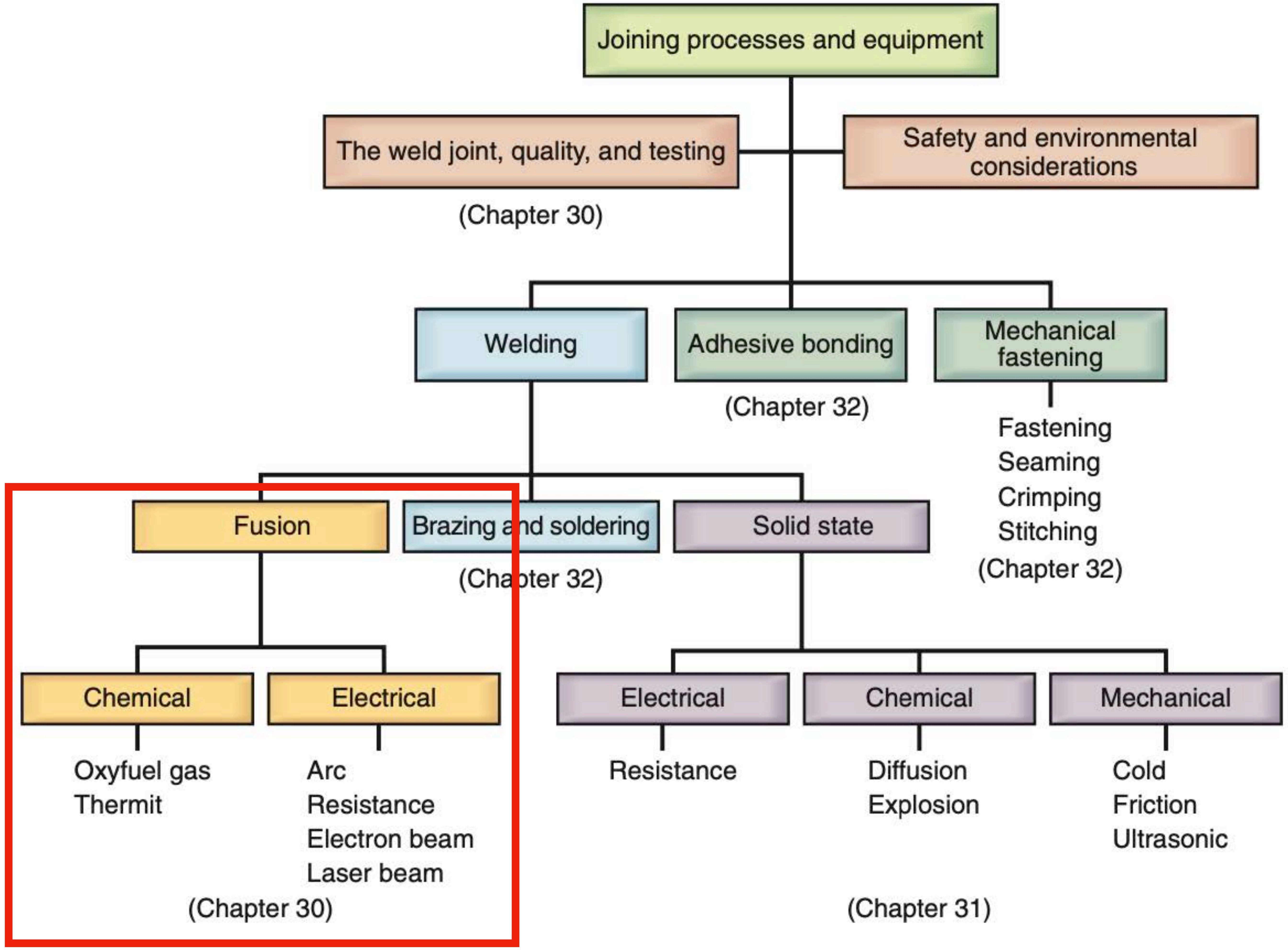
Other Solid State Processes

Friction Welding

- material surfaces sheared against each other



Joining Processes



Fusion Welding

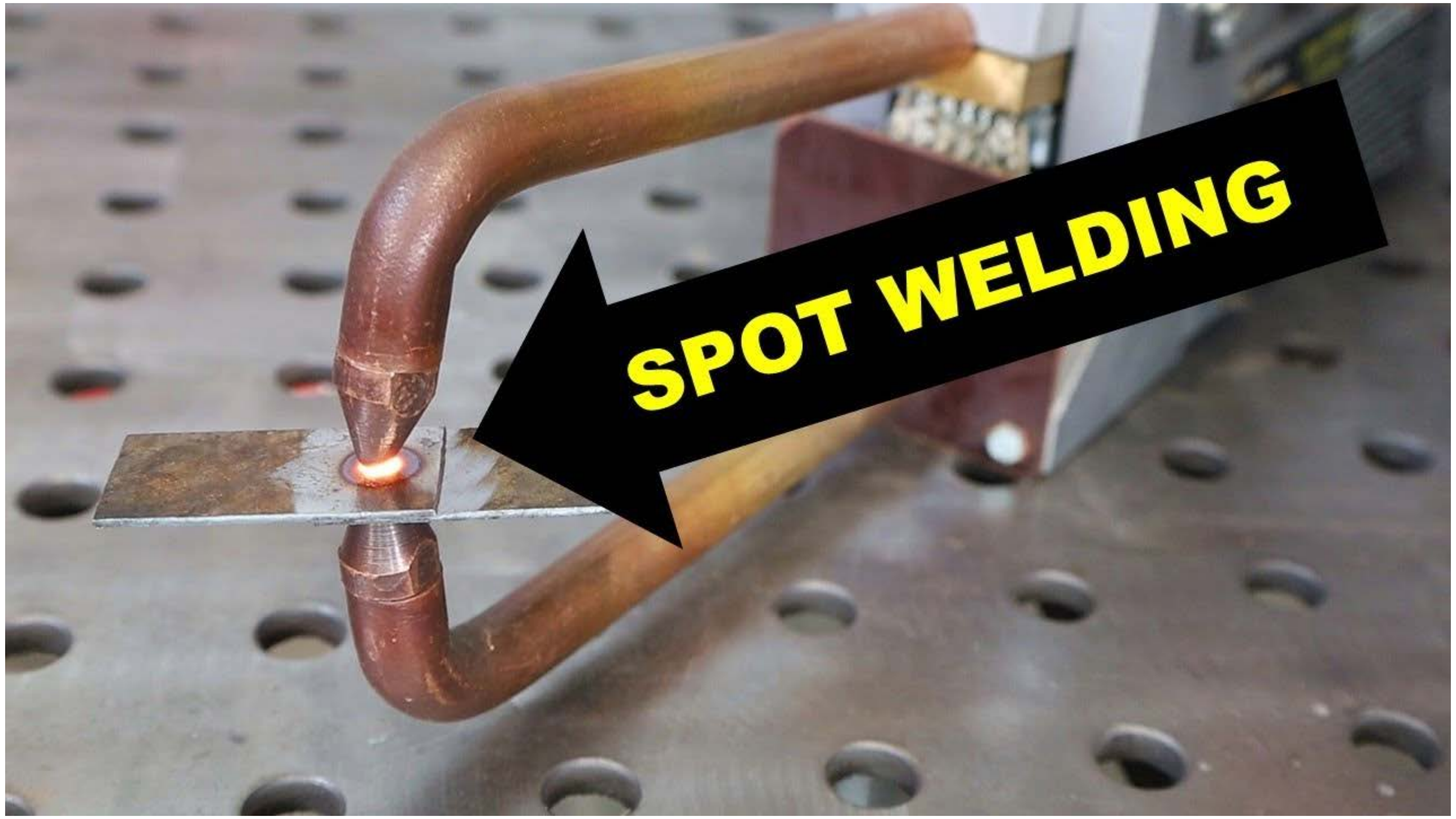
melting occurs at the interface

Fusion Welding

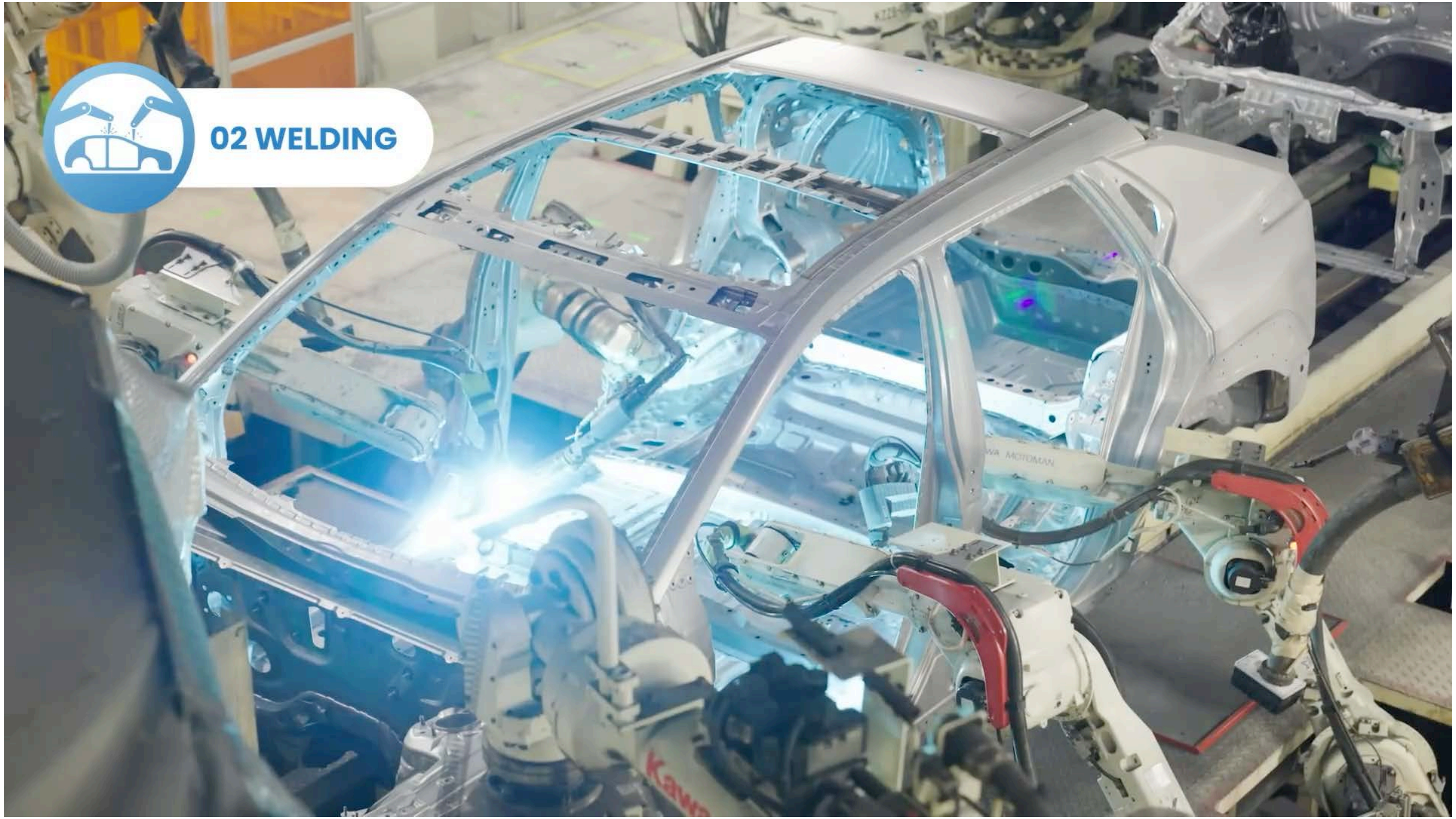
different examples of welded parts

spot welding: based on electrical resistance

resistance of the interface is highest: melts there first

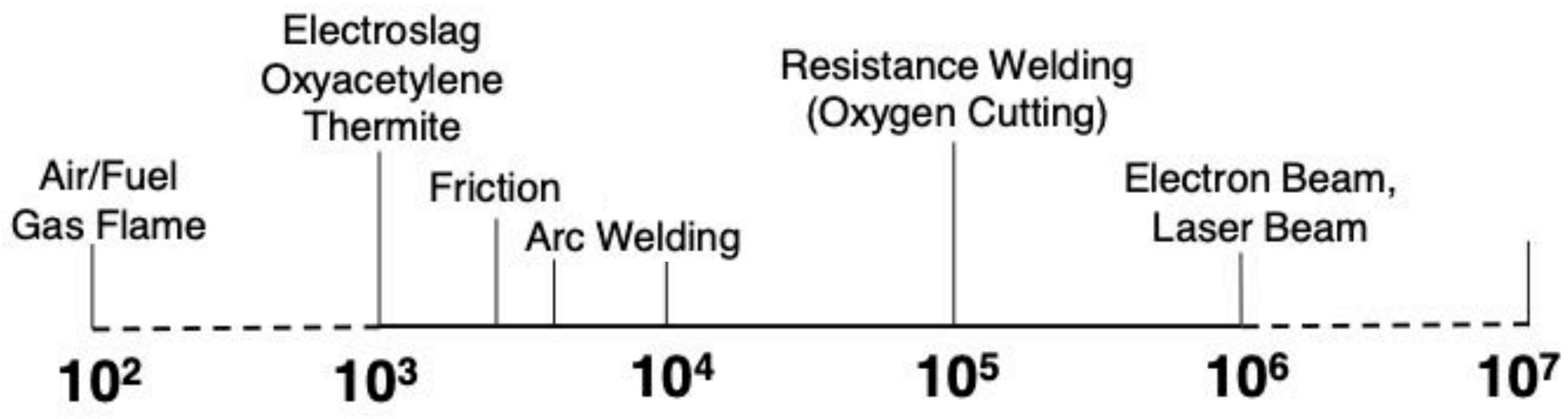


Fusion Welding



Fusion Welding

Radiation Intensity [W/cm²]



high power output   very focused beams

more intense source ➡ faster melting, but it's easy to over melt!

automation is essential for controlling the process

Heat Intensity Considerations

- over melting, evaporation
- heat affected zone (HAZ)
  - change in properties
- efficiency
  - lower intensity, slow down…
  - heat small area quickly
- depth/width ratio
  - more intense: penetrate deeper without width

Melt Pool Depth

How fast do you have to move?

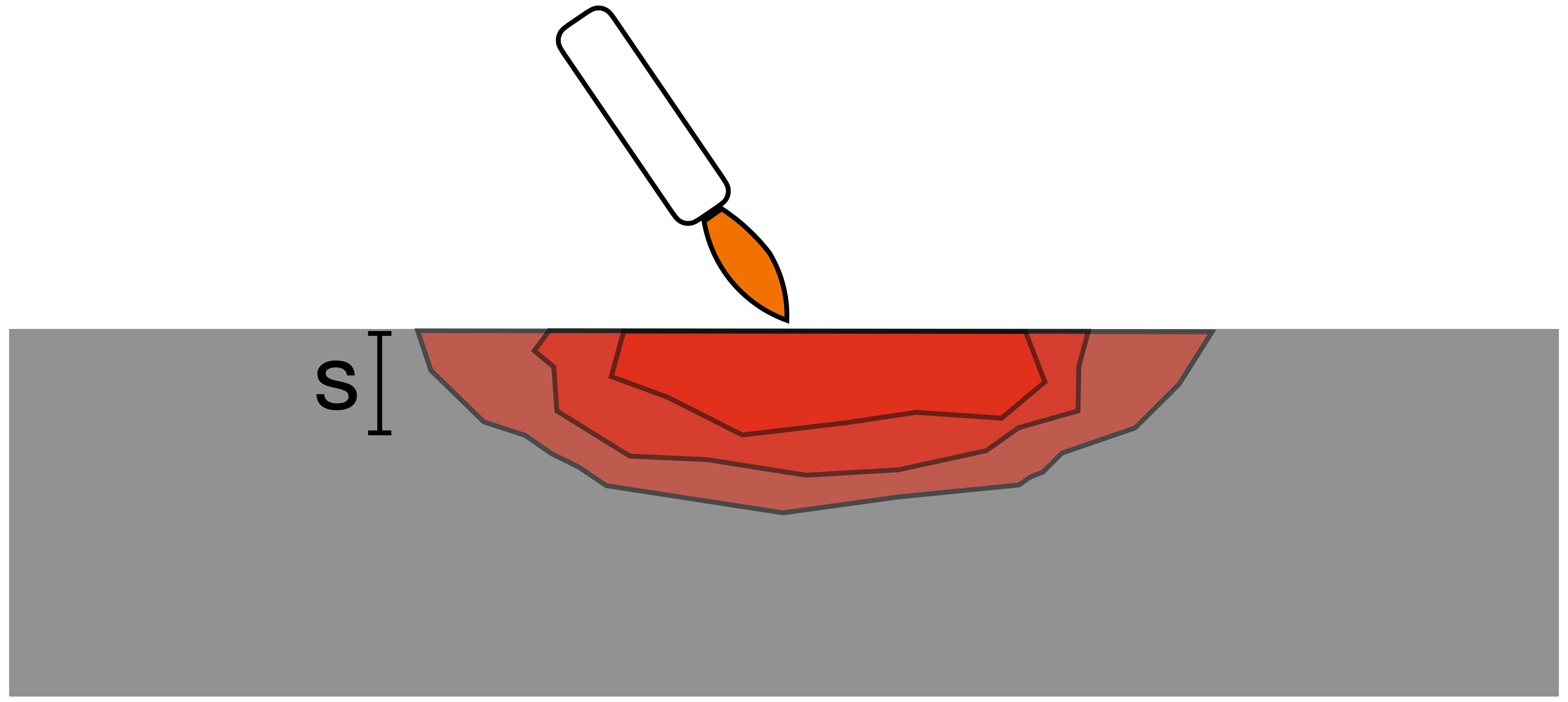
Jakob # $$J = \frac{c_p(T_{melt} - T_{initial})}{h_{fs}}$$

energy to get to melt temp

energy to convert to liquid

thermal diffusivity $$\alpha = \frac{k}{\rho c_p}$$

c_p: specific heat capacity [J/kg°K]
T_{melt}: melting temperature [°K]
$T_{initial}$: starting temperature [°K]
h_{fs}: specific latent heat of fusion [J/kg]
k: thermal conductivity [W/mK]
ρ: density [kg/m^3]
s: melt pool depth [m]
t_{max}: time to reach depth s [s]



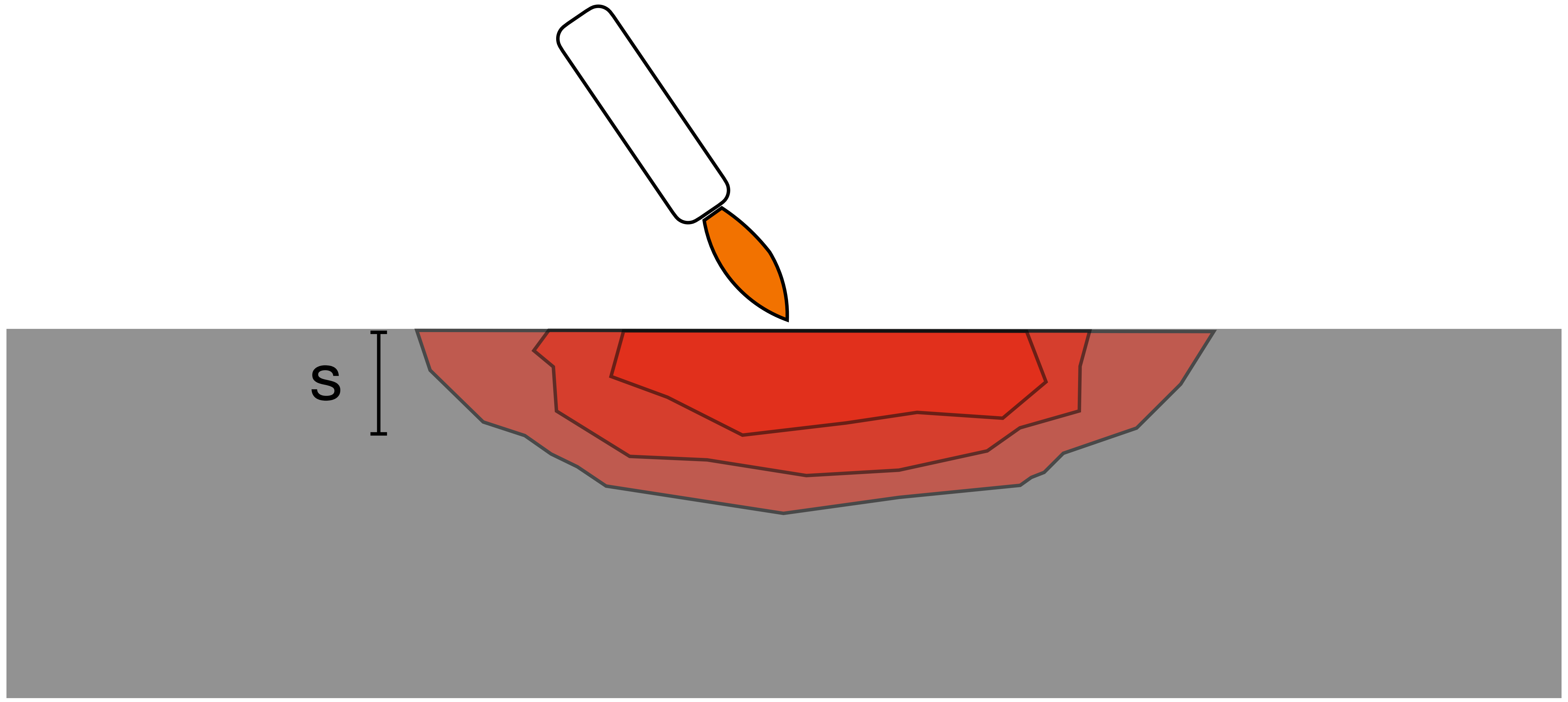
$$s \approx \sqrt{2\ \alpha\ J\ t_{max}}$$

depth of melt pool over time, so:

$$t_{max} \approx \frac{s^2}{2\alpha J}$$

stay any longer, and you will over-melt!

HAZ: Heat Affected Zone



region near the weld pool is affected by heat

- the microstructure changes

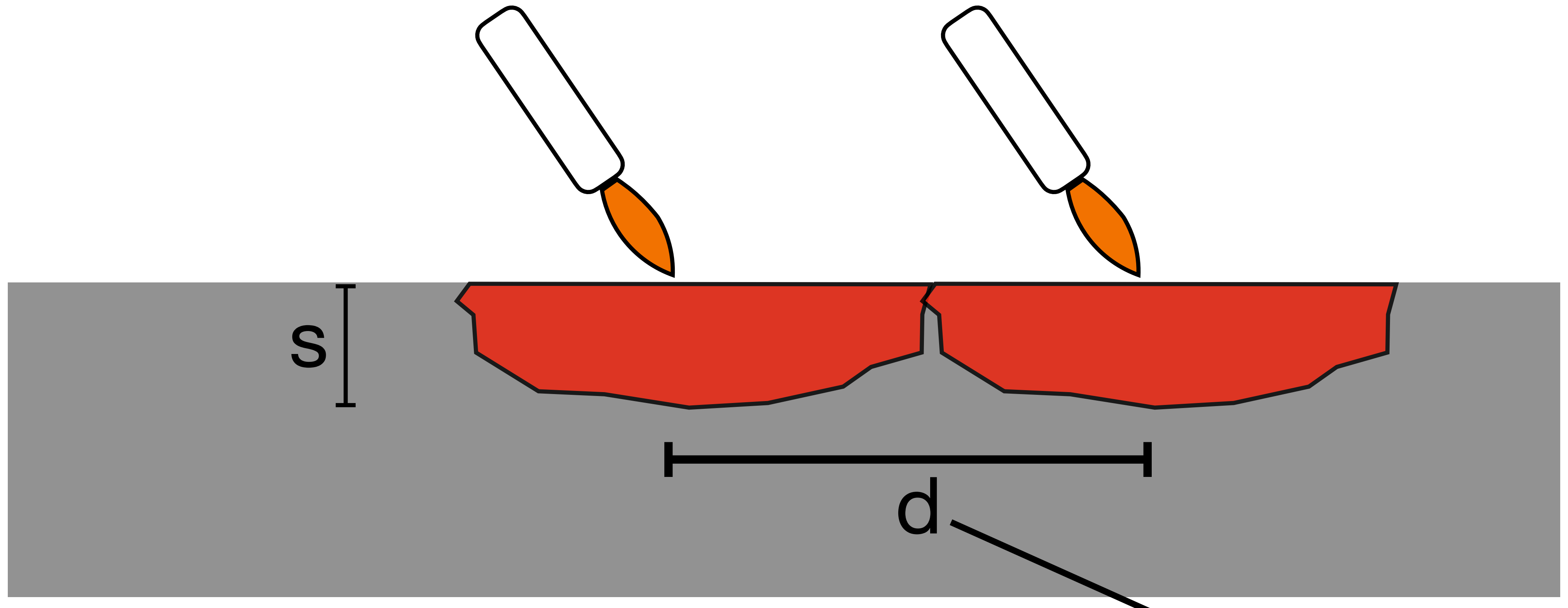
the size of the HAZ is controlled by the thermal diffusivity α

- why α? ⬇ α means more localized heating
- soldering iron on plastic: small weld pool
- on metal, you heat the whole piece!

lower heat intensity takes longer: allows for more time to diffuse

- you want high intensity with less time to diffuse: more efficient (faster) and more localization (no over-melting)

Melt Front Velocity



$$t_{max} = \frac{s^2}{2\alpha J} \longrightarrow v_{min} = \frac{d}{t_{max}}$$

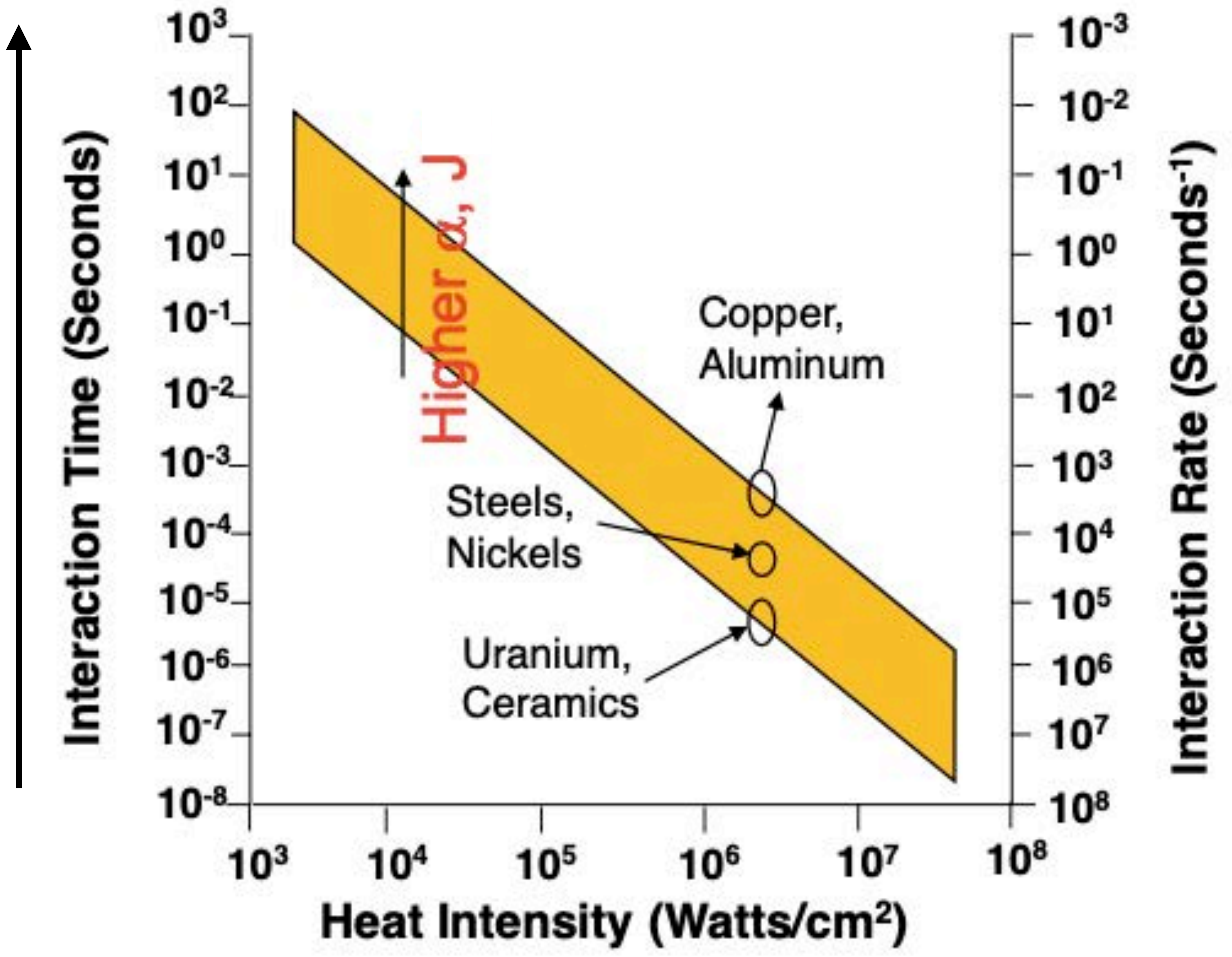
you need to feed at least this fast to prevent over melting

Welding Rate

the rate at which the welding device must be moved is governed by:

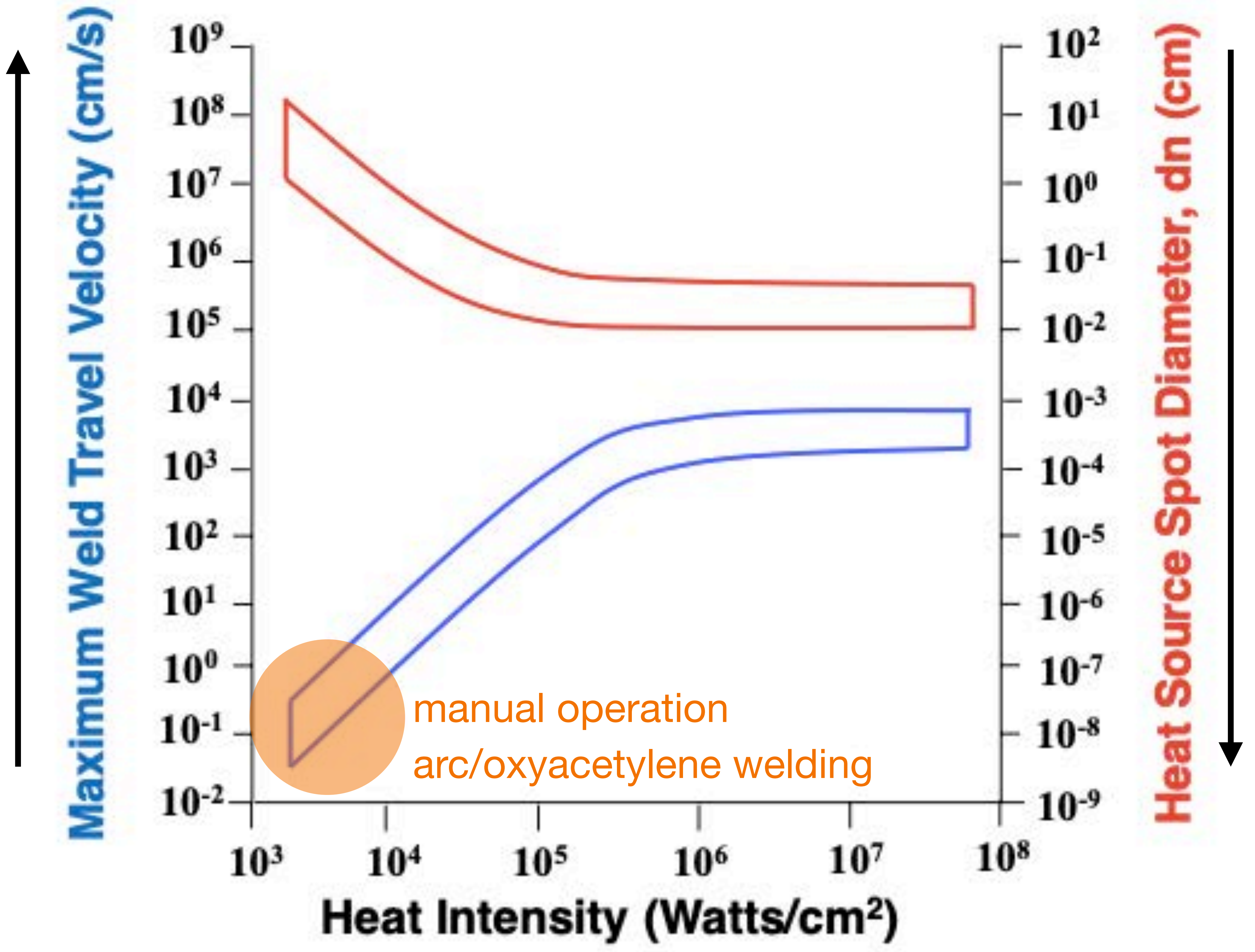
- the Heat Intensity: the greater the intensity, the faster the device must move to keep the melt depth s constant
- αJ: the larger this product, the faster the melt front moves

Weld Pool: Heat Source Interaction Time



Main factor : Thermal diffusivity

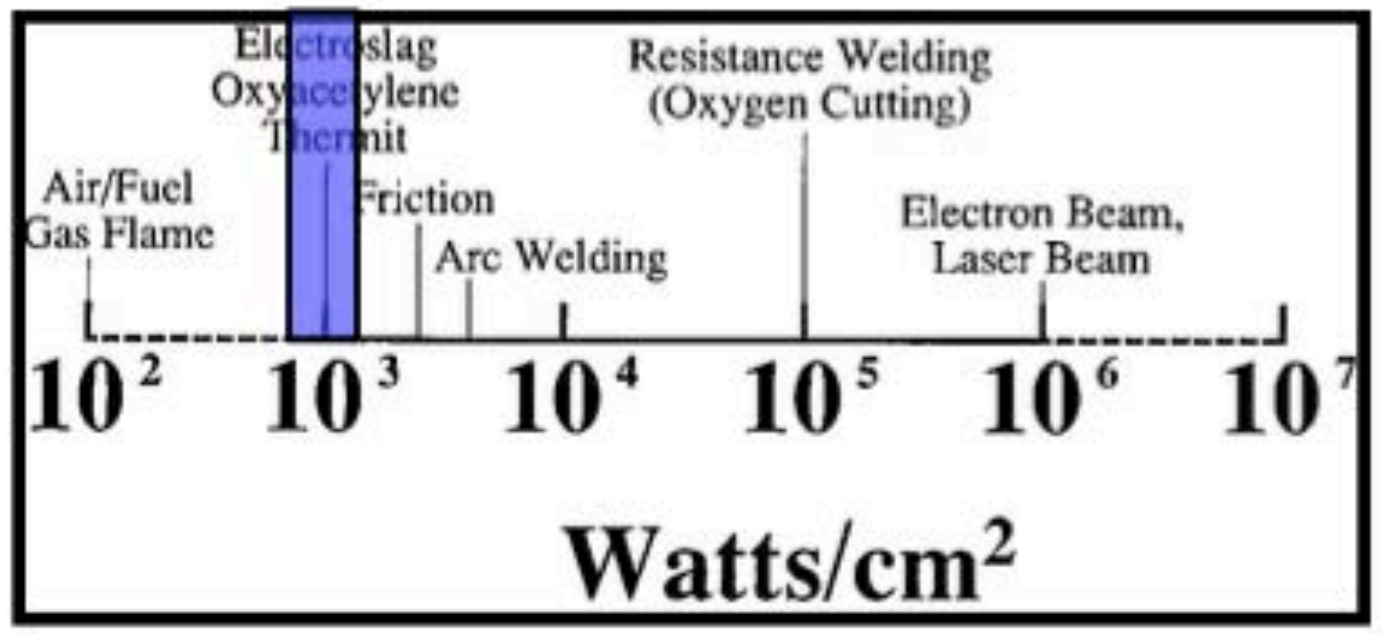
Weld Velocity



Oxyfuel Gas Welding

air/fuel welding

- low-cost and portable
- oxidizing (high oxygen), reducing (low oxygen), and neutral flames

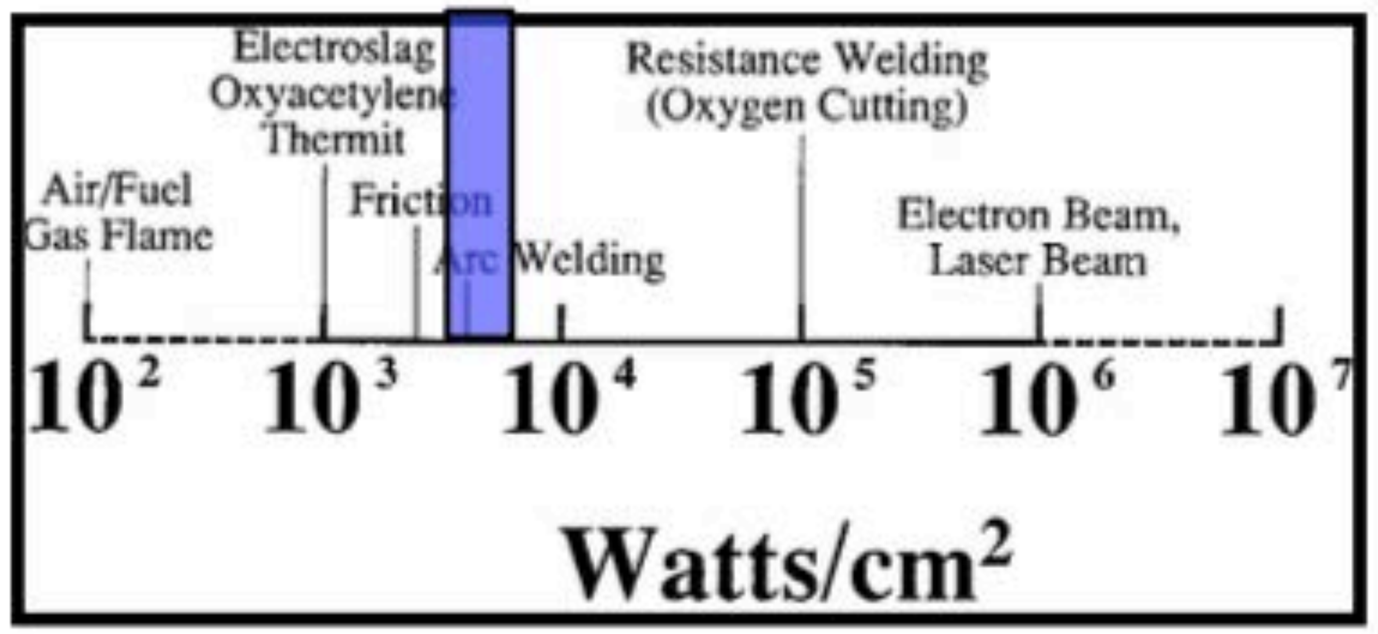


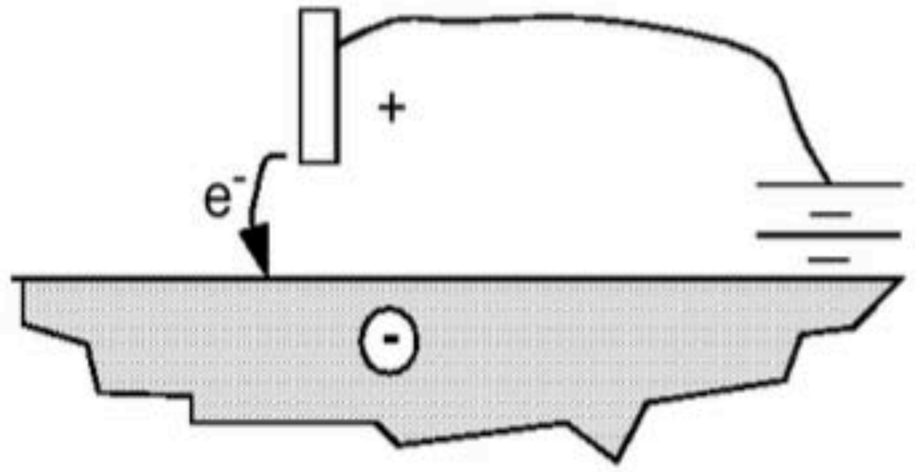
Arc Welding

voltage difference between electrode and workpiece

- voltage ~100-500V
- current ~50-300A

electrode may be consumed





Arrangement for consumable electrodes

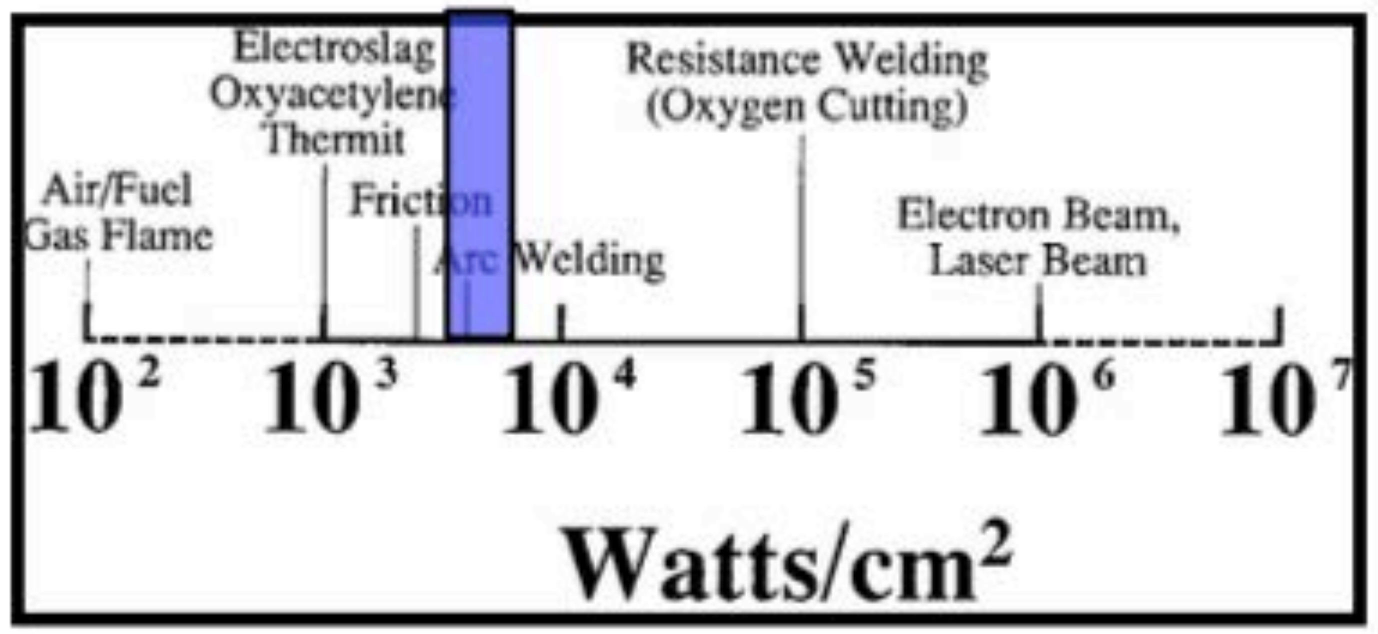
Arc Welding

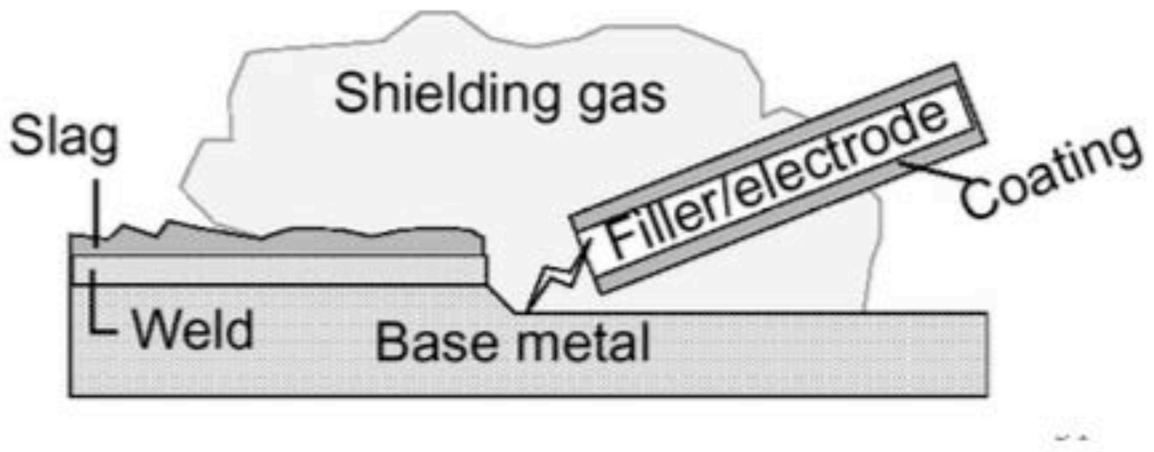
filler metals

- adds material to the weld zone
- flux on/in filler prevents oxidation
- slag protects molten puddle from oxidation

shielding

- protects weld area contaminants

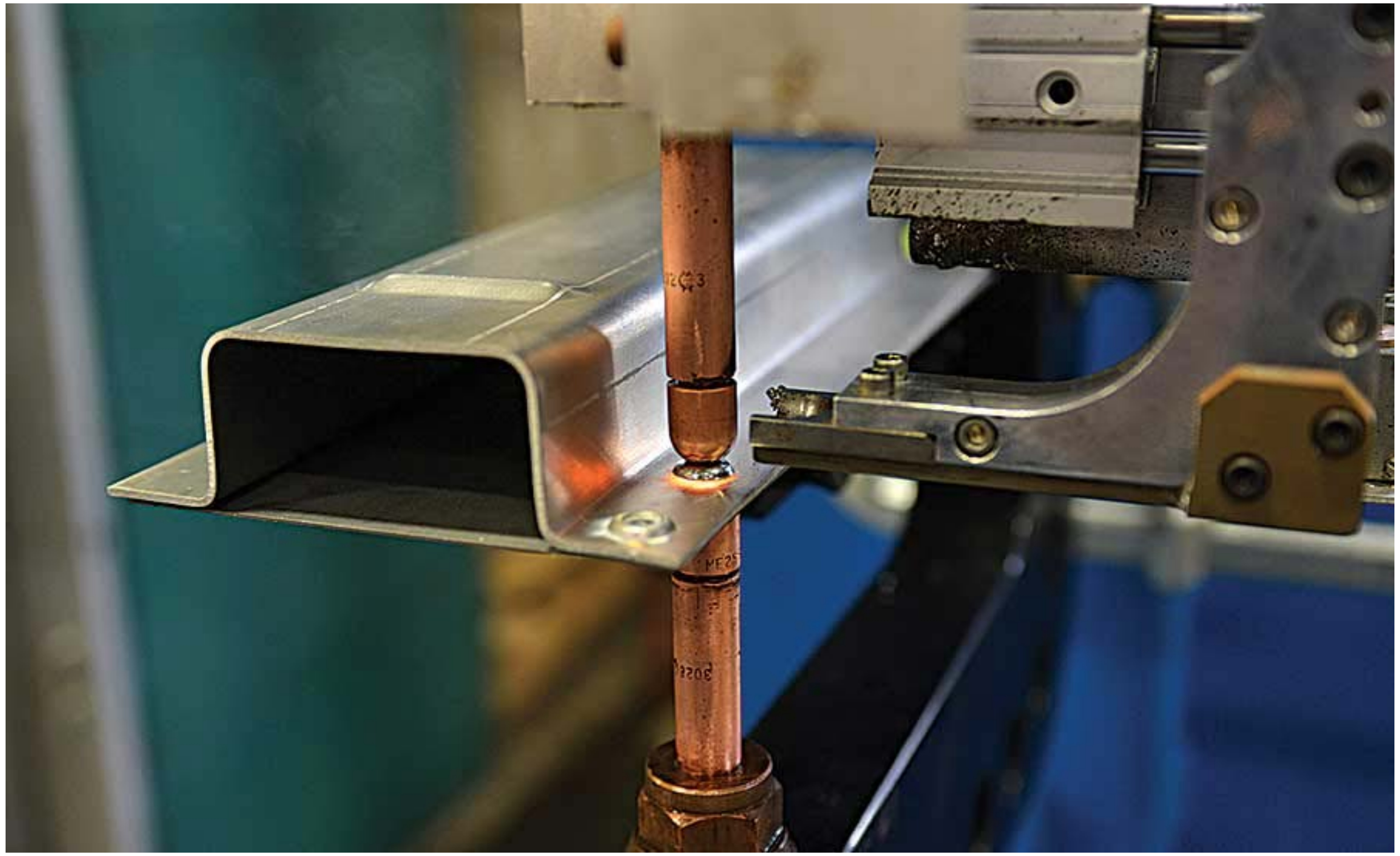


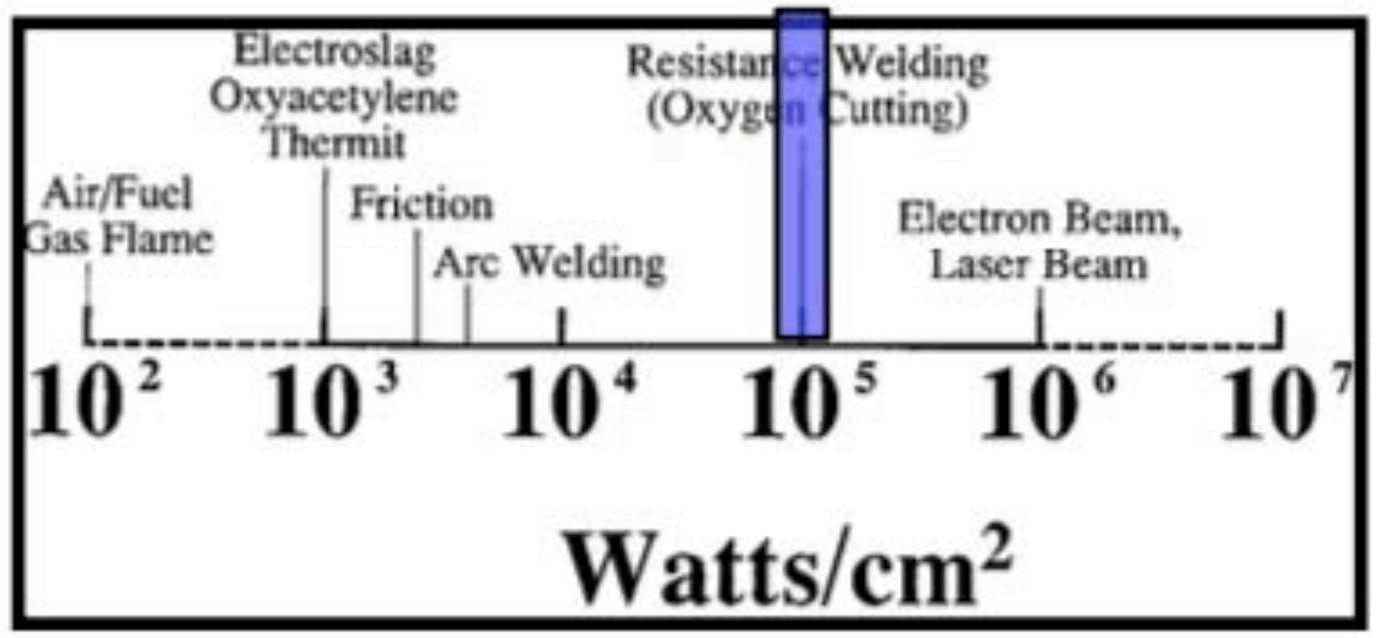


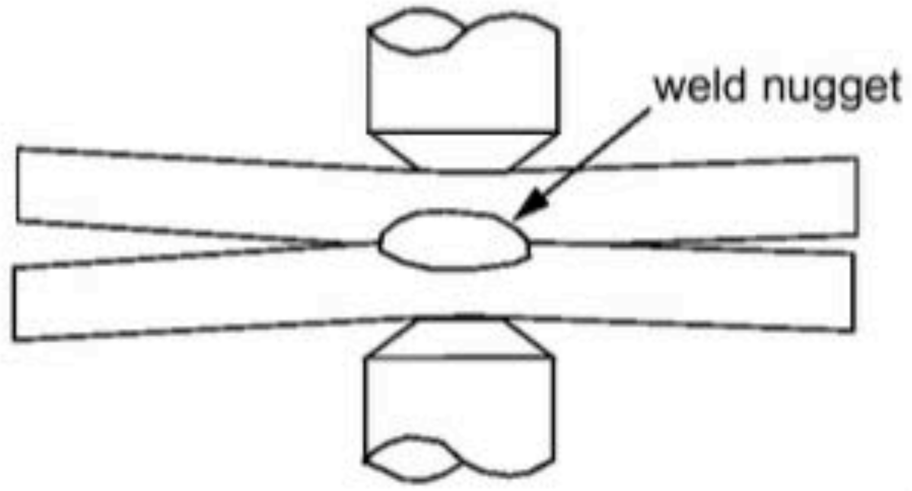
Resistance Welding

high current: 3k-40k Amps

- contact pressure + current + time
- simple and reliable
- welds difficult to inspect
- energy: i^2Rt
- melting in steel: ~1400 J/g







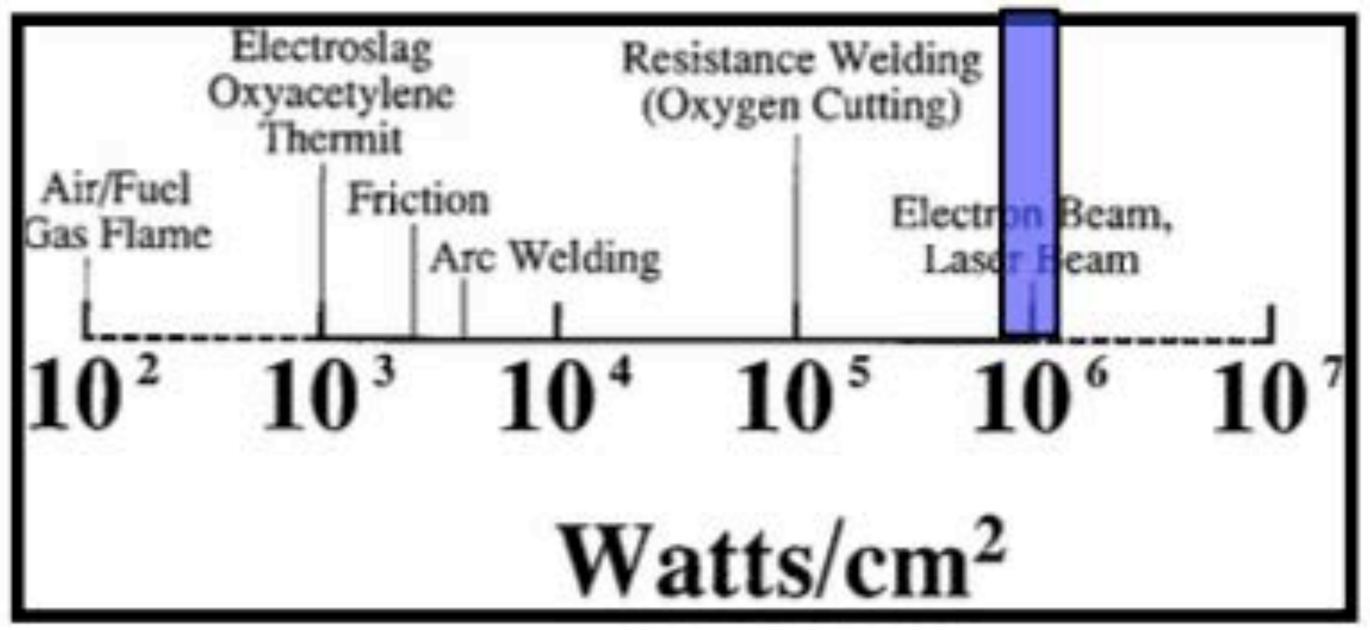
Fusion Welding

electron beam welding: electrons transfer energy

laser welding: photons transfer energy

small HAZ

expensive, careful fixturing needed



DF: Welding

cracks open in tension

part preparation is critical

welds are hard to machine

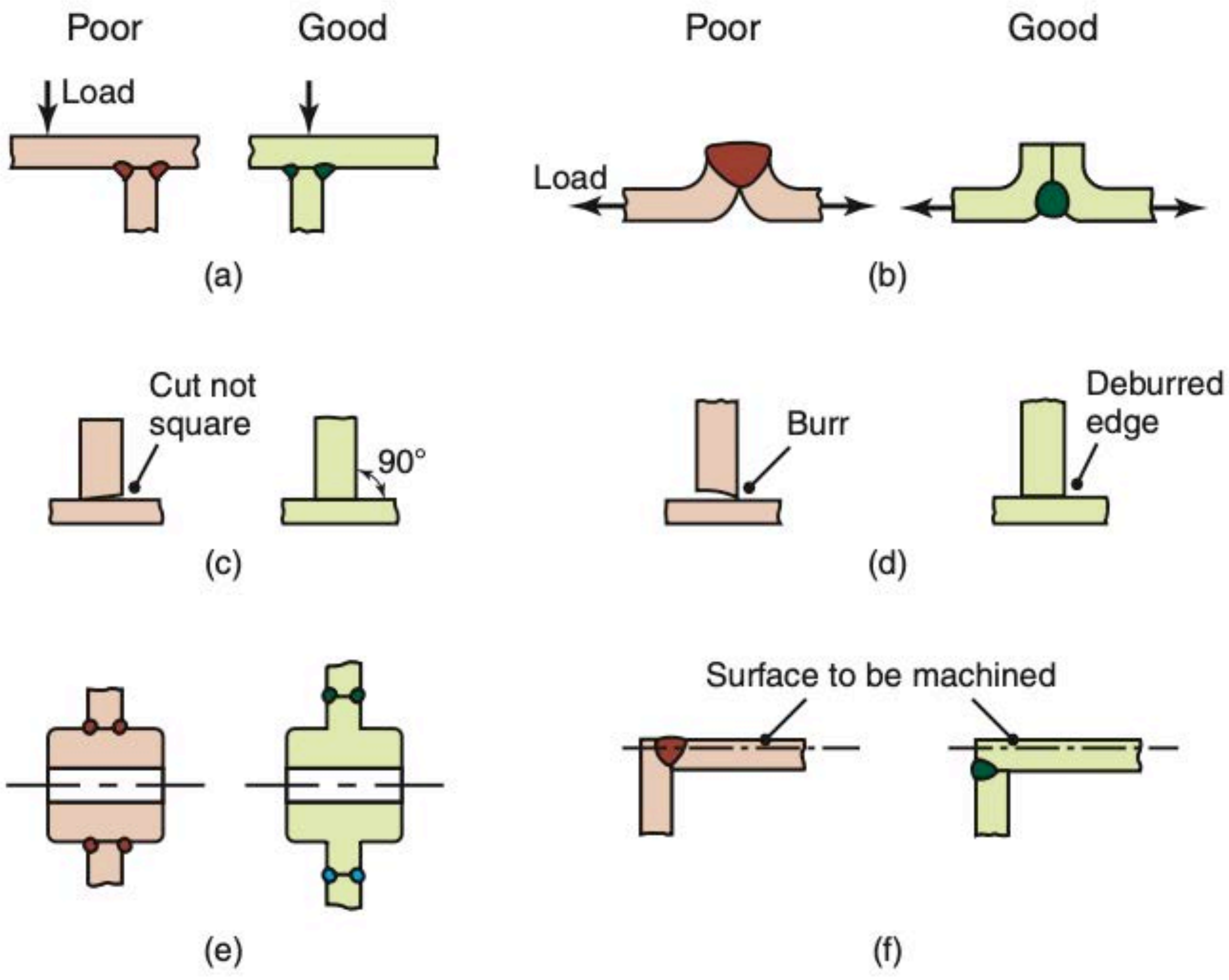
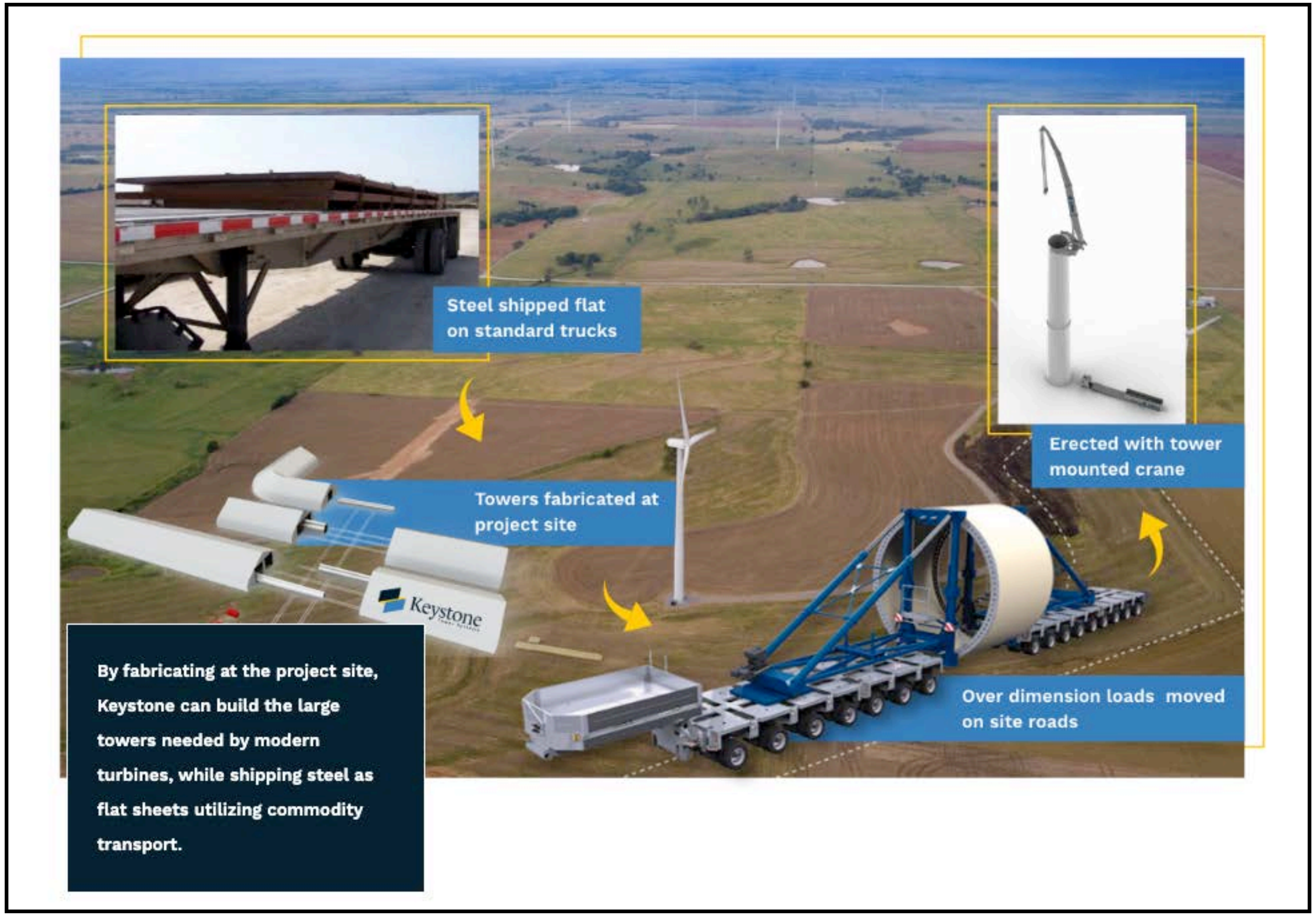


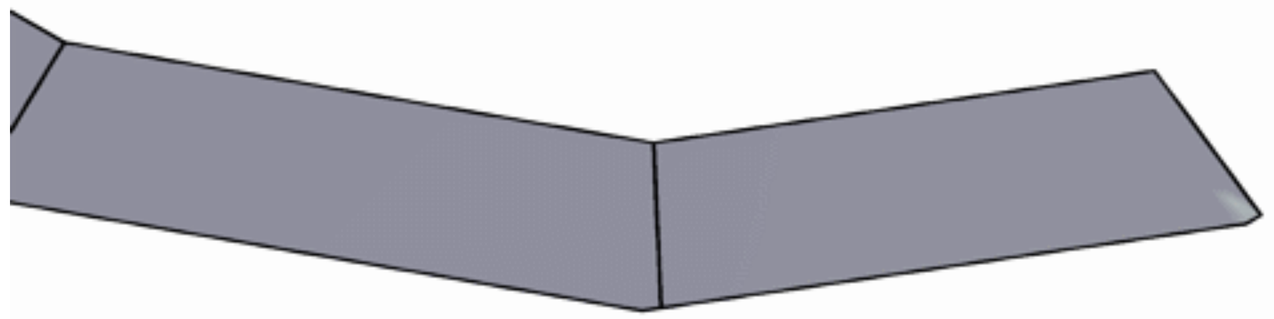
Figure 30.31: Some design guidelines for welds. *Source:* After J.G. Bralla.

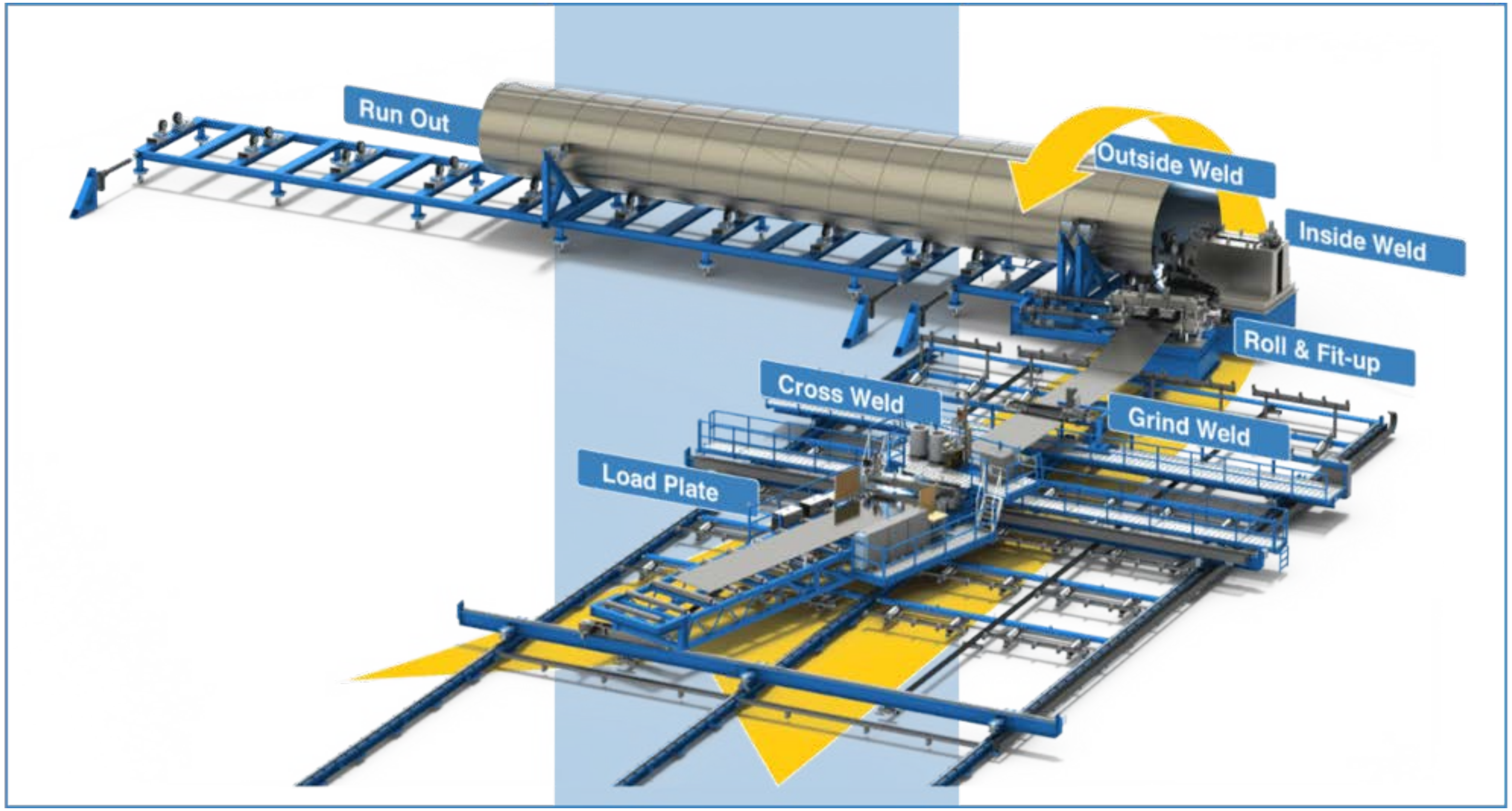
Sustainable Energy: Spiral Welding

Sustainable Energy: Spiral Welding

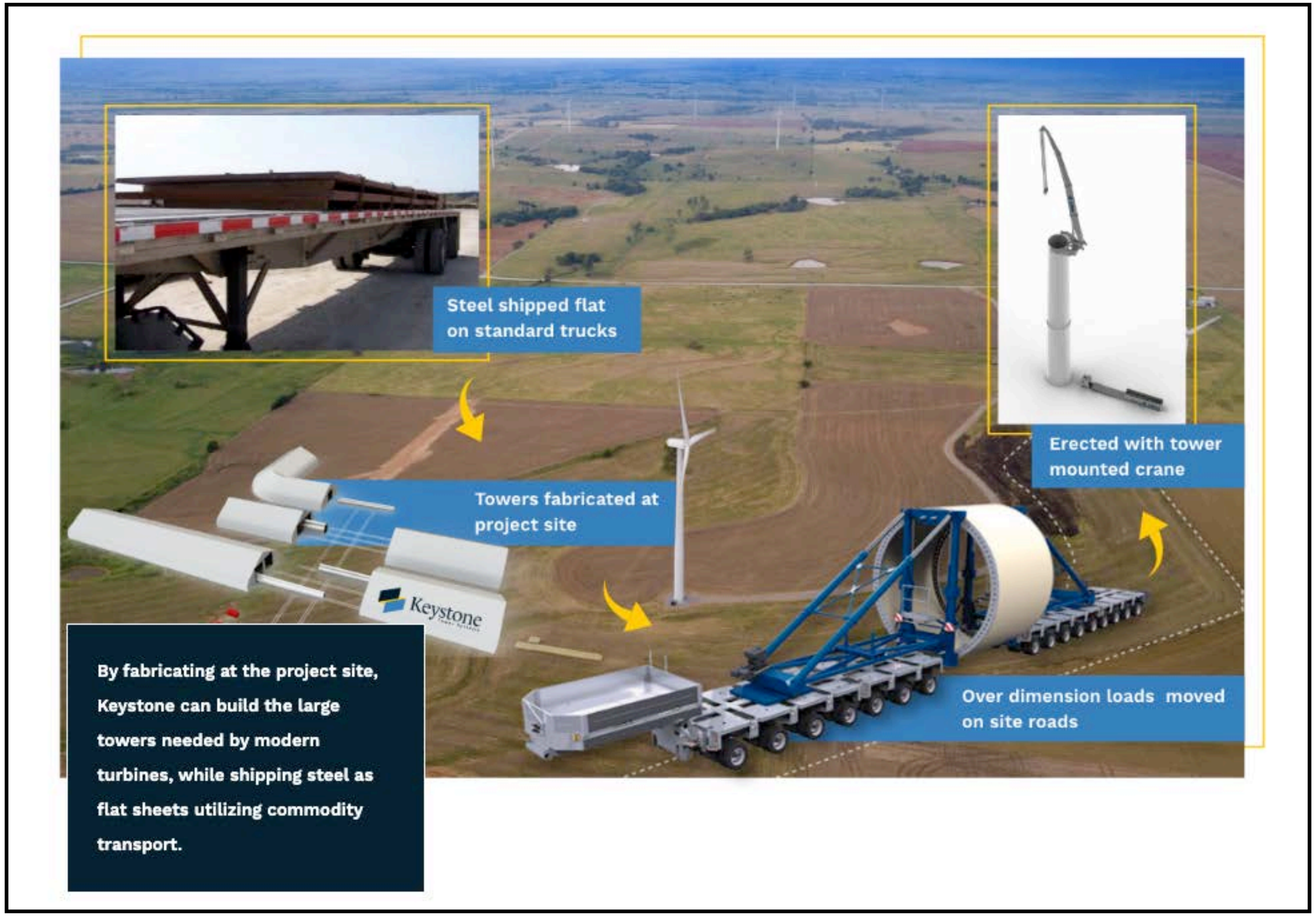


Sustainable Energy: Spiral Welding





Sustainable Energy: Spiral Welding



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Slides 47–51: