IE 309 Manufacturing Processes I
Joining Processes and Equipment

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Joining and Assembly

Products are assembled from components that have been manufactured as individual parts.

- Bonding of windshield to car body
- Fasteners
- Bolted engine assembly
- Soldered electrical circuitry
- Brazed joint for emission control
- Adhesively bonded fabric
- Spot-welded car body
- Mechanical fastening of body trim
- Welded pipes for exhaust system
- Seamed body components
- Seam-welded muffler
Joining and Assembly Distinguished

Joining

• Welding, brazing, soldering and adhesive bonding
• These processes form a permanent joint between parts

Assembly

• Mechanical methods of fastening parts together
• Some of these methods allow for easy disassembly while others do not
Welding

Joining process in which two (or more) are coalesced at their contacting surfaces by application of heat and/or pressure

• Many welding processes are accomplished by heat alone, with no pressure applied
• Others by a combination of heat and pressure
• Still others by pressure alone with no external heat
• In some welding processes a filler material is added to facilitate coalescence
Why Welding is Important

Provides a permanent joint

• Welding components become a single entity

Usually the most economical way to join parts in terms of material usage and fabrication costs

• Mechanical fastening usually requires additional hardware (e.g., screws) and geometric alterations of the assembled parts (e.g., holes)

Not restricted to a factory environment

• Welding can be accomplished “in the field”
Limitations and Drawbacks of Welding

Most welding operations are performed manually and are expensive in terms of labor cost.

Most welding processes utilize high energy and are inherently dangerous.

Welded joints do not allow for convenient disassembly.

Welded joints can have defects that are difficult to detect.
Definitions

Faying surface: the part surfaces in contact or close proximity that are being joined

- Welding involves localized coalescence of the two metallic parts at their faying surfaces

Types of joints

- Butt, Corner, Lap, Tee, Edge
Types of Welding Processes

Some 50 different types of welding processes have been cataloged by the American Welding Society (AWS)

Can be divided into two major categories:

• Fusion welding
  - Involves melting and coalescing materials by means of heat, supplied by fuel gas, electricity or high energy beams

• Solid state welding
  - Joining without fusion, i.e., no liquid (molten) phase in the joint
Fusion Welding Processes

Oxyfuel gas welding

Arc welding
  • Consumable and Non-consumable electrode

High energy beam welding
  • Electron beam
  • Laser beam
Typical Fusion Welded Joint

Typical fusion weld joint in which filler metal has been added consists of:

- Fusion zone
- Weld interface
- Heat affected zone (HAZ)
- Unaffected base metal zone

Cross section of a typical fusion welded joint: (a) principal zones in the joint, and (b) typical grain structure
Oxyfuel Gas Welding

Fusion welding performed by a high temperature flame from combustion of a fuel gas and oxygen

- Flame is directed by a welding torch
- Filler metal is sometimes added
  - Composition must be similar to base metal
  - Filler rod often coated with flux to clean surfaces and prevent oxidation

Common fuel gas

- Acetylene (C2H2) (most common)
- Alternative:
  - Methylacetylene-Propadiene (MAPP)(CH32=C=CH2), hydrogen, propylene (C3H6), propane (C3H8), natural gas
  - Lower flame temperature
Oxyacetylene Welding

Gas mixture

Welding torch

Flame

Solidified weld metal

Base metal

Molten weld metal

Filler rod
Flame Types

proportion of acetylene and oxygen in the gas is important

At a ratio of 1:1 the flame is considered to be neutral

A flame with excess oxygen is called oxidizing flame

When there is insufficient oxygen, it is called reducing or carburizing flame
Arc Welding

A fusion welding process in which coalescence of the metals is achieved by the heat from an electric arc between an electrode and the work

- Electric energy from the arc produces temperatures ≈ 5500 °C, hot enough to melt any metal
- Most AW processes add filler metal to increase volume and strength of weld joint

Electric arc - a discharge of electric current across a gap in a circuit

- It is sustained by an ionized column of gas (plasma) through which the current flows
- To initiate the arc in AW, electrode is brought into contact with work and then quickly separated from it by a short distance
Arc Welding

A pool of molten metal is formed near electrode tip, and as electrode is moved along joint, molten weld pool solidifies in its wake.
Two Basic Types of Arc Welding Electrodes

Consumable electrode

• Electrode consumed during welding process
• Source of filler metal in arc welding

Non-consumable electrode

• Electrode not consumed during welding process
• Filler metal must be added separately if it is needed
Arc Shielding

At high temperatures in AW, metals are chemically reactive to oxygen, nitrogen, and hydrogen in air

- Mechanical properties of joint can be degraded by these reactions

- To protect operation, arc must be shielded from surrounding air in AW processes

Arc shielding is accomplished by:

- Shielding gases, e.g., argon, helium, CO₂
- Flux
Flux

A substance that prevents formation of oxides and other contaminants in welding, or dissolves them and facilitates removal

- Provides protective atmosphere for welding
- Stabilizes arc
- Reduces spattering

Various flux application method

- Pouring granular flux onto welding operation
- Stick electrode coated with flux material that melts and gives off vapors during welding to cover operation and form slags
- Tubular electrodes in which flux is contained in the core and released as electrode is consumed
Slag

A compound of oxides, fluxes and electrode coating materials

• Protects the weld as it cools

• Must be removed completely due to corrosion

Incomplete removal of slag between passes affect the quality and strength of the weld joints
Power Source in Arc Welding

Direct current (DC) vs. Alternating current (AC)

- AC machines less expensive to purchase and operate, but generally restricted to ferrous metals
- DC equipment can be used on all metals and is generally noted for better arc control
Gas Tungsten Arc Welding
(non-consumable electrode)
Also known as: TIG welding

Melting point of tungsten = 3410 °C

Note: filler metal is less commonly used than in consumable electrode arc welding
Advantages and Disadvantages of GTAW

Advantages:

- High quality welds for suitable applications
- No spatter because no filler metal through arc
- Little or no post-weld cleaning because no flux

Disadvantages:

- Generally slower and more costly than consumable electrode AW processes
Plasma-arc Welding  
(non-consumable electrode)

Two types of plasma-arc welding processes: (a) transferred and (b) non-transferred. Deep and narrow welds can be made by these processes at high welding speeds.
Shielded Metal Arc Welding  
(consumable electrode)  
Commonly known as: stick welding

Typical Applications

- Used in half of all industrial and maintenance welding.
- Work piece thickness: 3-19mm
- Remote areas – highly portable

Power Considerations

- 50-300 Amper
- 10kW
Electron Beam Welding (EBW)

Fusion welding process in which heat for welding is provided by a highly-focused, high-intensity stream of electrons striking work surface

- Electron beam gun operates at:
  - High voltage (e.g., 10 to 150 kV typical) to accelerate electrons
  - Beam currents are low (milliamps)

- Power in EBW not exceptional, but power density is very high
Advantages and Disadvantages of EBW

Advantages:

- High-quality welds, deep and narrow profiles
- Limited heat affected zone, low thermal distortion
- No flux or shielding gases needed

Disadvantages:

- High equipment cost
- Precise joint preparation & alignment required
- Vacuum chamber required
- Safety concern: EBW generates x-rays
Laser-beam Welding

Process:

• High powered laser beam as source of heat

• As small as 10 micrometers in diameter

• Inert gas shielding may be applied

Typical Applications:

• Deep narrow joints

• Aluminum, titanium, ferrous metals, copper, super alloys, and refractory metals

• Automotive industry

• Butt welds on automotive body panels

• Transmission components

• Electronic components

• Hermetic welding of pace makers

• Adaptable to robotics
Comparison: LBW vs. EBW

No vacuum chamber required for LBW

No x-rays emitted in LBW

Laser beams can be focused and directed by optical lenses and mirrors

LBW not capable of the deep welds and high depth-to-width ratios of EBW

- Maximum LBW depth = ~ 19 mm, whereas EBW depths = 50 mm

Comparison of the sizes of weld beads: (a) laser-beam or electron-beam welding and (b) tungsten-arc welding.
Cutting

In addition to mechanical means, materials can be cut with the use of a heat source that melts and removes a narrow zone in the workpiece.

The sources of heat can be torches, electric arcs, or lasers.

Types:
- Oxyfuel-gas Cutting
- Arc Cutting
Oxyfuel-gas Cutting

Similar to oxyfuel welding, but the heat source is now used to remove a narrow zone from a metal plate.

This process is suitable particularly for steels.

(a) Flame cutting of a steel plate with an oxyacetylene torch, and a cross section of the torch nozzle. (b) Cross section of a flame-cut plate, showing drag lines.
Arc Cutting

Arc cutting processes are based on the same principles as arc-welding processes

A variety of materials can be cut at high speeds by arc cutting

• Air carbon-arc cutting (CAC-A)
• Plasma-arc cutting (PAC)
• Electron beams and lasers
The Weld Joint and Quality

Three distinct zones can be identified in a typical weld joint:

• Base metal
• Heat-affected zone
• Weld metal.
Solidification of The Weld Metal

After the application, the weld joint is allowed to cool down to ambient temperature.

The solidification process is similar to that in casting and starts with the formation of columnar grains.

Grains form parallel to the heat flow.
Solidification of The Weld Metal

(a)

(b)

Grain structure in (a) a deep weld and (b) a shallow weld.
The heat-affected zone (HAZ) is within the base metal itself.

Its microstructure is different than that of the base metal prior to welding.

Microhardness (HV) profile across a weld bead.
Quality

The major discontinuities that affect weld quality are

• Porosity
• Slag Inclusion
• Incomplete fusion and incomplete penetration
• Underfilling or undercutting weld profile
• Cracks and tears
• Surface damage
• Residual stresses
Quality

(a) Bridging
(b) Incomplete fusion
(c) Incomplete fusion
(d) Underfill, Crack, Inclusions
(e) Overlap, Undercut, Porosity, Lack of penetration
(f) Good weld
Types of cracks developed in welded joints

Distortion of parts after welding
Quality

Residual stresses developed in a straight-butt joint.

Distortion of a welded structure.
Solid-state Welding

Joining without fusion, i.e., no liquid (molten) phase in the joint.

Coalescence results from application of pressure alone or a combination of heat and pressure

• If heat is used, temperature is below melting point of metals being welded

• No filler metal is added in solid state welding
Solid-state Welding Processes

Cold welding
Ultrasonic welding
Friction welding
Resistance welding
Explosion welding
Diffusion bonding
Cold Welding (CW)

Pressure is applied to the mating faces by dies or rolls (roller bonding); Plastic deformation of one or both parts leads to welding.

Interface can be precleaned using wire or power brush.

Best bond strength happens between similar materials.

Brittle intermetallic compounds may form between dissimilar metals leading to weak interface.

Applied to small work pieces of soft, ductile metals, such as electrical connections, wire stock, sealing of heat sensitive containers.

US quarter coins
Top/bottom: 75%Cu-25%Ni
Middle: 100% pure copper
Ultrasonic Welding

In USW, the faying faces are subjected to a static normal force + oscillating shear stress. The shear stress is applied by the tip of a transducer, freq = 10-75 kHz. Shearing stress causes small scale plastic deformation at the interface, breaking up oxide film and contaminants. Temperatures well below Tm. Extensively used in joining plastics in automotive and electronics industry.
Friction Welding (FRW)

Coalescence is achieved by frictional heat combined with pressure

- When properly carried out, no melting occurs at faying surfaces
- Can be used to join dissimilar metals
- Widely used commercial process, amenable to automation and mass production
Applications and Limitations of Friction Welding

Applications

• Shafts and tubular parts

• Industries: automotive, aircraft, farm equipment, petroleum and natural gas

Limitations

• At least one of the parts must be rotational

• Flash must usually be removed (extra operation)

• Upsetting reduces the part lengths (Which must be taken into consideration in product design)
Inertia Friction Welding

This process is a modification of friction welding.

The energy required for frictional heating in inertia friction welding is supplied by the kinetic energy of a flywheel.

The flywheel is accelerated to the proper speed, the two members are brought into contact, and an axial force is applied.

As friction at the interface slows the flywheel, the axial force is increased.

The weld is completed when the flywheel has come to a stop.
Linear Friction Welding

The interface of the two components to be joined is subjected to a linear reciprocating motion, as opposed to a rotary motion.

The components do not have to be circular or tubular in their cross section.

The process is capable of welding square or rectangular components.
Friction Stir Welding

Different from linear friction welding

A third body (small rotating pin) is rubbed against the two surfaces to be joined

The pin is plunged into the joint, causing frictional heating, leading to heating, mixing or stirring of the material in the joint

Most commonly used for butt joints of aluminum and titanium alloys in aerospace industry, now also in polymers and composites

The principle of the friction-stir-welding process. Aluminum alloy plates up to 75 mm (3 in.) thick have been welded by this process.
Advantages and Disadvantages of Friction Stir Welding

Advantages

• Superior weld strength
• Little distortion or shrinkage
• Good weld appearance

Disadvantages

• An exit hole is produce when tool is withdrawn
• Heavy duty clamping of parts is required
• Incomplete welding at the bottom of the interface
Example

13 foot (4 meters) diameter Titanium nacelle lip skin

(from Boeing Frontiers/July 2010)
Resistance Welding (RW)

A group of welding processes that use a combination of heat and pressure to accomplish coalescence

- Heat generated by electrical resistance to current flow at junction to be welded \( H = I^2 R t \)
- \( V = 0.5-10V, I< 100,000A \)
- Principal RW process is resistance spot welding (RSW)

Five basic method of RW

- Spot (primary)
- Seam
- Projection
- Flash
- Upset
Resistance Spot Welding

Resistance welding process in which welding of faying surfaces of a lap joint is achieved at one location by opposing electrodes

- Used to join sheet metal parts
- Widely used in mass production of automobiles, metal furniture, appliances, and other products
  - Typical car body has ~ 10,000 spot welds
  - Annual production of automobiles in the world is measured in tens of millions of units
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Resistance Spot Welding

(a) Sequence of events in resistance spot welding.

(b) Cross section of a spot weld, showing the weld nugget and the indentation of the electrode on the sheet surfaces.
Resistance Seam Welding (RSEW)

Uses rotating wheel electrodes to produce a series of overlapping spot welds along lap joint

- Can produce air-tight joints
- Applications:
  - Gasoline tanks
  - Automobile mufflers
  - Various sheet metal containers
Resistance Projection Welding

Resistance welding process in which coalescence occurs at one or more small contact points on the parts

- Contact points determined by design of parts to be joined
  - May consist of projections, embossments, or localized intersections of parts
Advantages and Drawbacks of Resistance Welding

Advantages:

• High production rates possible
• Lends itself to mechanization and automation
• Lower operator skill level than for arc welding
• Good repeatability and reliability

Disadvantages:

• High initial equipment cost
• Limited to lap joints for most RW processes
Explosion Welding

Contact pressure is applied by detonating a layer of explosives placed over one of the mating members.

Kinetic energy of the flyer plate striking the mating member produces a turbulent, wavy interface, mechanically interlocking the two surfaces.

Common applications:

- Cladding plates and slabs with dissimilar metals in chemical industry.
- Resulting materials can be further rolled into thin section.
- Eg. tube and pipe jointed to the holes in header plates of boilers and tubular heat exchanges.

Titanium (top) and low-carbon steel (bottom).
Advantages and Disadvantages

Explosion welding can produce a bond between two metals that cannot necessarily be welded by conventional means.

Large areas can be bonded extremely quickly.

Weld is very clean, due to the fact that the surface material of both metals is violently expelled during the reaction.

A major disadvantage of this method is that an expansive knowledge of explosives is needed before the procedure may be attempted.
Diffusion Welding (DFW)

SSW process uses heat and pressure, usually in a controlled atmosphere, with sufficient time for diffusion and coalescence to occur

- Temperatures $\leq 0.5 \, T_m$
- Plastic deformation at surfaces is minimal
- Primary coalescence mechanism is solid state diffusion
- Limitation: time required for diffusion can range from seconds to hours

Applications:

- Joining of high-strength and refractory metals in aerospace and nuclear industries
- Can be used to join either similar and dissimilar metals
- For joining dissimilar metals, a filler layer of different metal is often sandwiched between base metals to promote diffusion
The sequence of operations in the fabrication of a structure by the diffusion bonding and superplastic forming of three originally flat sheets.
Brazing, Soldering, Adhesive-bonding, and Mechanical Fastening

In the previously explained joining processes fusion takes place at the interface

Brazing and Soldering require lower temperatures

Temperatures for Soldering are lower than those for brazing, and the strength of a soldered joint is much lower

Adhesive bonding is the ancient method of joining parts with animal-derived glues which has been developed for use in metallic and nonmetallic materials

Mechanical fastening is used when joints are required that are not permanent
Brazing

A filler metal is placed at or between the faying surfaces to be joined, and the temperature is raised to melt the filler metal, but not the working pieces. The molten metal fills the gap by capillary action. Upon cooling and solidification of the filler metal, a strong joint is formed.
Brazing

Filler metal for brazing melt above 450° C, but below $T_m$ of the workpieces

Heat source: torch, furnace, induction, resistance, laser or electron beam, etc

Optimal clearance in brazing is 0.025-0.2 mm

Good joint strength, principally used for maintenance and repair
Soldering

Filler metal (solder) melts below 450° C

Heat source: soldering iron, torches, or ovens

Solder joints has limited use in elevated temperature

Usually low strength, not for load bearing

Gull wing lead

Circuit board

Solder

SEM image of wave-soldered joint on surface mount device
Adhesive Bonding

Numerous parts and components can be joined and assembled by adhesives rather than by one or more of the joining methods described thus far.

A common example of adhesive bonding is plywood, where several layers of wood are bonded with wood glue.

Adhesives may require the following properties:

- Strength: shear and peel
- Toughness
- Resistance to various fluids and chemicals
- Resistance to environmental degradation, including heat and moisture
- Capability to wet the surfaces to be bonded.
Mechanical Fastening

Joints can be fastened mechanically when they are needed to be taken apart during their service life

Mechanical fastening/assembly may be preferred for the following reasons:

• Ease of manufacturing

• Ease of assembly and transportation

• Ease of disassembly, maintenance, parts replacement, or repair

• Ease in creating designs that require movable joints such as hinges, sliding mechanisms, and adjustable components and fixtures

• Lower overall cost of manufacturing the product.