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# Chapter 5: Assembly Processes

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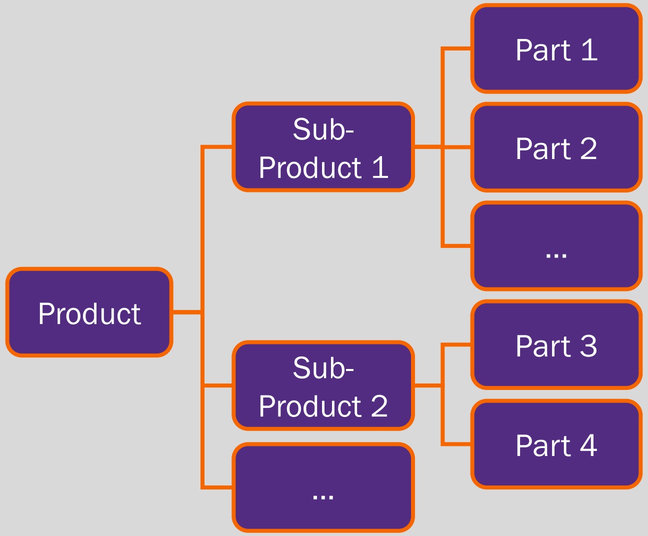
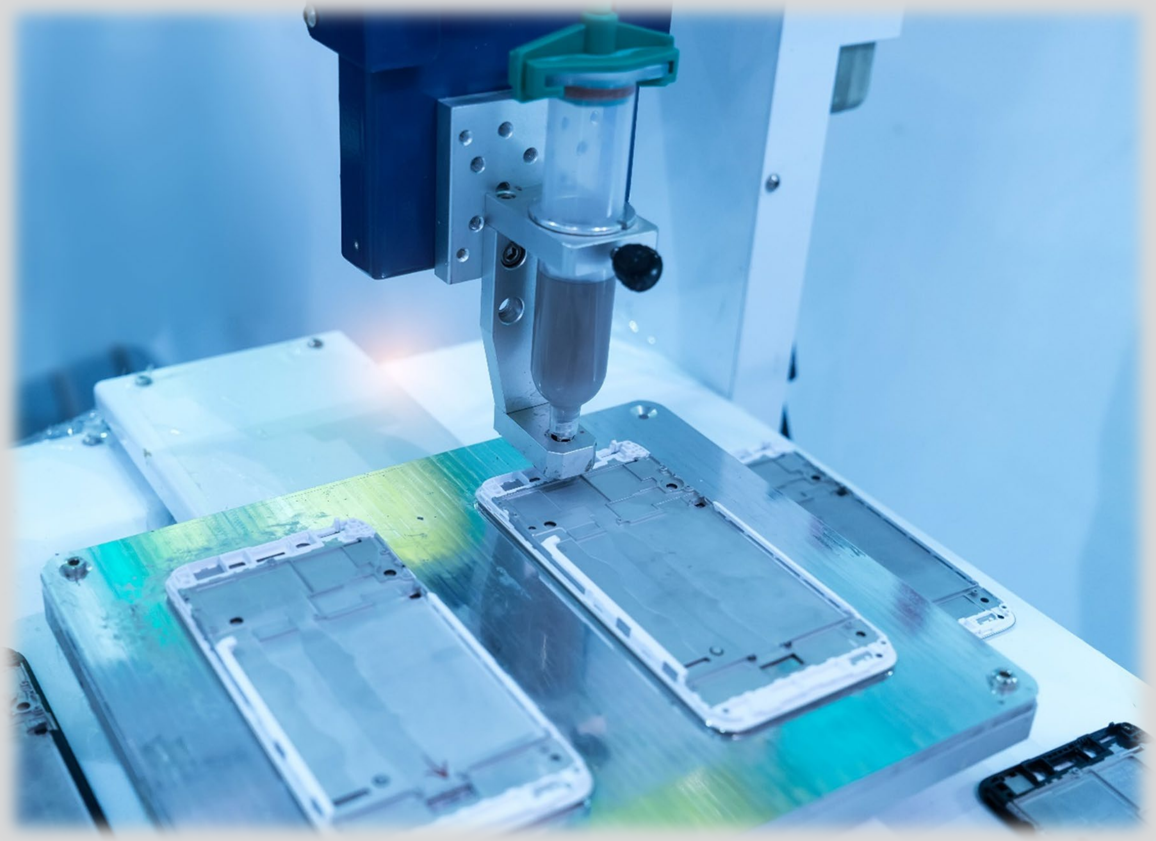
# Outline

# Assembly Operations

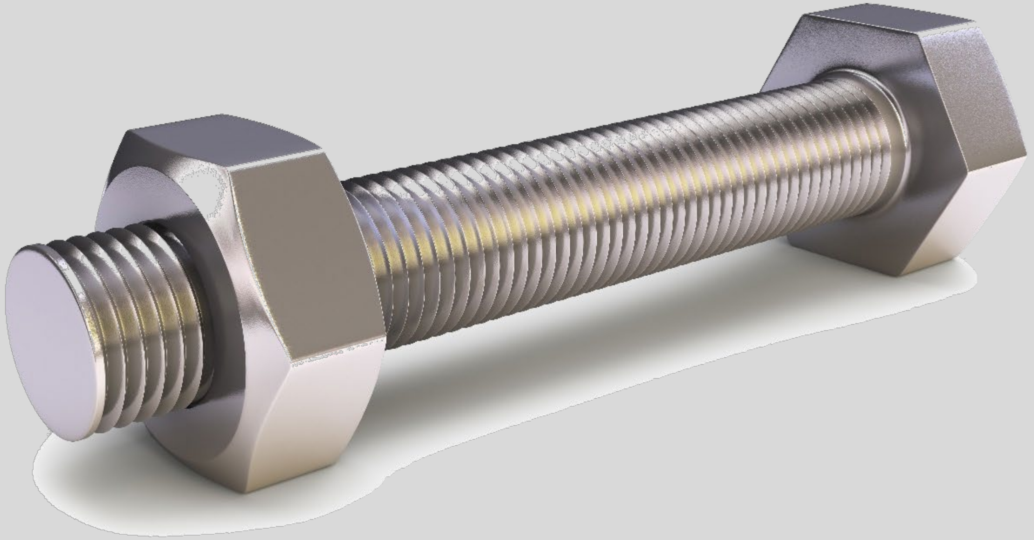
- We obtain products (and sub-products) by performing assembly operations on individual parts.
- Mechanical joining, welding and bonding are examples of Assembly Operations .



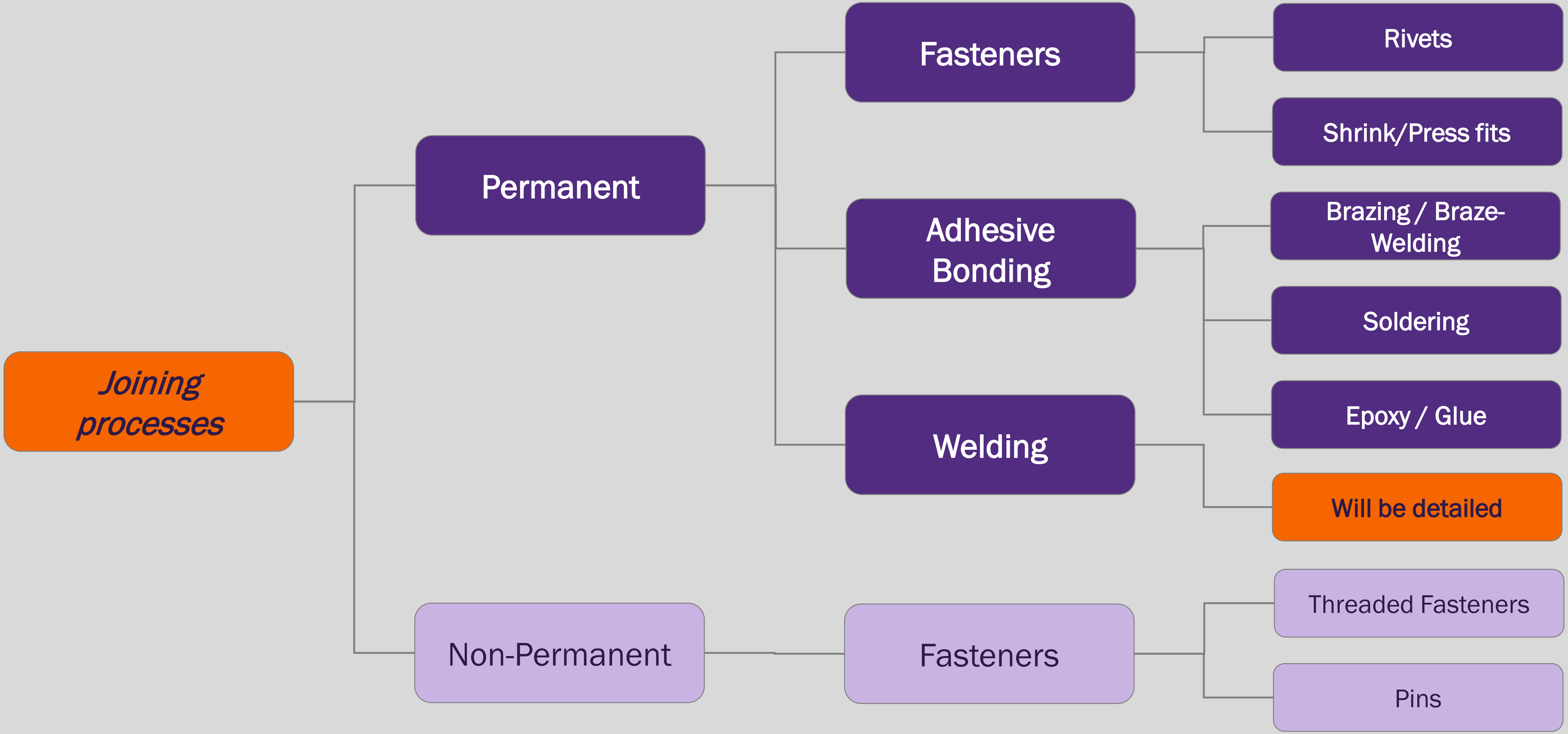



# Assembly – Concept

- Assembly processes describe the joining of two or more work pieces, permanently or non-permanently, using fasteners, adhesive or cohesive bonding
- Assembly processes are used when:
  - Final product can not be manufactured as a individual piece
  - More economical to assemble product than to produce in one piece (e.g., tooling dimensions/cost)
  - Final product requires the option to be disassembled (e.g., for transportation purposes)
  - Different components or final product have contradicting/variating (material property) requirements (e.g., metal/Polymer combination)
  - Final product's design contains high degree of void space
  - Final product is a complex structure, e.g., automobiles, airplanes
  - Repair/maintenance capability through replacement parts



# Structure


Joining processes
Permanent
Non-Permanent
Fasteners
Adhesive Bonding
Welding
Fasteners
Rivets
Shrink/Press fits
Brazing / Braze-Welding
Soldering
Epoxy / Glue
Will be detailed
Threaded Fasteners
Pins

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# Permanent Processes

## Section I

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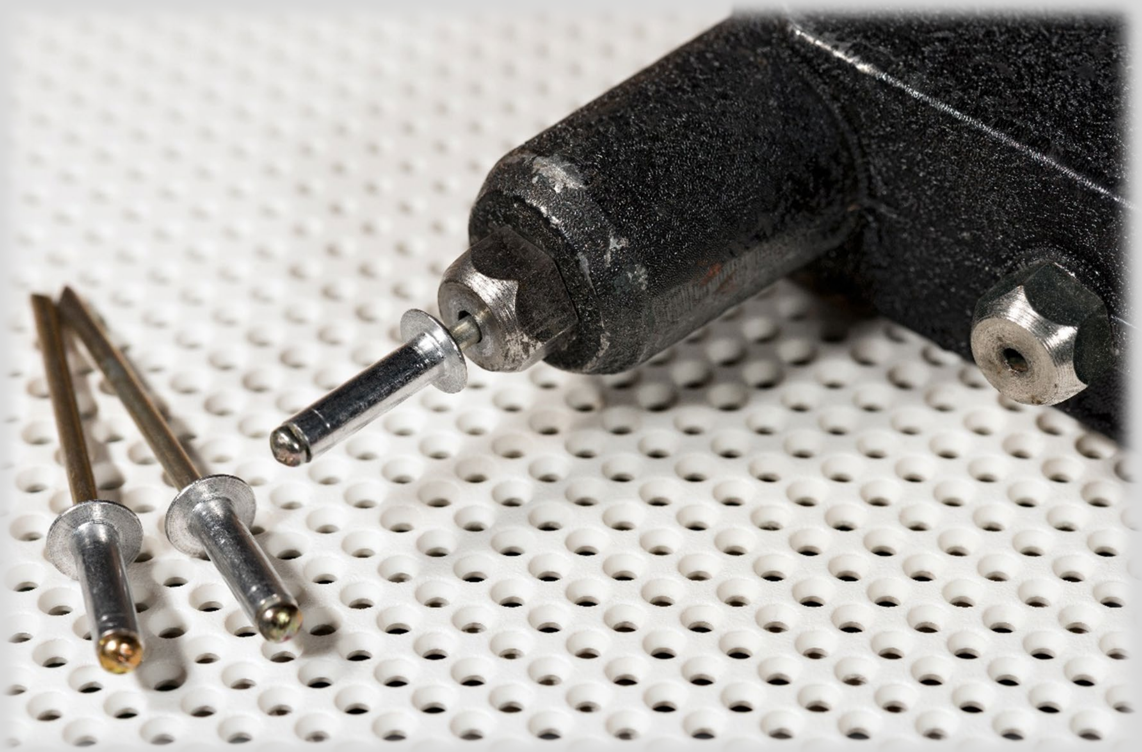
# I | Fasteners: Process Concept

- Fasteners are widely used in manufacturing assemblies and there is a huge variety of different systems and sizes available
- One way of structuring fasteners is by permanent and non-permanent nature
  - Permanent: Rivets; Shrink/Press fits, Seams, etc.
  - Non-Permanent: Threaded Fasteners, Pins, etc.
- Be aware of unit of measure (US/ISO/UK/...)
- Some non-permanent fasteners are made permanent by combining it with another joining process like welding (e.g., threaded stud is welded to base material)

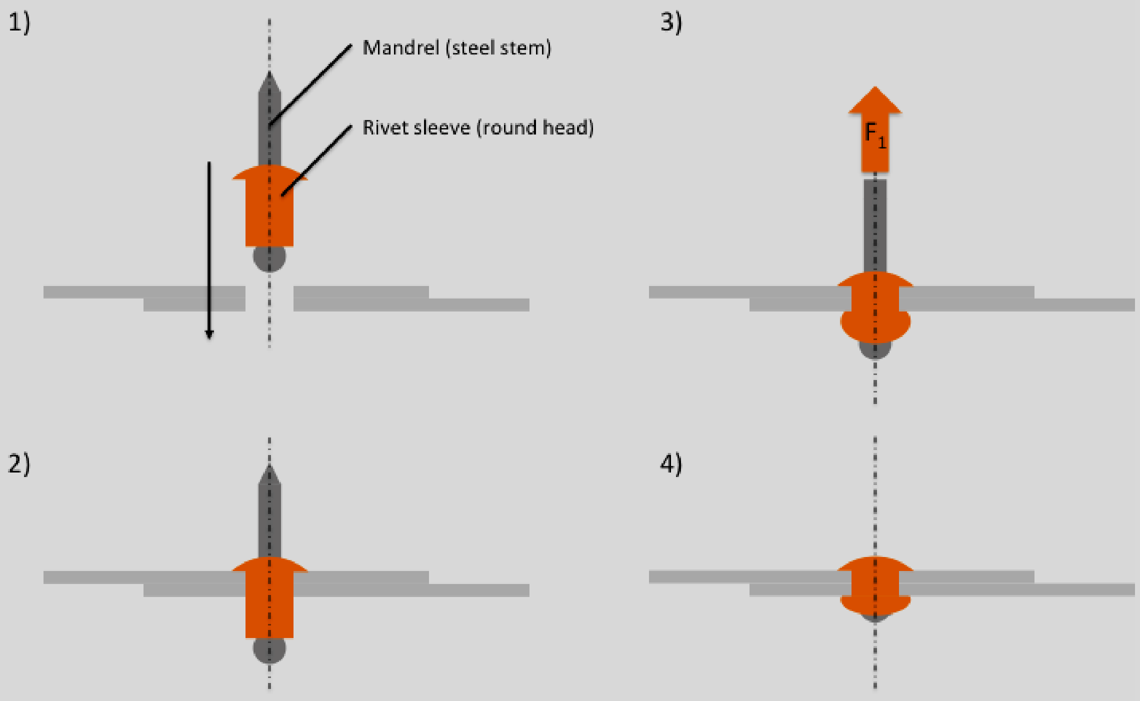
# I | Fasteners: Rivets

- Rivets are a very common type of **permanent fastener** used in a variety of industries
- Compared to threaded fasteners rivets are considered **more economical and stronger**
- Rivets are addressing shear and tension loads
- There are two types of rivet classes
  - **Solid rivets:** Solid material / used when both sides of assembly can be accessed
  - **Blind rivets:** Hollow material / used when only one side of assembly is accessible
  - Solid rivets are stronger when material/weight is similar
  - To achieve similar performance, blind rivets use stronger material and/or larger dimensions, and/or more blind rivets are used
  - Blind rivets are heavier than solid rivets due to steel stem (see on the right)
- **Selected products** commonly using rivets: Airplanes, Jeans, Bridges, Buildings, etc.



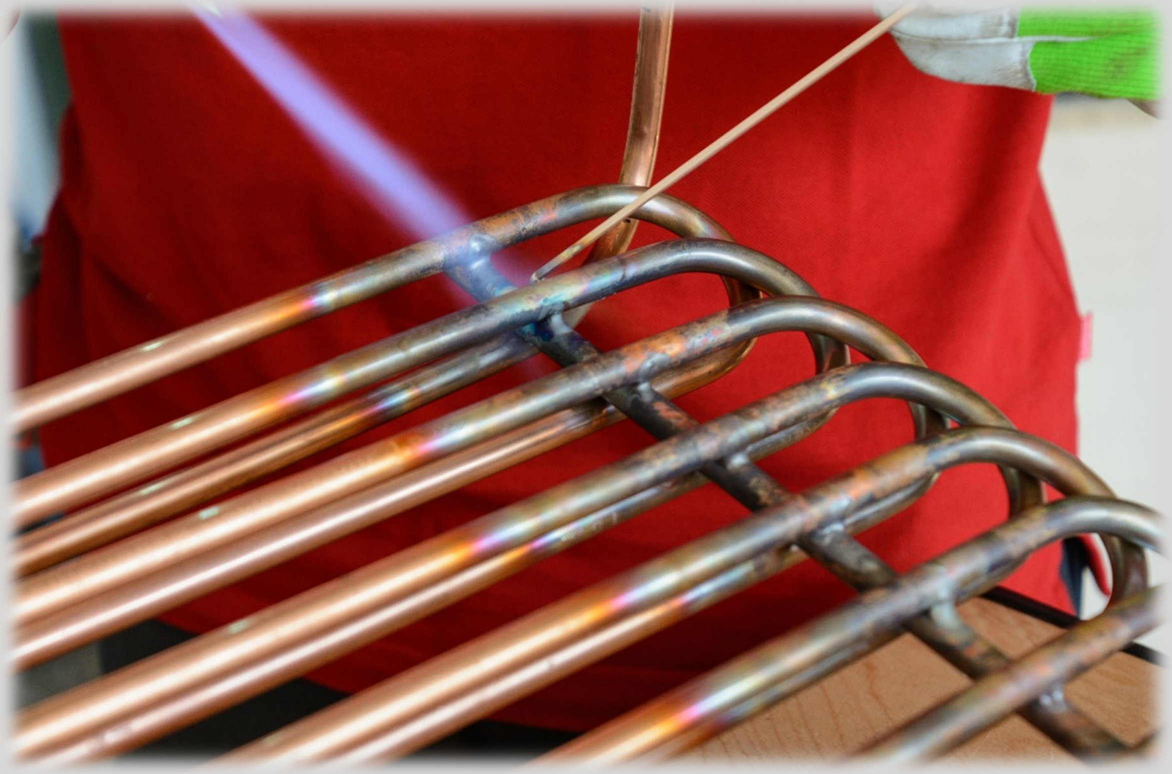
# I | Fasteners: Blind Rivets

- Riveting process:
  - a hole is drilled or punched in two adjacent sheets of material (most commonly sheet metal).
  - blind rivet is inserted in the hole
  - Once the head is aligned with the sheet metal, the rivet gun pulls the internal mandrel and thus deforms the rivet sleeve to effectively join the two sheets together.
  - Once the force exceeds a certain amount, the mandrel breaks (intentionally) and the rivet is installed, securely holding the two sheets permanently together.



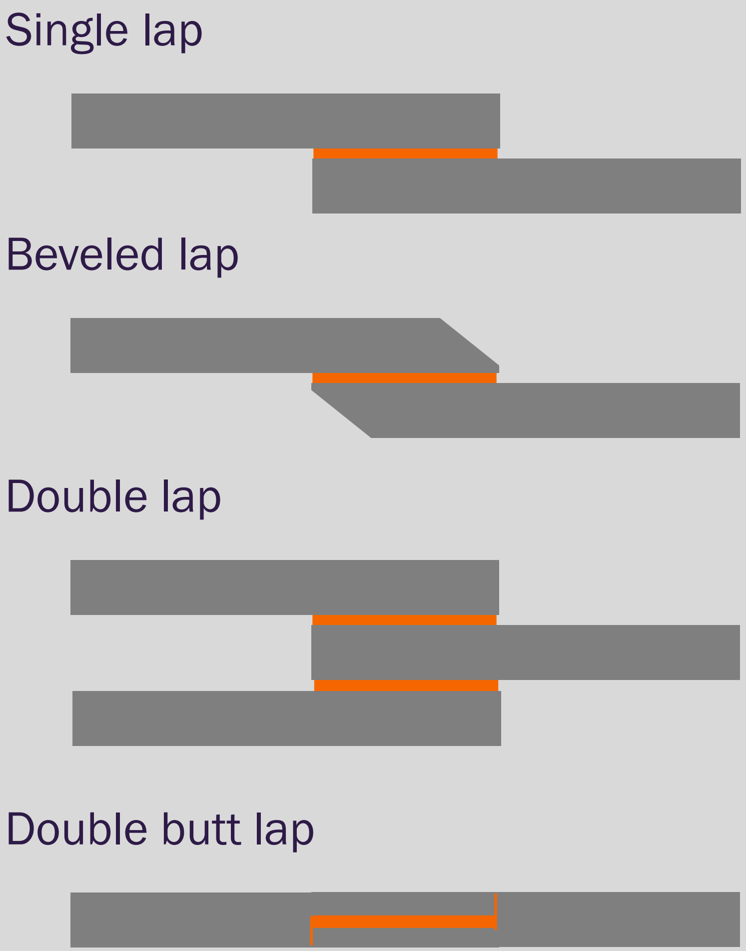
# II | Adhesive Bonding: Introduction

- Adhesive bonding processes describe the joining of two or more work pieces by using an adhesive as a bonding agent between the work piece materials being joined.
- Adhesive processes include brazing, soldering, gluing, and epoxies.
- Possible substructure for adhesive processes distinguishes
  - Metal adhesive processes: brazing, soldering, braze welding
  - Non-metal adhesive processes: epoxies, glues



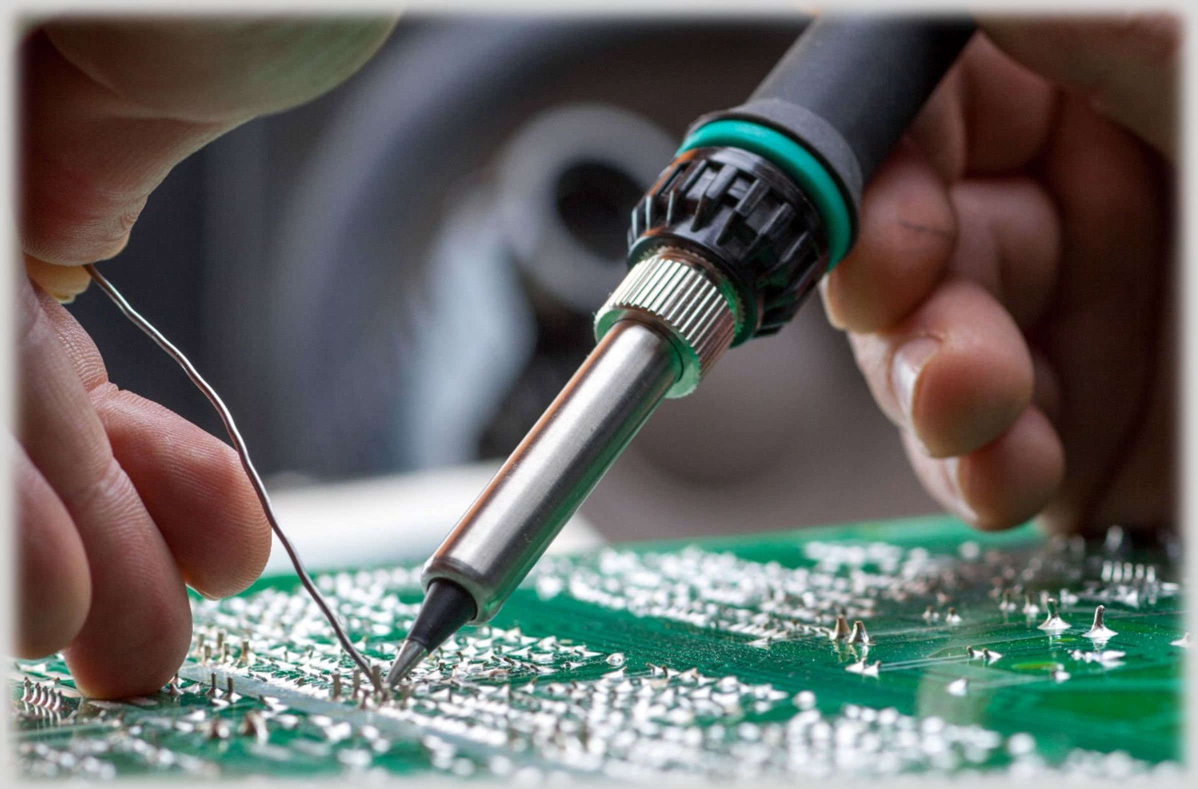
# II | Adhesive Bonding: Lab Joint

- Adhesive bonding processes require some design considerations for the joints
- Typical joint design is the lap joint (see different variations on the right)
- The typical loading that is designed for is shear



# II | Adhesive Bonding: Soldering

- Soldering described an adhesive bonding process using a **metallic filler material** as the bonding agent.
- Soldering distinguishes itself from brazing by the metallic filler material used. In soldering, the metallic filler material has a liquidus a) **below 840°F (450°C)** and b) below the **solidus of the base metal**
- The metallic filler material is distributed by capillary attraction during the soldering process.
- Soldering metallic filler material typically contains metals such as lead, tin, and cadmium



# II | Adhesive Bonding: Brazing

- Brazing described an adhesive bonding process using a metallic filler material as the bonding agent.
- Brazing distinguishes itself from soldering by the metallic filler material used. In brazing, the metallic filler material has a liquidus a) above 840°F (450°C) and b) below the solidus of the base metal
- The metallic filler material is distributed by capillary attraction during the brazing process.
- Brazing metallic filler material typically contains metals such as copper, silver, and gold

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# II | Adhesive Bonding: Glue/Epoxy

- Epoxies / Glue as adhesive bonding agents are often considered structural adhesives
- Epoxies/glue allows the joining of dissimilar materials (e.g., metal/wood/glass)
- Epoxies/glue can join materials with little or no elevated temperature which is required for some applications (e.g., thin materials)
- Can fulfill additional purposes for design (e.g., sealant and insulation)
- Epoxies/glue are (generally) comparably economical and easy to apply
- Process (generalized): 1) prepare surface(s); 2) prepare epoxy/glue; 3) apply epoxy/glue; 4) apply pressure; 5) cure
- Downsides (generalized) include
  - comparably lower joint and peel strength
  - restricted to lower temperature applications
  - low conductivity
  - reduced production time due to curing time

# III | Welding: Introduction

- Welding processes describe the **fusion** between two (metal) work pieces or a work piece and a metallic filler material
- Welding processes employ typically **high temperatures** (at or near the material melting temperature) (-> higher than lower temperature techniques like brazing/soldering)
- In some cases, bonding is achieved by exposing the work pieces to **extreme force** (e.g., forge welding)
- There are different energy sources used for melding, incl. electric, mechanical (pressure), chemical and optical (laser, electron beam)
- The higher the energy source, the deeper the penetration (e.g., laser welding 1+ in.)

# III | Welding: Classification

- There are many different **welding process variations** available
- Selected common welding classifications following **American Welding Societies** (AWS) designations are presented on the right
- The classification categories are determined based on the **mode of energy transfer**

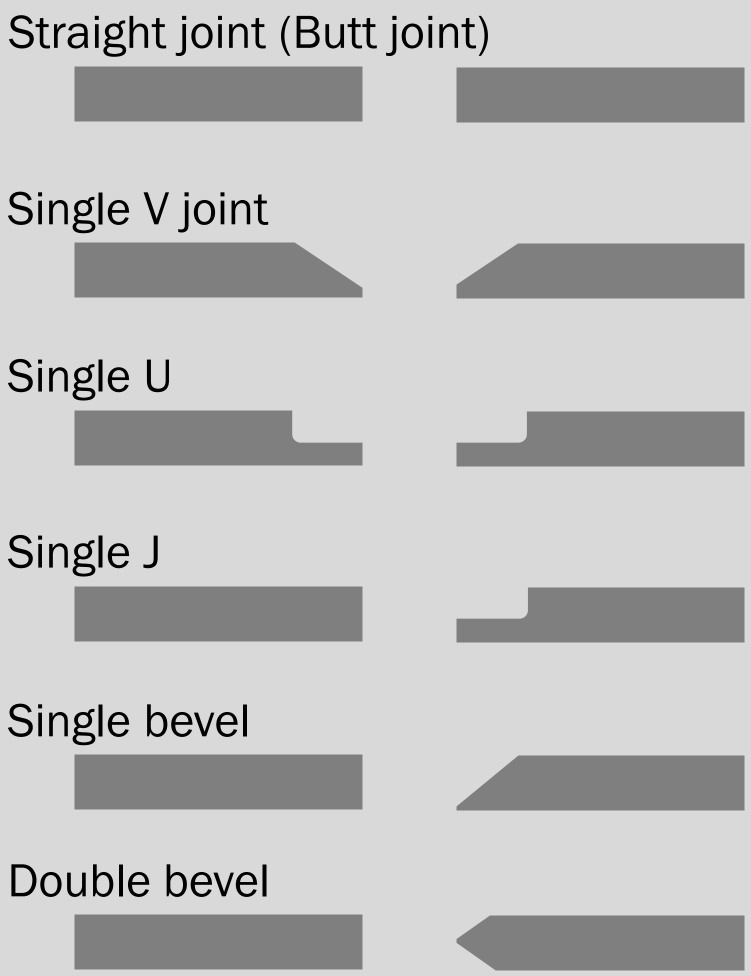
- Typical welding energy sources and their achievable parameters:

| Energy Source | Welding Process | Power density [W/cm²] | Operating Temp. [°C] |
|---|---|---|---|
| Chemical | Oxyacetylene Welding (OAW) | < $10^3$ | 2,000 - 4,000 |
| Electrical | Shielded Metal Arc Welding (SMAW) | $10^4$ | 6,000 - 8,000 |
| | Plasma Arc Welding (PAW) | $10^6$ | 15,000 - 30,000 |
| Radiation | Electron-Beam Welding (EBW) | $10^7$ | 20,000 - 25,000 |
| | Laser Beam Welding (LBW) | > $10^8$ | > 30,000 |

| Category | AWS Classification | Abbreviation |
|---|---|---|
| Oxyfuel Gas Welding *(Torch Welding)* | Oxyacetylene Welding | OAW |
| | Oxyhydrogen Welding | OHW |
| | Pressure Gas Welding | PGW |
| Arc Welding | Carbon Arc Welding | CAW |
| | Shielded Metal Arc Welding | SMAW |
| | Gas Metal Arc Welding | GMAW |
| | Gas Tungsten Arc Welding | GTAW |
| | Flux-cored Arc Welding | FCAW |
| | Submerged Arc Welding | SAW |
| | Plasma Arc Welding | PAW |
| | Stud Welding | SW |
| Resistance Welding | Resistance Spot Welding | RSW |
| | Resistance Seam Welding | RSW |
| | Projection Welding | RPW |
| Solid-State Welding | Forge Welding | FOW |
| | Cold Welding | CW |
| | Friction (Stir) Welding | FRW |
| | Ultrasonic Welding | USW |
| | Explosion Welding | EXW |
| | Roll Welding | ROW |
| Other / Special Welding Processes | Thermit Welding | TW |
| | Laser-Beam Welding | LBW |
| | Electroslag Welding | ESW |
| | Flash Welding | FW |
| | Induction Welding | IW |
| | Electron-Beam Welding | EBW |

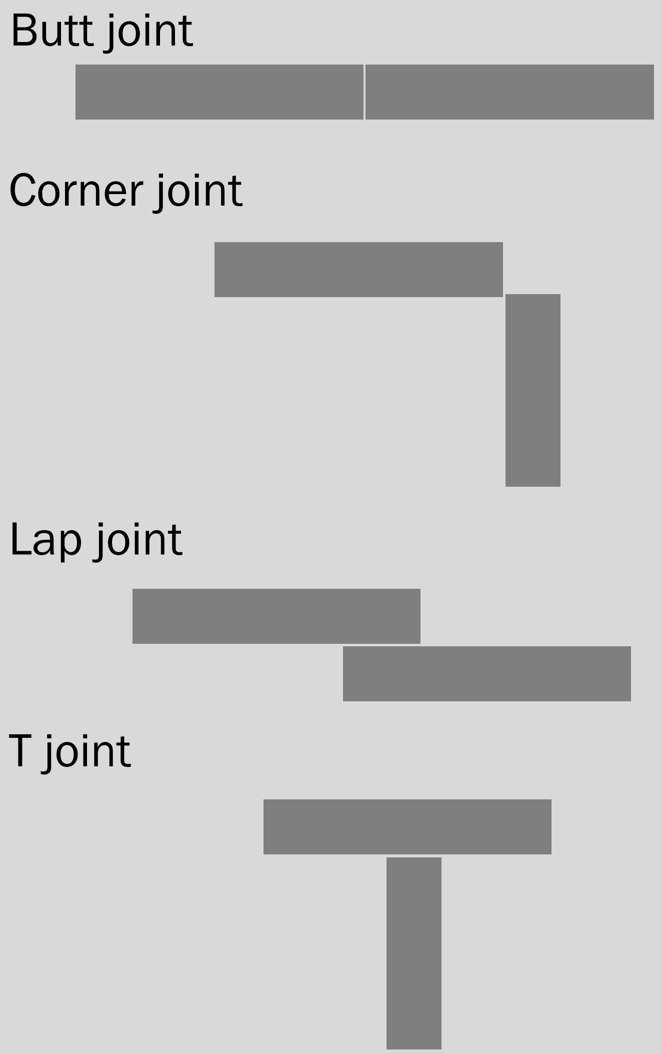
# III | Welding: Welding Joints

- There are several **different welding joint** designs in use today (see selected examples right)
- Selecting **suitable welding joint** design is crucial to achieve the desired properties
- Selection is informed by, e.g.,
    - Base metal (carbon vs. stainless steel)
    - Filler/weld metal
    - Welding technique (e.g., gas-tungsten arc welding vs. shielded metal arc welding)



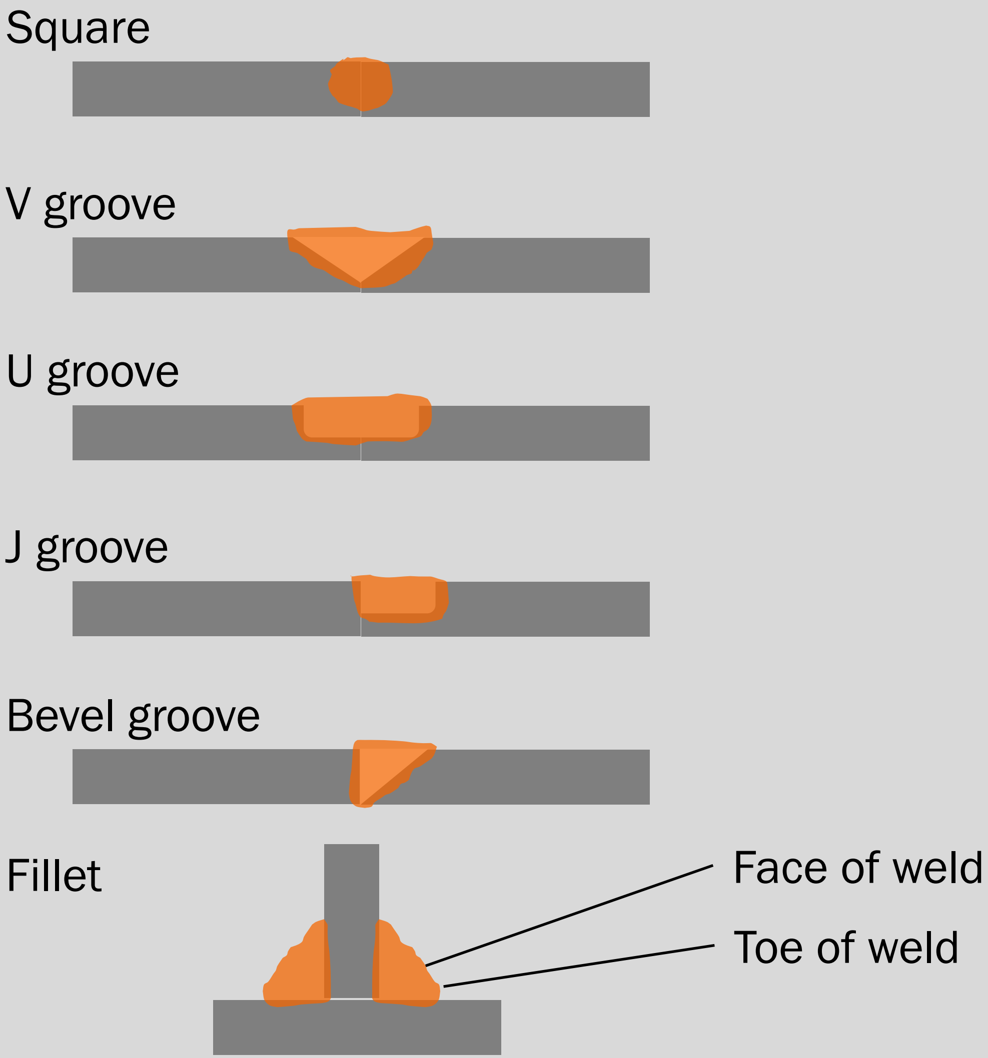
# III | Welding: Welding Joints

- Another **common joint terminology** is based on the relative arrangement of to-be-joint parts :
  - Butt joint
  - Corner joint
  - Edge joint
  - Lap joint
  - T-joint



# III | Welding: Welding Types

- **Fillet welds** are very common and describe the joining of 2 or more work pieces at an ~90° angle. e.g., a full filet defined as size of weld = thickness of smaller work piece
- **Groove welds** similarly common and describe the welding bead joining 2 or more work pieces
- There are other less commonly used **specialty variations** used: surface welds, seam welds flash welds, spot welds, upset welds, etc.

# III | Welding: Arc Welding

- Arc welding induced the energy required to fuse 2 or more metal work pieces together using electricity
- Process creates an arc between electrode and work piece(s), melting the material. Melting is mostly affecting base metal but with a consumable electrode, the electrode metal is included as well
- Arc welding is one of the most commonly used welding processes in industry
- Variations of arc welding processes available (sel.):
  - Shielded Metal Arc Welding (SMAW)
  - Gas Tungsten Arc Welding (GTAW)
  - Submerged Arc Welding (SAW)
  - Plasma Arc Welding (PAW)
- The electrode varies with the process used between consumable (e.g., SMAW, SAW) and non-consumable (e.g., GTAW, PAW) electrodes

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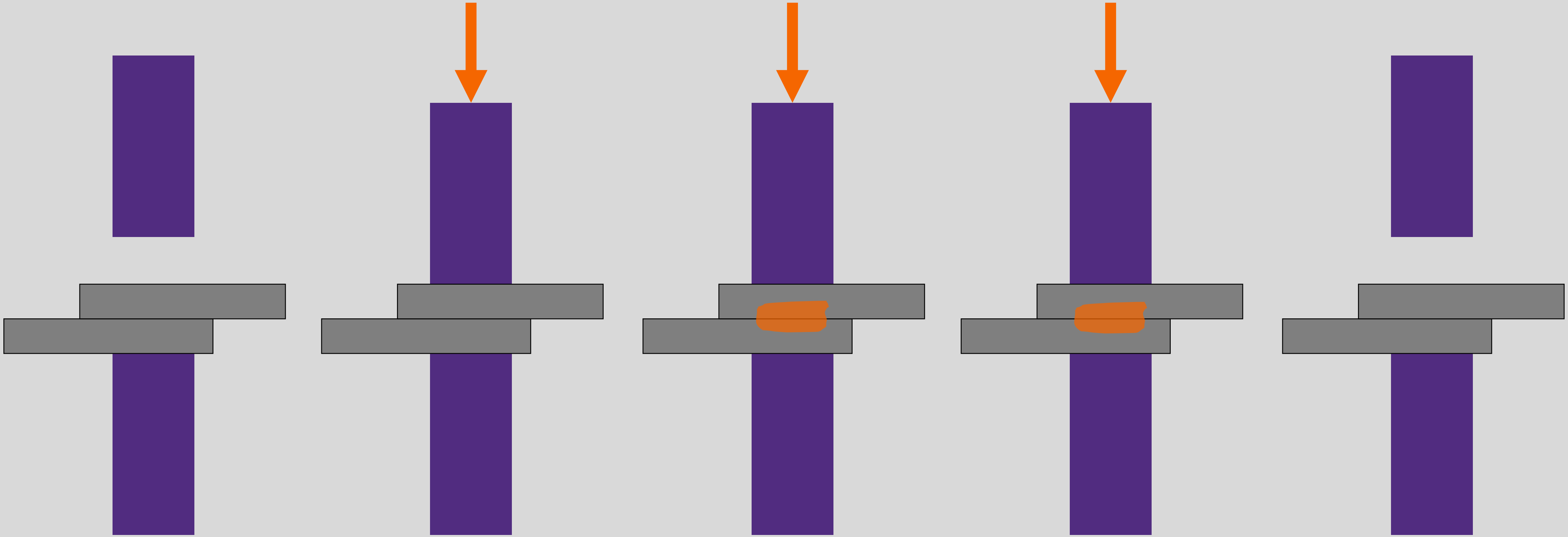
# III | Welding: Torch Welding

- Torch (or gas) welding describes the process of fusing 2 or more work pieces together using **thermal energy** (flame) often involving a filler metal
- One of the most common torch welding processes is Oxy Fuel Welding (OFW) with **Oxygen-Acetylene Welding**, Oxygen-Hydrogen Welding and Pressure Gas Welding subgroups
- Torch welding has the **advantage** that the energy induced as well as amount of added filler material can be closely controlled by the (experienced) operator

# III | Welding: Spot Welding

- Part of the Resistance Welding family that uses electricity/pressure to create the welding nugget
- Very common process in the automotive industry especially in sheet metal joining processes
- Spot welding in the automotive industry is mostly fully automated and integrated with robotic platforms
- The spot-welding cycle includes the application of current for a short interval while maintaining the joint under pressure

# III | Welding: Spot Welding



Loading

Pressure

Pressure + Current

Pressure

Unloading

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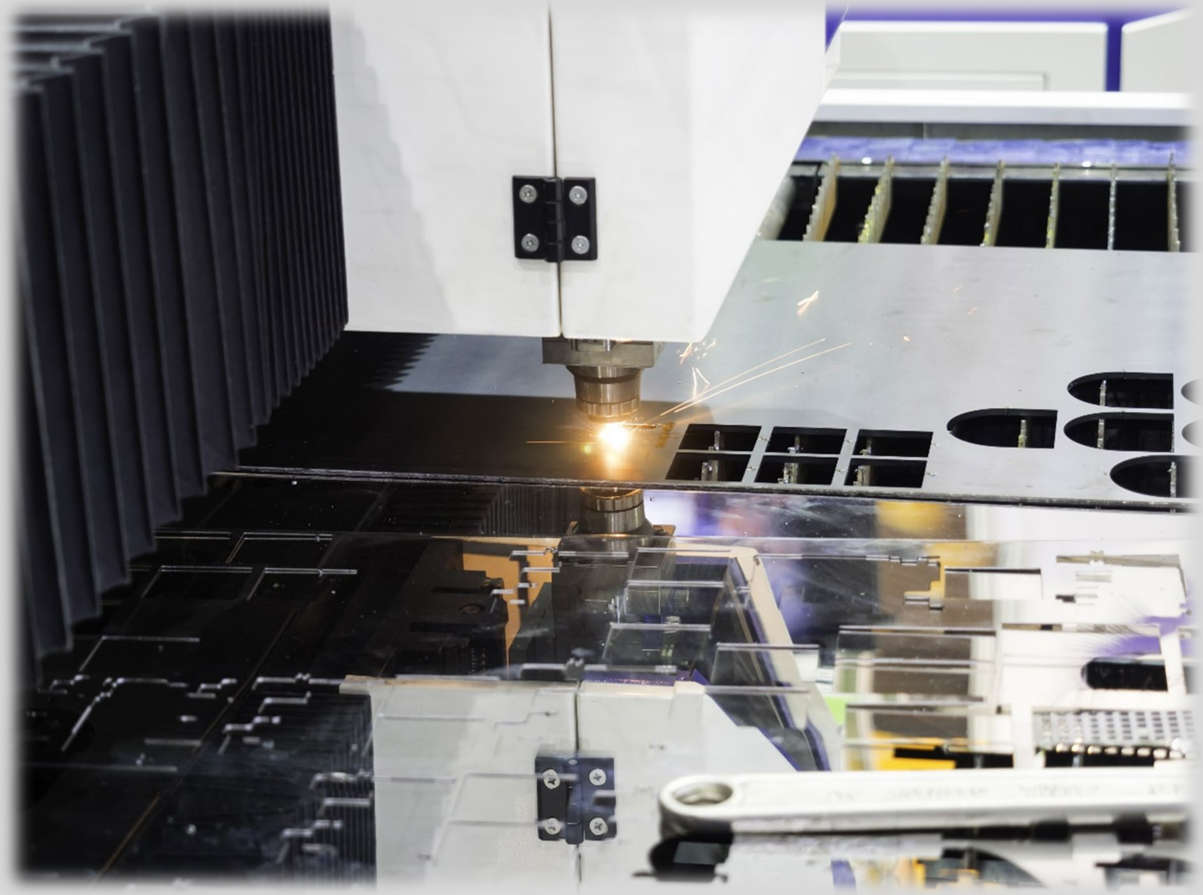
# III | Welding: Laser Welding

- Laser Welding describes the process of fusing 2 or more workpieces by inducing energy via a laser system
- Laser welding combines the desired properties: high speed and high precision
- Process: The laser vaporizes metal material where it meets the base metal and creates a keyhole which remains open as long as the process is running and is then subsequently filled by molten material of the weld pool
- The process is very complex and thus difficult to control. Using high-speed cameras as an input for process control challenges even the most advanced analytics methods due to the enormous amount of data produced

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# Knowledge Check

In solid state welding, gas is used to provide the melting heat

A. True
B. False

# Knowledge Check

In solid state welding, gas is used to provide the melting heat

A. True

B. **False**

# Knowledge Check

Identify the above joint

A. Corner
B. Butt
C. Lap
D. T Joint

# Knowledge Check

Identify the above joint

A. Corner
**B. Butt**
C. Lap
D. T Joint

# Knowledge Check

Identify the above joint

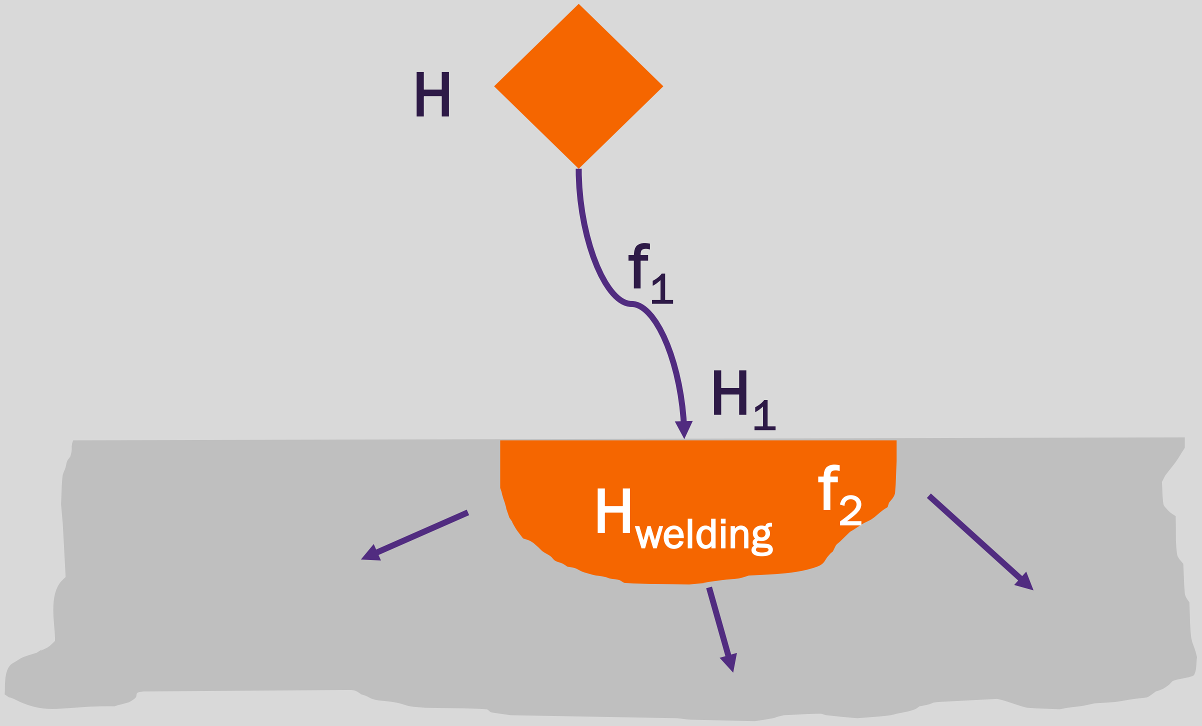
A. V groove
B. J groove
C. U groove
D. Double V groove

# Knowledge Check

Identify the above joint

A. **V groove**
B. J groove
C. U groove
D. Double V groove

# IV | Welding: Physics




- The amount of heat performing the welding operation experiences two losses from the source:
- First loss due to heat transfer ($f_1$)
- Second loss due to conduction ($f_2$)

$$H_{welding} = f_1 \, f_2 \, \mathrm{H}$$

- The same amount of heat is melting the welding volume V and is the function of the unit energy required for melting

$$H_{welding} = \mathrm{V \times Unit\ Melting\ Energy}$$

# Knowledge Check

What is the unit melting energy (in J/mm3) for low steel alloys?

A. 1700
B. 3.9
C. 9.6
D. 16.9
E. 840

# Knowledge Check

What is the unit melting energy (in J/mm3) for low steel alloys?

A. 1700
B. 3.9
C. 9.6
D. 16.9
E. 840

$U_m = KT_m^2 = 3.33 \times 10^{-6}(1700)^2 = 9.6$ J/mm$^3$

# Class Exercise 1:

- A SMAW operation is accomplished in a work cell using a fitter and a welder. The fitter takes 5.5 min to place the unwelded components into the welding fixture at the beginning of the work cycle, and 2.5 min to unload the completed weldment at the end of the cycle. The total length of the several weld seams to be made is 2000 mm, and the travel speed used by the welder averages 400 mm/min.
- Every 750 mm of weld length, the welding stick must be changed, which takes 0.8 min. While the fitter is working, the welder is idle (resting); and while the welder is working, the fitter is idle.
- (a) Determine the average arc time in this welding cycle.
- (b) How much improvement in arc time would result if the welder used FCAW (manually operated), given that the spool of flux-cored weld wire must be changed every five weldments, and it takes the welder 5.0 min to accomplish the change?
- (c) What are the production rates for these two cases (weldments completed per hour)?

# Class Exercise 2:

- An RSW operation is used to make a series of spot welds between two pieces of aluminum, each 2.0 mm thick.
- The unit melting energy for aluminum = 2.90 J/mm3.
- Welding current = 6,000 amps, and time duration = 0.15 sec. Assume that the resistance = 75 micro-ohms.
- The resulting weld nugget measures 5.0 mm in diameter by 2.5 mm thick.
- How much of the total energy generated is used to form the weld nugget?

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# Non-Permanent Processes

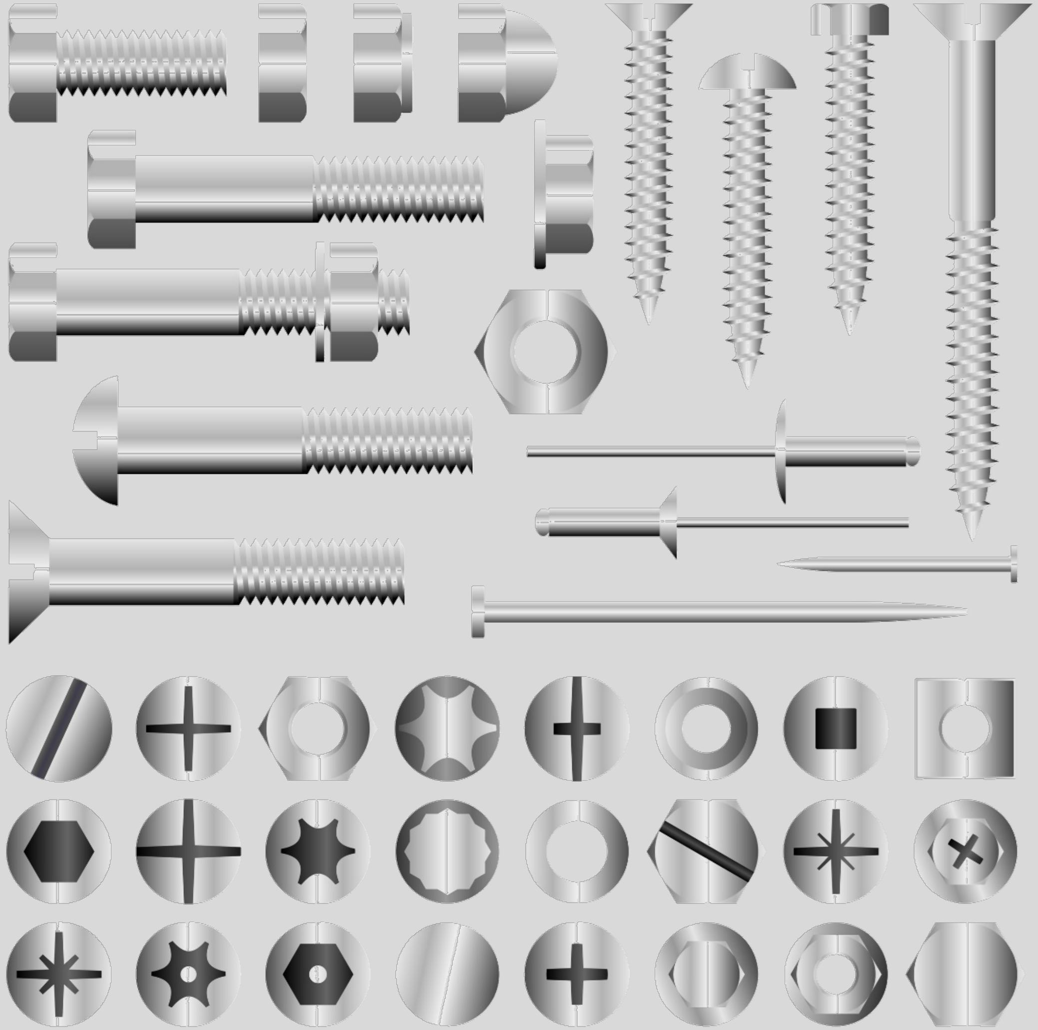
## Section II

# I | Fasteners: Process Concept

- Fasteners are widely used in manufacturing assemblies and there is a huge variety of different systems and sizes available
- One way of structuring fasteners is by permanent and non-permanent nature
  - Permanent: Rivets; Shrink/Press fits, Seams, etc.
  - Non-Permanent: Threaded Fasteners, Pins, etc.
- Be aware of unit of measure (US/ISO/UK/...)
- Some non-permanent fasteners are made permanent by combining it with another joining process like welding (e.g., threaded stud is welded to base material)

# I | Fasteners: Threaded Fasteners I

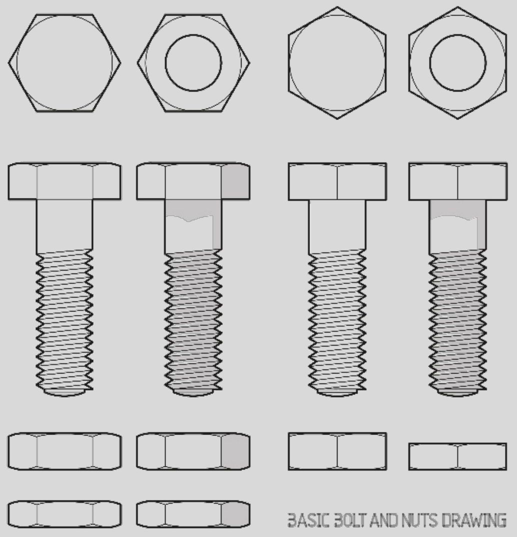
- Bolts consist of two parts
  - External (male thread): e.g., screw or bolt
  - Internal (female thread): e.g., nut, insert, tapped hole
  - Most commonly used thread system: bolt & nut
- Screws do not require nut
  - External threads (often with self-drilling design)
  - Holes might be drilled in work piece prior
- Studs are similar to bolts
  - Are headless fasteners with external threads
  - Common uses: One end of stud mates with (tapped hole) in work piece and the other with nut or both ends mate with two nuts

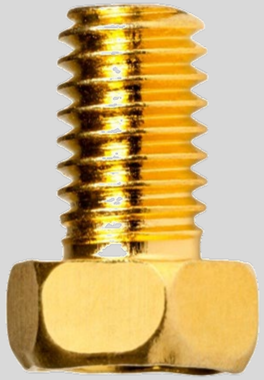


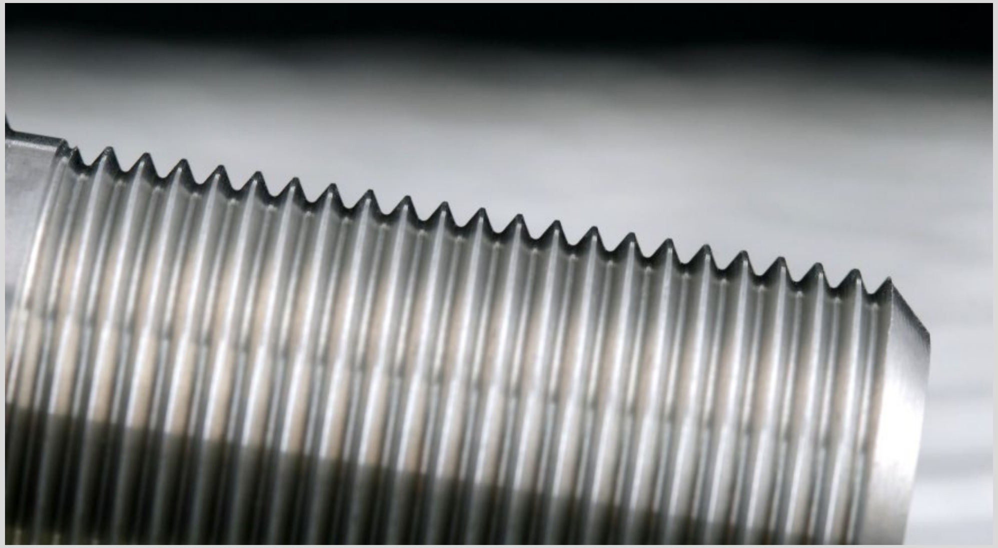
# I | Fasteners: Threaded Fasteners II

Common designations

- Thread Pitch
  - Metric: Pitch in thread designation (e.g., ‘M10 x 1.5’ -> P = 1.5)
  - US: Pitch inverse of thread count (e.g., 3 threads per in. -> P = 1/3)
- Thread variations
  - Sharp V
  - Metric
  - Square
  - Buttress
  - Witworth Standard
  - etc.





# I | Fasteners: Threaded Fasteners III

- Designing the bolt based on the assembly requirement (and expected use) is essential
- Not only **strength of bolt** have to be considered but also the expected **failure mode** ("It's not a bug, it's a feature!")
- There are three common failure modes that can occur using threaded fasteners:
  - **Tensile failure** of bolt (**preferred in most cases**) (compare **a)** on right side)
  - Shear failure of **external threads** of bolt (compare **b)** on right side)
  - Shear failure of **internal threads** of nut / tapped hole

# I | Fasteners: Pins

- Pins are used to precisely define and ensure the position of different parts (2+) of an assembly relative to each other
- A commonly used differentiations is
  - Dowel pins: No (or only little) force required
  - Straight pins: Force required to insert
- Pins can serve multiple purposes in an assembly:
  - Ensure tight tolerances for precise alignment
  - Provide extra support
  - Control exact positioning of parts
- Previous (subtractive) manufacturing processes:
  - Pin: Turning on lathe
  - Corresponding hole: Reaming process

# II | Snap Fit:

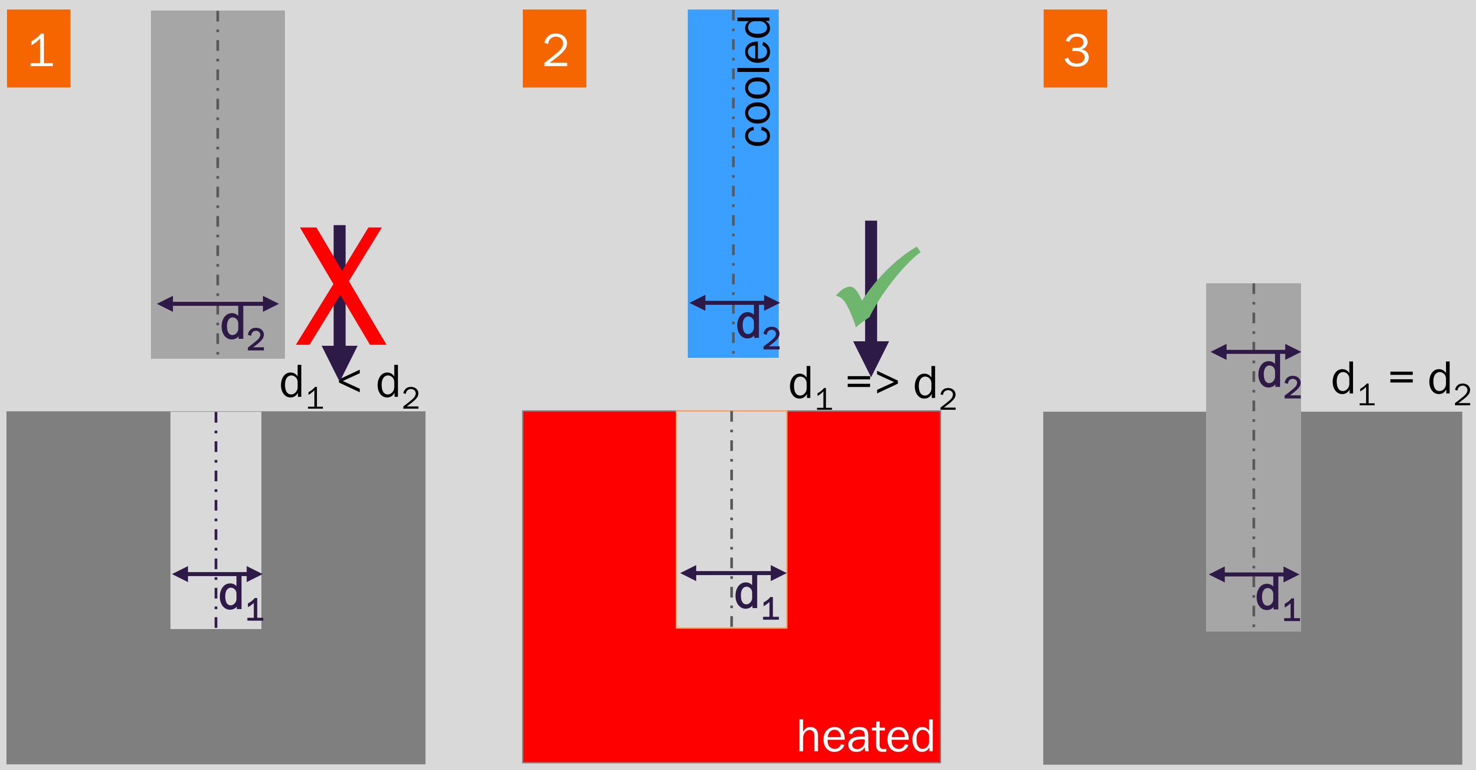
- Part is flexible and enable temporary extension to ‘snap fit’ into the final assembly

- Commonly applied on plastic parts

- Popular examples: covers for smartphones

# III | Shrink Fit: (Rather permanent)

- Shrink fit describes the permanent joining of two workpieces through interference fit making use of the (thermal) expansion/shrinkage of (metal) materials
- Variations include heating OR cooling of one workpiece or (depicted on the right) the heating of receiving AND cooling of the to-be-inserted part
- While the two diameters are becoming closer to being the same, there is often still a certain amount of force required to insert the workpiece in the receiving part
- Shrink fits are resulting in extremely high accuracy and also reduce the number of parts required in an assembly

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# Knowledge Check

Rivets require access to both sides of an assembly to be considered?

A. True
B. False

# Knowledge Check

Rivets require access to both sides of an assembly to be considered?

A. True

B. **False**

# Knowledge Check

Pins are a viable alternative to bolts for non-permanently joining two parts of an assembly.

A. True
B. False

# Knowledge Check

Pins are a viable alternative to bolts for non-permanently joining two parts of an assembly.

A. True

B. False

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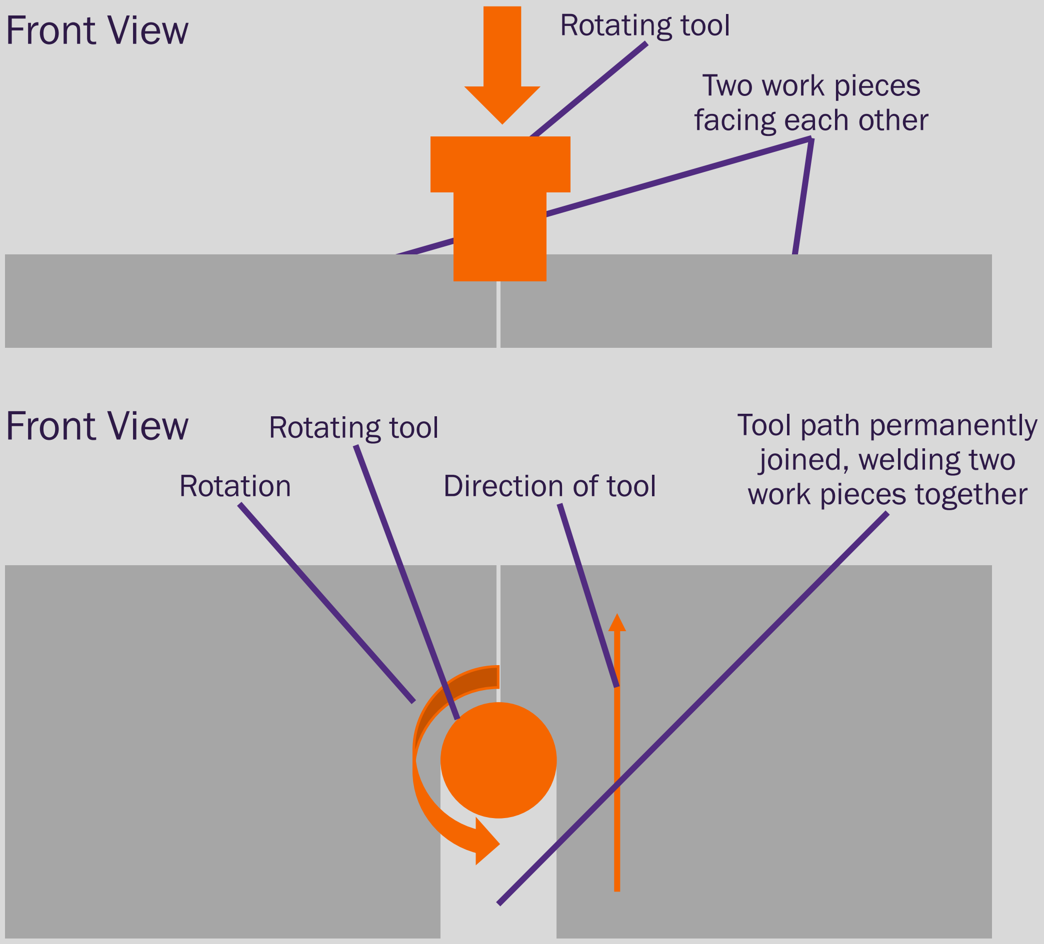
# Recent Trends

## Section III

# I | Friction Stir Welding

- Friction (Stir) Welding is a sub-process of the Solid-State Welding Category
- Used to join workpieces that face each other by use of heat energy, generated by friction between the workpieces and the rotating tool
- Tool rotates at the area where the two workpieces face each other. A force is applied to the tool, increasing the friction and thus the heat generated (mechanically)
- The resulting heat energy induced joins the two workpieces without melting the materials
- Mainly used in conjuncture with metal or polymer (thermoplastics) materials
- Applications range from automotive to aerospace parts



# II | Nontraditional Assembly Methods

- Friction Stir Welding
- Induction Welding
- Co-curing
- 3D Printing

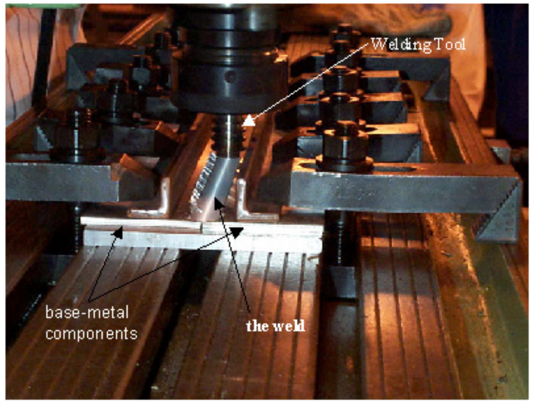
FSW Mechanical Engineering USC

FSW University of South Carolina
Mechanical Engineering

- News
- About FSW
- Program Management
- Research Fields
- Apparatus
- Publications
- Events
- Links

## Friction Stir Welding

Invented in 1991 at The Welding Institute (UK), Friction Stir Welding (FSW) is a solid-state joining process wherein severe plastic deformation in a confined region results in intimate contact between material on either side of the joint line. This intimate contact results in a strong, metallurgical bond. Heating is produced by relative motion between a non-consumable, rotating tool and the two plates to be joined. The shape of the tool promotes high hydrostatic pressure along the joint line, causing consolidation of the material softened by the combination of frictional and deformation heating. The process may be described as a combination of in situ extrusion and forging. The microstructure of a friction stir weld is unlike that of a fusion weld in that no solidification products are present and the grains in the weld region are equiaxed and highly refined. Indeed, the FSW microstructure is that of a wrought rather than a cast product.




Friction stir weld being made on the USC welder.

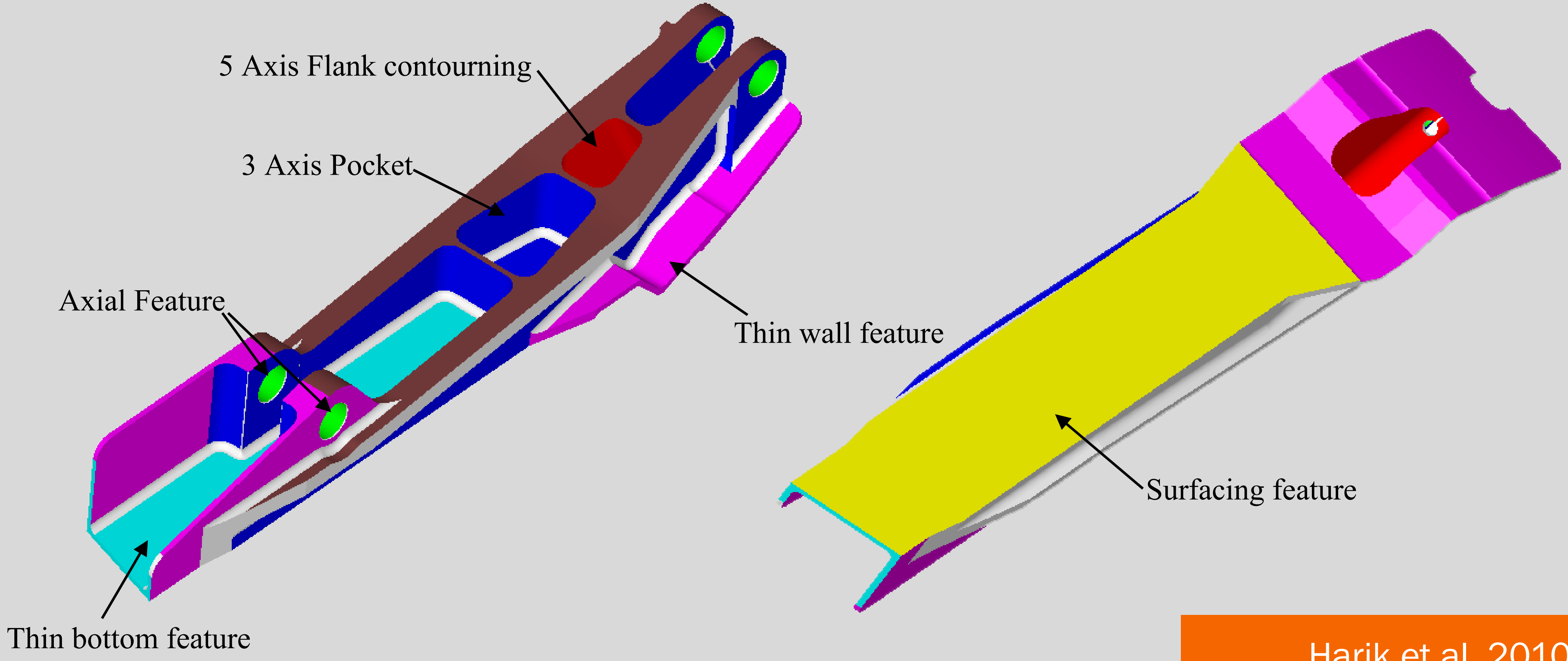
Although FSW has been put to use in full-scale production of ferry boats and space launch components made from aluminum, there is still a great deal to learn about the basic mechanisms and the details of the process. In addition, a great deal of work must be performed to extend the benefits of FSW from aluminum alloys to other, more refractory materials. Our work at USC encompasses both process modeling (with accompanying experimental verification) and joint performance analysis. The overall goal of our research is to develop a complete understanding of the interrelationship between weld processing parameters, base metal properties, and weld performance so that optimum welding conditions can be specified with a minimum of trial and error. Friction stir welding work at USC is being or has been supported by NASA, AFRL/ML, ONR, DOE (Savannah River Site), and Lockheed-Martin Corp.

# DFMA+

- Design for manufacturing and assembly (DFMA) concepts have proven to give us the ability to estimate assembly and part manufacturing costs at the earliest stages of product design.
- Not only cost and time are reduced but the **sequence of manufacturing processes is more efficient**, in addition to the significantly improved quality of the product
- Other benefits may include improved maintenance and repair
- As DFMA has been playing a vital role for the industries applying it, working on broadening its application would be very beneficial economically and environmentally
- Generally, DFMA technologies/guidelines should be based on the concept of: Eliminate whenever possible then re-order to optimize
- [Zirmi 2005] compared several DFMA methodologies and concluded that some methodologies achieve a **time reduction of up to 70%**

Harik et al, 2010

# Sample of Feature Recognition




Harik et al, 2010

THANK YOU

- This set of slides is retrieved from the textbook: Intro to Advanced Manufacturing, Harik/Wuest, ISBN 978-0-7680-9327-8 978-0-7680-9327-8
- Link of the textbook: https://www.sae.org/publications/books/content/r-463/
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