

## PART VII JOINING & ASSEMBLY PROCESSES FUNDAMENTALS OF WELDING

**Joining** - welding, brazing, soldering, and adhesive bonding to form a permanent joint between parts  
**Assembly** - mechanical methods (usually) of fastening parts together  
 Some of these methods allow for easy disassembly.

1. Overview of Welding Technology
2. The Weld Joints
3. Physics of Welding
4. Features of a Fusion Welded Joint

1

### 1. Overview

- **Welding** – A joining process of two materials that coalesced at their contacting (faying) surfaces by the application of pressure and/or heat.
  - Weldment – The assemblage
  - Sometime a filler material to facilitate coalescence.
- **Advantage:** portable, permanent, stronger than the parent materials with a filler metal, the most economical method to join in terms of material usage and fabrication costs .
- **Disadvantage:** Expensive manual Labor, high energy and dangerous, does not allow disassemble and defects

2

### Two Types of Welding

- **Fusion Welding** – melting base metals
  - Arc Welding (AW) – heating with electric arc
  - Resistance welding (RW) – heating with resistance to an electrical current
  - Oxyfuel Welding (OFW) – heating with a mixture of oxygen and acetylene (oxyfuel gas)
  - Other fusion welding – electron beam welding and laser beam welding
- **Solid State Welding** – No melting, No fillers
  - Diffusion welding (DFW) – solid-state fusion at an elevated temperature
  - Friction welding (FRW) – heating by friction
  - Ultrasonic welding (USW) – moderate pressure with ultrasonic oscillating motion

3

### Welding Operation

- 50 types processes (American Welding Society)
- Applications: Constructions, Piping, pressure vessels, boilers and storage tanks, Shipbuilding, Aerospace, Automobile and Railroad
- **Welder** - manually controls placement of *welding gun*
- **Fitter** assists by arranging the parts prior to welding
- Welding is inherently dangerous to human workers
  - High temperatures of molten metals,
  - Fire hazard fuels in gas welding,
  - Electrical shock in electric welding
  - Ultraviolet radiation emitted in arc welding (a special helmet with a dark viewing window) and
  - Sparks, spatters of molten metal, smoke, and fumes (good ventilation).
- Automation - Machine, Automatic and Robotic welding

4

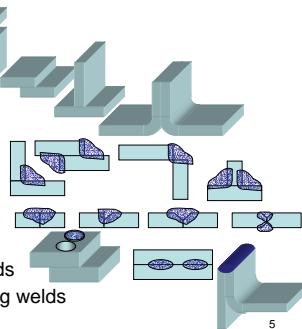
### 2. The Weld Joint

#### Types of Joints

- Butt joint
- Corner joint
- Lap joint
- Tee joint
- Edge joint

#### Types of Welds

- Fillet weld
- Groove weld
- Plug and slot welds
- Spot and Seam welds
- Flange and Surfacing welds



5

### 3. Physics of Welding

- Coalescing Mechanism: Fusion via high-density energy
- Process plan to determine the rate at which welding can be performed, the size of the region and power density for fusion welding
- Powder density (PD):  $PD = \frac{P}{A}$

where  $P$  = power entering the surface, W (Btu/sec); and  
 $A$  = the surface area,  $\text{mm}^2$  ( $\text{in}^2$ )

- With too low power density, no melting due to the heat conducted into work
- With too high power density, metal vaporizes in affected regions
- Must find a practical range of values for heat density.
- In reality, pre & post-heating and nonuniform
- For metallurgical reason, less energy and high heat density are desired.

6

## Physics of Welding II

- The estimated quantity of heat:  
 $U_m = KT_m^2$  where  $K=3.33 \times 10^{-6}$
- Heat waste:
  - Heat transfer efficiency,  $f_1$ , between heat source and surface
    - Heat problem: Oxyfuel gas welding is inefficient while Arc welding is relatively efficient.
  - Melting efficiency,  $f_2$ , due to the conduction of a work material
    - Conduction problem: Al and Cu have low  $f_2$
- Net Heat Available for Welding:  $H_w = f_1 f_2 H$
- Balance between energy input and energy for welding:  
 $H_w = U_m V$
- Rate Balance:
 

$$HR_w = U_m WVR$$

$$= f_1 f_2 HR = U_m A_w V$$

where  $WVR$ =volume rate of metal welded

7

## Approximate Power Densities and Efficiency

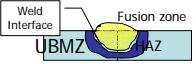
Welding process	W/mm <sup>2</sup>	(Btu/sec-in <sup>2</sup> )
Oxyfuel	10	(6)
Arc	50	(30)
Resistance	1,000	(600)
Laser beam	9,000	(5,000)
Electron beam	10,000	(6,000)

Arc Welding Process	$f_1$
Shield Metal Arc Welding	0.9
Gas Metal Arc Welding	0.9
Flux-cored Arc Welding	0.9
Submerged Arc Welding	0.95
Gas Tungsten Arc Welding	0.7

8

## 4. Features of Fusion Welded Joint



- A typical fusion weld joint consists of fusion zone, weld interface, heat affected zone and unaffected base metal zone.
- Fusion zone: a mixture of filler metal and base metal melted together homogeneously due to convection as in casting. Epitaxial grain growth (casting)
- Weld interface – a narrow boundary immediately solidified after melting.
- Heat Affected Zone (HAZ) – below melting but substantial microstructural change even though the same chemical composition as base metal (heat treating) – usually degradation in mechanical properties
- Unaffected base metal zone (UBMZ) – high residual stress

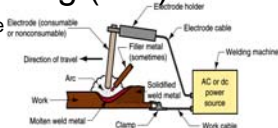
9

## WELDING PROCESSES

- Fusion welding – Heat & melting**
  - Arc Welding
  - Resistance Welding
  - Oxyfuel Welding
  - Other Fusion Welding
- Solid-state welding – Heat and pressure, but no melting & no filler**
  - Weld Quality
  - Weldability
  - Design Consideration

10

## 1. Arc Welding (AW)



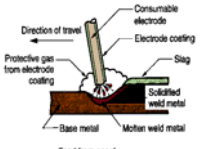
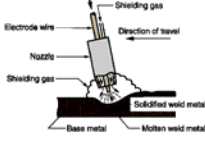
- A fusion welding where the coalescence of the metals (base metals and filler) is achieved by the heat from electric arc.
- Productivity: Arc time
- Technical issues
  - Electrodes – consumable and non-consumable electrodes
  - Arc Shielding – To shield the arc from the surrounding gas. Helium and argon are typically used. Flux does a similar function.
  - Power source – dc for all metals or ac for typically steels
- Heat loss due to convection, conduction and radiation

Arc Welding Process	$f_1$
Shield Metal Arc Welding	0.9
Gas Metal Arc Welding	0.9
Flux-cored Arc Welding	0.9
Submerged Arc Welding	0.95
Gas Tungsten Arc Welding	0.7

where  $f_1$  is the heat efficiency  
 $f_2$  is the melting efficiency  
 $H$  is the total heat generated  
 $V$  is the metal volume melted

11

## AW with Consumable Electrodes

- Shielded Metal Arc Welding (SMAW)**
  - A consumable electrode – a filler metal rod coated with chemicals for flux and shielding (230-460mm long and 2.5-9.4mm in diameter)
  - The filler metal must be comparable with base metals.
  - Current: 30-300A and Voltage: 15-45V
  - Cheaper and portable than oxyfuel welding
  - Less efficient and variation in current due to the change in length of consumable electrodes during the process.
- Gas Metal Arc Welding (GMAW)**
  - Use a bare consumable electrode
  - Flooding the arc with a gas which depends on the metal
  - No slag build-up and higher deposition rate than SMAW
  - Metal Inert Gas (MIG) or CO<sub>2</sub> welding

12

### AW with Consumable Electrodes

- Flux-cored Arc Welding (FCAW)
  - Use a continuous consumable tube with flux and others such as deoxidizer and alloying elements
  - Two types
    - Self-shielded – flux has an ingredient for shielding
    - Gas-shielded – external gas
  - Produce high quality weld joint
- Electrogas Welding (EGW)
  - Flux-cored or bare electrode with external shield gas and water-cooled molding shoes.
  - Used in shipbuilding
- Submerged Arc welding (SAW)
  - Shielding is provided by the granular flux
  - Large structures

13

### AW with non-consumable Electrodes

- Gas Tungsten Arc Welding (GTAW)
  - Tungsten (Wolfram) Inert Gas (TIG) Welding
  - With or without a filler metal
  - Tungsten melts at 3410°C
  - Shielding gas: argon, helium or a mixture
  - All metals (commonly Al and Stainless steels) in a wide range of thickness
  - Slow and costly but high quality weld for thin sections
- Plasma Arc Welding (PAW) – a special form of GTAW but with a constricted plasma gas to attain a higher temperature
- Carbon Arc Welding – Graphite is used as electrode
- Stud Welding – for cookware, heat radiation fin.

14

### 2. Resistance Welding

- RW – heat and pressure to accomplish coalescence.
- Power source: heat generated:  $H = I^2 Rt$
- Resistance Welding Processes
  - Resistance spot welding (RSW)
    - Electrodes – Cu-based or refractory (Cu+W)
    - Rocker-arm spot welders
  - Resistance seam welding (RSEW)
  - Resistance projection welding (RPW)
  - Flash welding (FW) – Heating by resistance
    - Upset welding – similar to FW but pressed during heating and upsetting
    - Percussion welding – similar to FW but shorter duration
  - High-frequency (induction and resistance) welding

15

### Spot Welding Cycle

16

### 3. Oxyfuel gas Welding

- Oxyfuel gas weldings (OFW) – Use various fuels mixed with oxygen
- Oxyacetylene welding – A mixture of acetylene and oxygen
  - Total heat:  $55 \times 10^6 \text{ J/m}^3$
  - Acetylene: odorless but commercial acetylene has a garlic order.
  - Unstable at 1atm thus dissolved in acetone.
- Other gases
  - MAPP (Dow), Hydrogen, Propylene, Propane and Natural gas

17

### 4. Other Fusion Welding

- Electroslag Welding – similar to electrogas welding, no arc is used
- Thermit (from Thermite™) Welding, dated 1900, is a fusion – welding process that uses a mixture of Al powder and iron oxide in 1:3 ratio for exothermic reaction (reaching 2500°C)
  - Used in railroad, repair cracks in ingot and large frame and shaft.

18

## High Energy beam Welding

- Electron Beam Welding
  - A high-velocity, narrow-beam electron converting into heat to produce a fusion weld in a vacuum (Multiple degrees of vacuum)
  - From foil to plate as thick as 150mm
  - Very small heat affected zone
  - Power density  $PD = \frac{I \cdot V}{A}$
- Laser Beam welding
  - A high-power laser beam as the source of heat to produce a fusion weld without a filler material
  - Due to the high density energy on a small focused area, narrow and deep penetration capability
  - Pulsed beam for spot-weld thin samples
  - Continuous beam for deep weld and thick sample
  - e.g.: Gillette Sensor razor

19

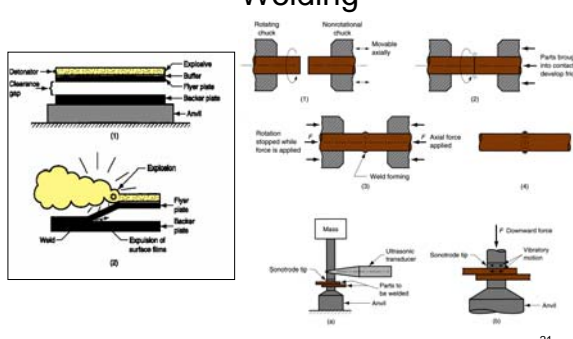
## 5. Solid-State Welding

- No filler metals but w/o local melting with either pressure-alone or heat and pressure.
- Intimate contact is necessary by a through cleaning or other means.
- Solid-state Welding Processes
  - Forge welding – Samurai sword
  - Cold welding – high pressure
  - Roll welding
  - Hot-pressure welding
  - Diffusion welding at  $0.5T_m$
  - Explosive welding – mechanical locking commonly used to bond two dissimilar metals, in particular to clad one metal on top of a base metal over large areas
  - Friction welding – friction to heat
  - Ultrasonic welding – oscillatory shear stresses of ultrasonic



20

## Explosive, Friction & Ultrasonic Welding



21

## Comparison

TABLE 12.1  
Comparison of Various Joining Methods

Method	Characteristics									
	Strength	Process Versatility	Weld Size	Large Area	Thickness	Weldability	Line of Mismatch	Visual Inspection	Cost	Time
Arc welding	1	2	3	1	1	1	1	2	2	2
Resistance welding	1	2	1	1	1	1	1	1	1	1
Beaming	1	1	1	1	1	1	1	1	1	1
Roll and seam	1	1	1	1	1	1	1	1	1	1
Rolling	2	1	1	1	1	1	1	1	1	1
Explosive	1	1	1	1	1	1	1	1	1	1
Seamless, striping	1	1	1	1	1	1	1	1	1	1
Adhesive bonding	1	1	1	1	1	1	1	1	1	1

TABLE 12.2  
General Characteristics of Joining Processes

Joining Process	Operation	Advantage	Weld Level Required	Welding Position	Current Type	Distortion*	Cost of Equipment
Welded metal on substrate	Manual	Portable and flexible	High	SD	ac, dc	1 to 2	Low
Gas metal arc	Automatic	High deposition	Low to medium	SD and horizontal	ac, dc	1 to 2	Medium to high
Gas tungsten arc	Manual or automatic	Works with most metals	Low to high	SD	ac	2 to 3	Medium
Flux-cored arc	Automatic	High deposition	Low to high	SD	ac	1 to 3	Medium
Shielded metal arc	Manual	Portable and flexible	High	SD	ac	2 to 4	Low
Electron beam	Automatic	Works with most metals	Medium to high	SD	ac	1 to 1	High

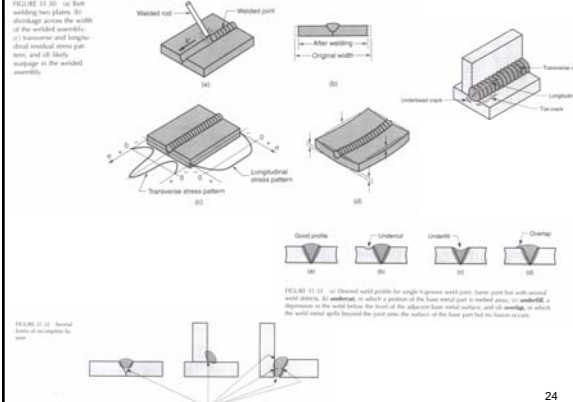
\*1. Spatter; 2. Scales; 3. Cracks

22

## 6. Weld Quality

- Residual Stress and Distortion
  - Welding fixtures, Heat sink, Tack welding, control weld condition, Preheating, Stress-relief heat treatment, Proper design
- Welding Defects
  - Cracks, Cavities, Solid Inclusions, *Incomplete Fusion*
  - Imperfect shape, Miscellaneous Defects such as arc strike and excessive spatter.
- Visual Inspection – Most widely used welding inspection,
  - dimensional, *warpage*, crack
- Limitations:
  - Only surface defects are detectable
  - Internal defects cannot be discovered
  - Welding inspector must also determine if additional tests are warranted
- Nondestructive
  - dye- and fluorescent-penetrant - detecting small defects open to surface
  - Magnetic particle testing – iron filings sprinkled on surface reveal subsurface defects by distorting magnetic field
  - Ultrasonic - high frequency sound waves directed through specimen, so discontinuities detected by losses in sound transmission
  - Radiograph - x-rays or gamma radiation to provide photographic film record of any internal flaws
- Destructive – mechanical & metallurgical tests

23



24

## Mechanical Tests for Welding

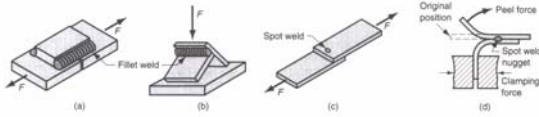


FIGURE 31.34 Mechanical tests used in welding: (a) tension-shear test of arc weldment, (b) fillet break test, (c) tension-shear test of spot weld, (d) peel test for spot weld.

25

## 7. Weldability

- Similar to Machinability, it defines the capacity of a metal to be welded into a suitable design and the resulting weld joint to perform satisfactorily in the intended service.
- The factors affecting weldability, welding process, base metal, filler metal and surface condition.
- Base metal – melting point, thermal conductivity and CTE
- Dissimilar or filler materials, Strength, CTE mismatch and compatibility must be considered.
- Moisture and oxide film affects porosity and fusion respectively.

26

## 8. Design Considerations

- Design for welding
- Minimum parts
- Arc Welding
  - Good fit-up of parts
  - Access room for welding
  - Flat welding is advised
- Spot welding
  - Low carbon steel up to 3.2mm
  - For large components: reinforcing part or flanges
  - Access room for welding
  - Overlap is required

27

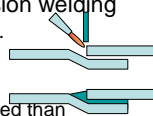
## BRAZING SOLDERING AND ADHESIVE BONDING

1. Brazing
2. Soldering
3. Adhesive Bonding

28

## Introduction

- Brazing and soldering – A filler metal is melted and distributed by capillary action but no melting of parent metals occurs.
- Brazing & soldering instead of fusion welding
  - Join the metals with poor weldability.
  - Join dissimilar metals.
  - No heat damage on the surfaces.
  - Geometry requirement is more relaxed than welding.
  - No high strength requirement
- Adhesive Bonding – similar to brazing and soldering but adhesives instead of filler metals.



29

## 1. Brazing

- If properly designed and performed, solidified joint will be stronger than filler metal.
- Why?
  - Small part clearances used in brazing
  - Metallurgical bonding that occurs between base and filler metals
  - Geometric constrictions imposed on joint by base parts
- Applications
  - Automotive (e.g., joining tubes and pipes)
  - Electrical equipment (e.g., joining wires and cables)
  - Cutting tools (e.g., brazing cemented carbide inserts to shanks)
  - Jewelry-making
  - Chemical process industry, plumbing and heating contractors join metal pipes and tubes by brazing
  - Repair and maintenance work

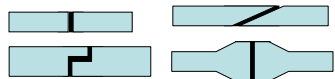
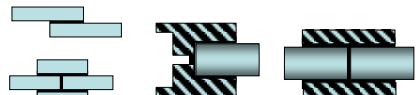
30

### Advantages and Disadvantage

- Advantages
  - Any metals can be joined
  - Certain methods are quickly and consistently or automatically done
  - Multiple brazing at the same time
  - Very thin parts can be joined
  - No heat affected zone
  - Joints inaccessible by welding can be brazed
- Disadvantage
  - Strength,
  - Low service temperature,
  - Color mismatch with the color of base metal parts

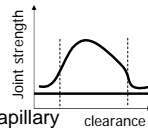
31

### Brazed Joints

- Butt 
- Lap – a wider area for brazing metal 
- Lap joints take more load than butt joints.

32

### Brazed Joints



- Clearance between mating surface for capillary action (0.025 and 0.25mm)
- Cleanliness of the joint – chemical (solvent cleaning & vapor degreasing) and mechanical (wire brushing & sand blasting) treatments
- Fluxes are used during brazing to clean surfaces and to promote wetting
- Common filler metals
  - Compatible melting temperature compatible with base metal
  - Low surface tension for wetting
  - High fluidity, Strength and no chemical and physical interactions with base materials

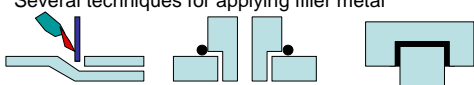
33

### Common Filler Metals

Filler Metal	Typical Composition	Brazing Temp.(°C)	Base metals
Al & Si	90Al, 10Si	600	Al
Cu	99.9Cu	1120	Ni and CU
Cu & P	95Cu, 5P	850	Cu
Cu & Zn	60Cu, 40Zn	925	Steels, Cast Iron and Ni
Au & Ag	80Au, 20Ag	950	Stainless steel and Ni alloys
Ni alloys	Ni, Cr, others	1120	Stainless steel and Ni alloys
Silver alloys	Ag, Cu, Zn, Cd	730	Ti, Monel, Inconel, Tool steel and Ni

34

### Brazing method

- Several techniques for applying filler metal 
- Brazing fluxes
  - Avoids oxide layers or unwanted by-product
  - Low melting, low viscosity, wetting, protection until brazing metals solidify
  - Borax, borates, fluorides and chlorides in a form of powder, paste or slurries
- Brazing methods depending on heat source
  - Torch, Furnace, Induction, Resistance, Dip (either molten salt bath or molten metal bath), Infrared and brazing welding

35

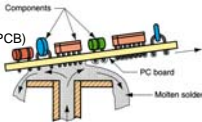
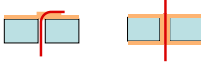
### 2. Soldering

- Similar to Brazing but the filler material melts below 450°C
- A filler material is solder and sometimes tinning (coating the faying surfaces) is needed.
- Typical clearance ranges from 0.076 to 0.127mm.
- After the process, the flux residue must be removed.
- Advantage
  - Low energy, variety of heating methods, good electrical and thermal conductivity, air-tight & liquid-tight seams and reparable
- Disadvantage
  - Low strength, weak in high temperature applications
- For mechanical joints, the sheets are bent and the wires are twisted to increase joint strength.
  - Electronic applications: electrical connection.
  - Automotive application: vibration.

36

### Materials and Methods

- **Solders** – mainly alloys of tin and lead (low melting point) but in soldering copper, intermetallic compounds of copper and tin and in soldering alloys silver and antimony.
- **Fluxes:** Melt at soldering temperature, Remove oxide films, Prevent oxide formation, Promote wetting, Displaced by the molten solder
  - Types: Organic and inorganic
- **Methods**
  - Hand soldering – soldering gun
  - Wave soldering
    - Multiple lead wires on a printed circuit board(PCB)

- Reflow soldering – A solder paste consists of solder powders in a flux binder, which is heated either using vapor phase reflow or infrared reflow.

37

### 3. Adhesive bonding

- The filler material is called adhesive (usually polymer) requiring curing sometime with heat.
- Strength depends on chemical bonding, physical interaction (secondary bonds) and mechanical locking.
- **Surface preparation**
  - clean and rough surfaces
- **Application methods**
  - Brushing, rollers, silk screen, flowing, splaying, roll coating
- **Advantage**
  - a wide variety of materials, different sizes, bonding over an entire surface and flexible adhesives, low temp. curing, sealing, simple joint design
- **Disadvantage**
  - weaker bonding, compatible, limited service temperature, curing times and no inspection method

38

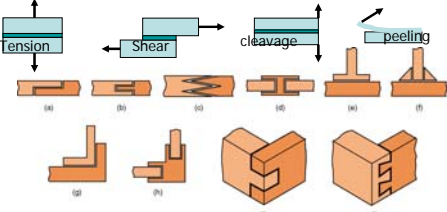
### Adhesive types

- **Natural adhesives** - derived from natural sources, including gums, starch, dextrin, soy flour, collagen
  - Low-stress applications: cardboard cartons, furniture, bookbinding; or large areas: plywood
- **Inorganic** - based principally on sodium silicate and magnesium oxychloride
  - Low cost, low strength
- **Synthetic adhesives** - various thermoplastic and thermosetting polymers
  - Most important category in manufacturing
  - Synthetic adhesives cured by various mechanisms, such as Mixing catalyst or reactive ingredient with polymer prior to applying, Heating to initiate chemical reaction, Radiation curing, such as ultraviolet light, evaporation of water from liquid or paste, Application as films or pressure-sensitive coatings on surface of one of adherents

39

### Joint Design

- Adhesive joints are not as strong as welded, brazed, or soldered joints
- Joint contact area should be maximized
- Adhesive joints are strongest in shear and tension
- Joints should be designed so applied stresses are of these types
- Adhesive bonded joints are weakest in cleavage or peeling
- Joints should be designed to avoid these types of stresses



40