FUNDAMENTALS OF WELDING

1. Overview of welding technology
2. The weld joint
3. Physics of welding
4. Features of a fusion welded joint

Joining and Assembly Distinguished

Joining - welding, brazing, soldering, and adhesive bonding

- These processes form a permanent joint between parts

Assembly - mechanical methods (usually) of fastening parts together

- Some of these methods allow for easy disassembly, while others do not

Welding

Joining process in which two (or more) parts 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
  - Welded 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 quality defects that are difficult to detect

Faying Surfaces in Welding

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
- Welding is usually performed on parts made of the same metal
  - However, some welding operations can be used to join dissimilar metals

Types of Welding Processes

- Some 50 different types of welding processes have been catalogued by the American Welding Society (AWS)
- Welding processes can be divided into two major categories:
  - Fusion welding
  - Solid state welding

Fusion Welding

Joining processes that melt the base metals

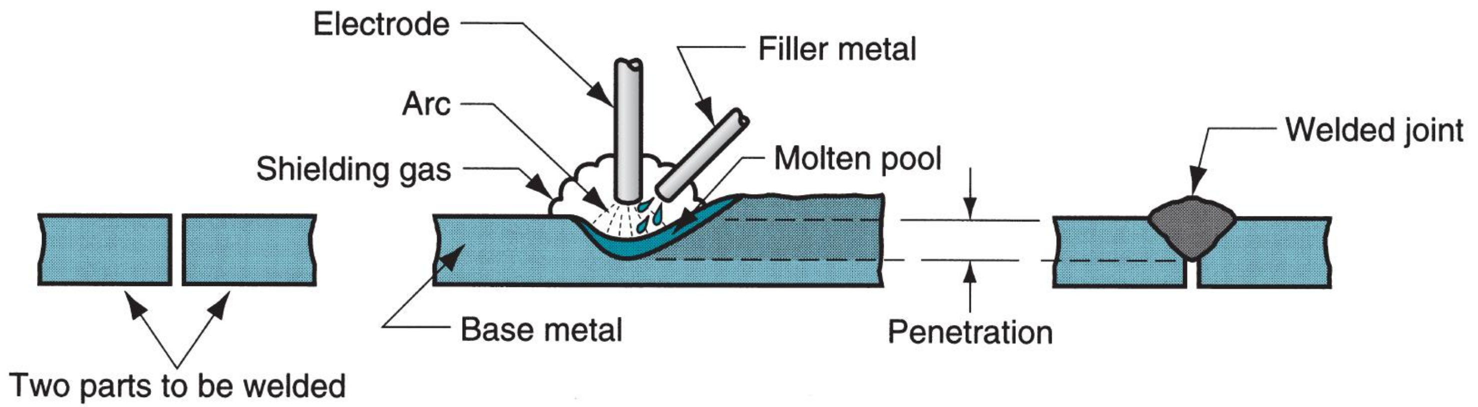
- In many fusion welding operations, a filler metal is added to the molten pool to facilitate the process and provide bulk and added strength to the welded joint
- A fusion welding operation in which no filler metal is added is called an *autogenous* weld

Some Fusion Welding Processes

- Arc welding (AW) – melting of the metals is accomplished by an electric arc
- Resistance welding (RW) - melting is accomplished by heat from resistance to an electrical current between faying surfaces held together under pressure
- Oxyfuel gas welding (OFW) - melting is accomplished by an oxyfuel gas such as acetylene

Arc Welding

- Basics of arc welding: (1) before the weld; (2) during the weld, the base metal is melted and filler metal is added to molten pool; and (3) the completed weldment



(1) End view (before)

(2) Cross-sectional (side) view (during welding)

(3) End view (after)

Solid State Welding

Joining processes in which 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

Some Solid State Welding Processes

- Diffusion welding (DFW) –coalescence is by solid state fusion between two surfaces held together under pressure at elevated temperature
- Friction welding (FRW) - coalescence by heat of friction between two surfaces
- Ultrasonic welding (USW) - coalescence by ultrasonic oscillating motion in a direction parallel to contacting surfaces of two parts held together under pressure

Principal Applications of Welding

- Construction - buildings and bridges
- Piping, pressure vessels, boilers, and storage tanks
- Shipbuilding
- Aircraft and aerospace
- Automotive
- Railroad

Welder and Fitter

- The welder manually controls the path or placement of welding gun
- Often assisted by second worker, called a *fitter*, who arranges the parts prior to welding
  - Welding fixtures and positioners are used to assist in this function

The Safety Issue

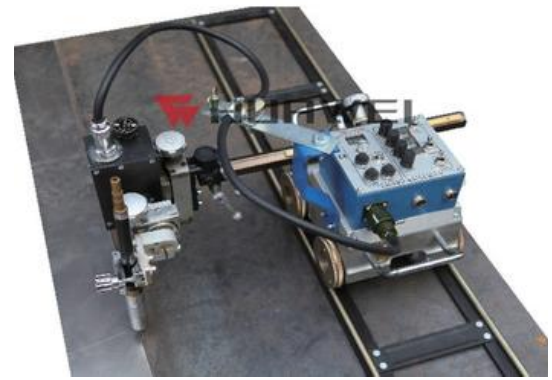
- Welding is inherently dangerous to human workers
  - High temperatures of molten metals
  - In gas welding, fuels (e.g., acetylene) are a fire hazard
  - Many welding processes use electrical power, so electrical shock is a hazard

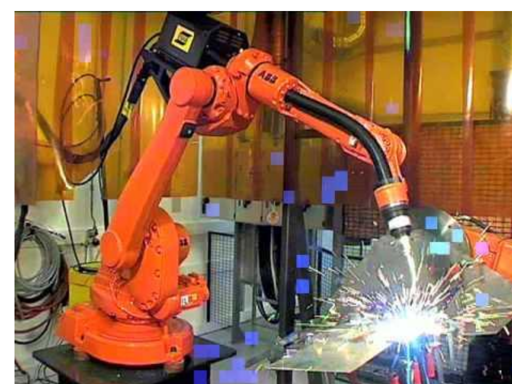
Special Hazards in Arc Welding

- Ultraviolet radiation emitted in arc welding is injurious to human vision
  - Welder must wear special helmet with dark viewing window
    - Filters out dangerous radiation but welder is blind except when arc is struck
- Sparks, spatters of molten metal, smoke, and fumes
  - Ventilation needed to exhaust dangerous fumes from fluxes and molten metals

Automation in Welding

- Because of the hazards of manual welding, and to increase productivity and improve quality, various forms of mechanization and automation are used
  - Machine welding – mechanized welding under supervision and control of human operator
  - Automatic welding – equipment performs welding without operator control
  - Robotic welding - automatic welding implemented by industrial robot





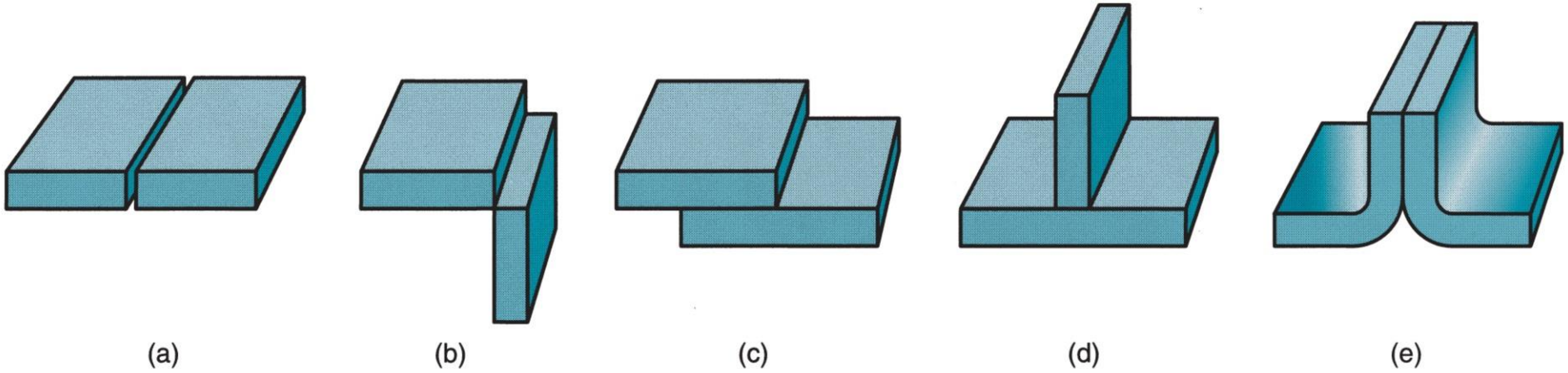
The Weld Joint

The junction of the edges or surfaces of parts that have been joined by welding

- Two issues about weld joints:
  - Types of joints
  - Types of welds used to join the pieces that form the joints

Five Types of Joints

(a) Butt joint, (b) corner joint, (c) lap joint, (d) tee joint, and (e) edge joint



Types of Welds

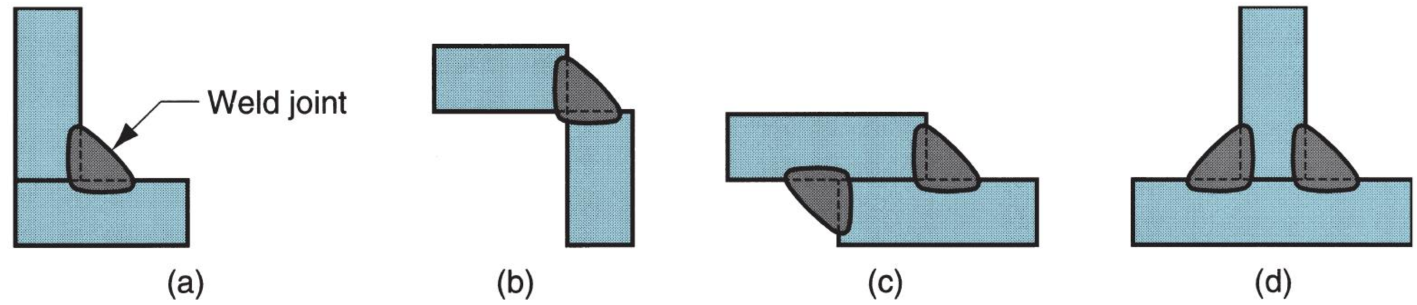
- Each of the preceding joints can be made by welding
- Other joining processes can also be used for some of the joint types
- There is a difference between joint type and the way it is welded - the weld type

Fillet Weld

- Used to fill in the edges of plates created by corner, lap, and tee joints
- Filler metal used to provide cross section in approximate shape of a right triangle
- Most common weld type in arc and oxyfuel welding
- Requires minimum edge preparation

Fillet Welds

- (a) Inside single fillet corner joint; (b) outside single fillet corner joint; (c) double fillet lap joint; (d) double fillet tee joint (dashed lines show the original part edges)

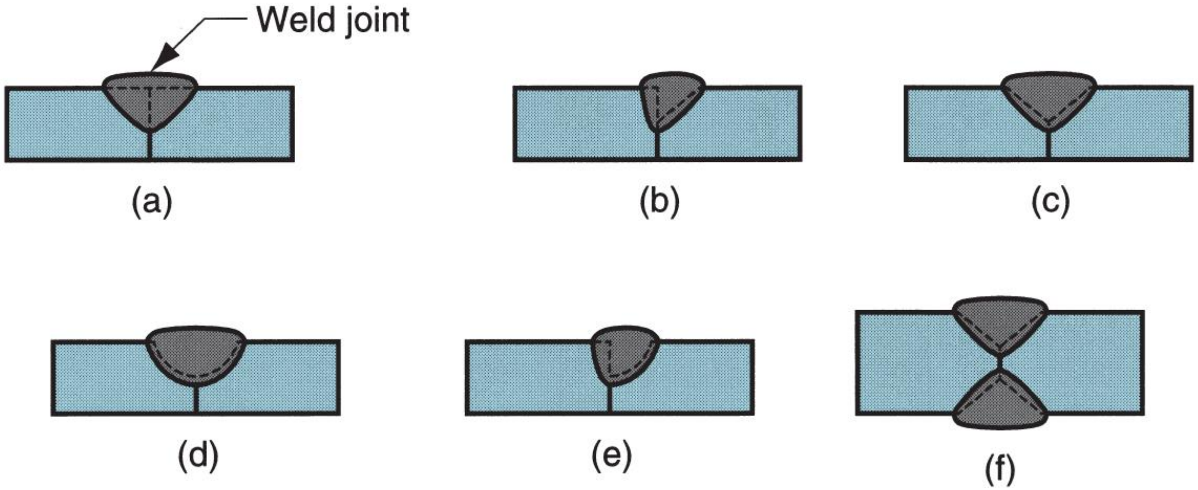


Groove Welds

- Usually requires part edges to be shaped into a groove to facilitate weld penetration
- Edge preparation increases cost of parts fabrication
- Grooved shapes include square, bevel, V, U, and J, in single or double sides
- Most closely associated with butt joints

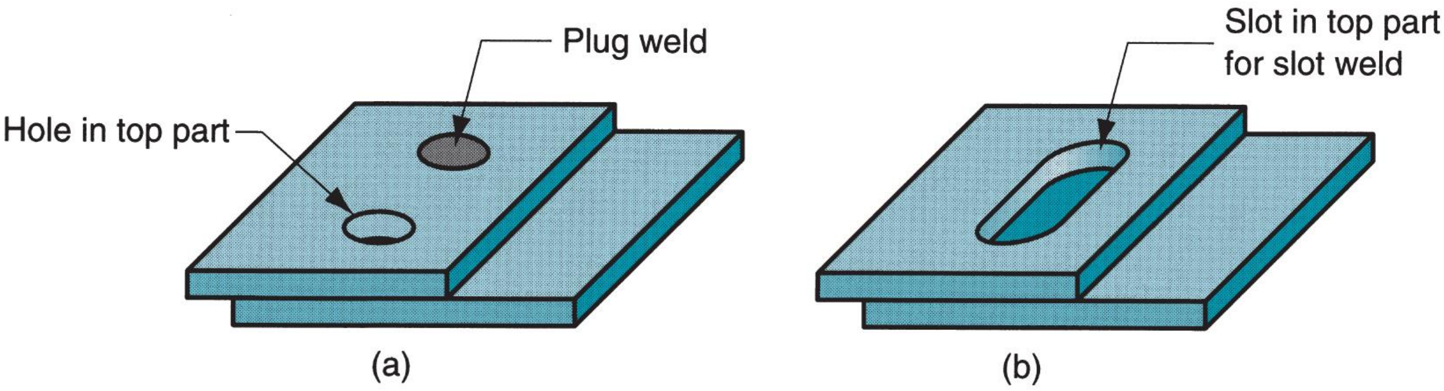
Groove Welds

- (a) Square groove weld, one side; (b) single bevel groove weld; (c) single V-groove weld; (d) single U-groove weld; (e) single J-groove weld; (f) double V-groove weld for thicker sections (dashed lines show original part edges)



Plug Weld and Slot Weld

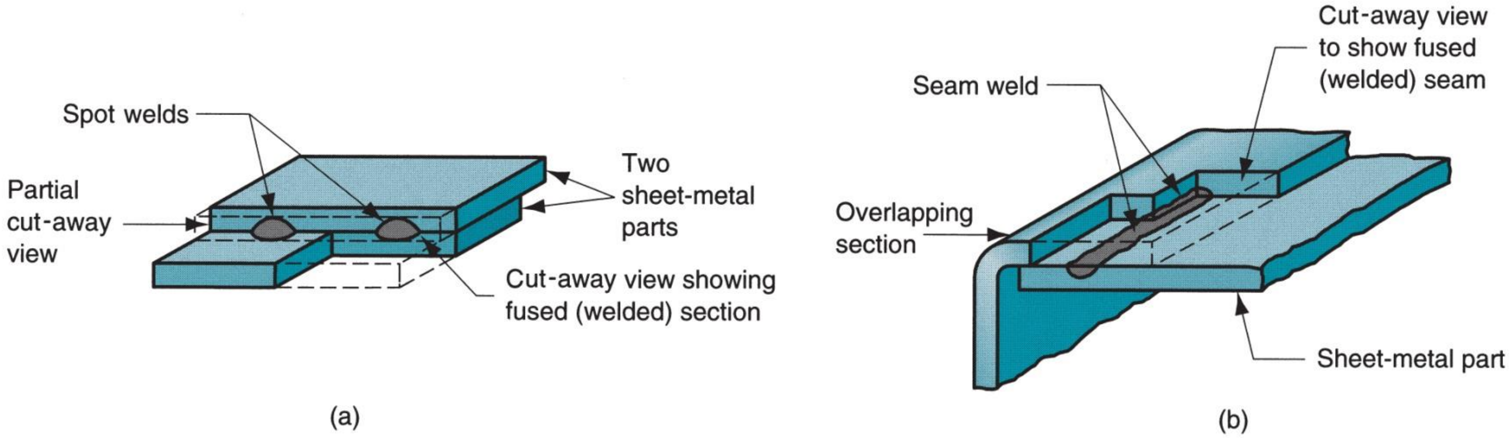
- (a) Plug weld and (b) slot weld



Spot Weld and Seam Weld

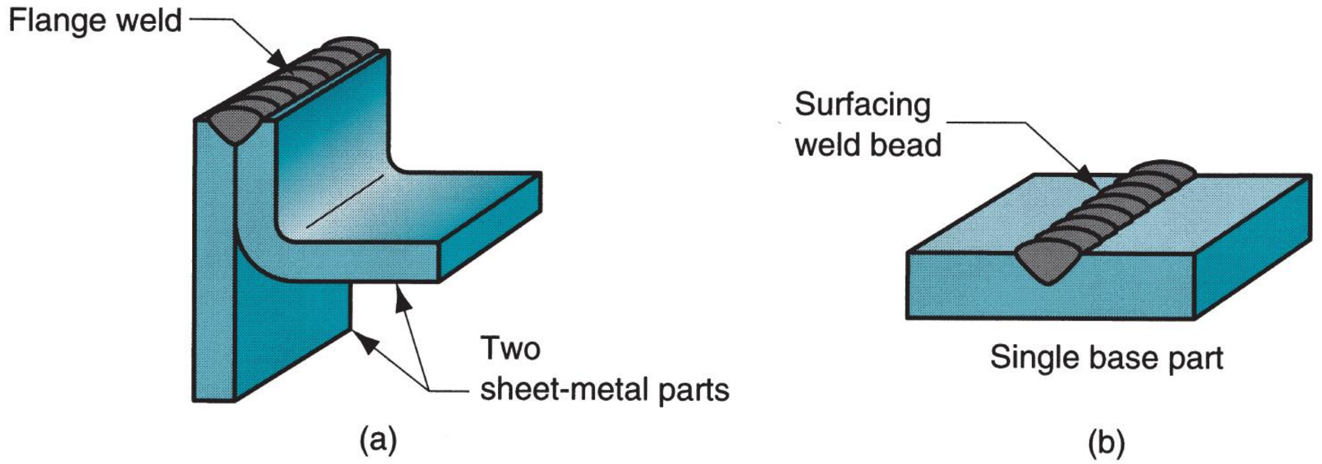
Fused section between surfaces of two sheets or plates: (a) spot weld and (b) seam weld

- Used for lap joints
- Closely associated with resistance welding



Flange Weld and Surfacing Weld

- (a) Flange weld and (b) surfacing weld used not to join parts but to deposit filler metal onto surface of a base part



Physics of Welding

- Fusion is most common means of achieving coalescence in welding
- To accomplish fusion, a source of high density heat energy must be supplied to the faying surfaces
  - Resulting temperatures cause localized melting of base metals (and filler metal, if used)
- For metallurgical reasons, it is desirable to melt the metal with minimum energy but high heat densities

Power Density

Power transferred to work per unit surface area, W/mm^2 (Btu/sec-in^2)

- If power density is too low, heat is conducted into work, so melting never occurs
- If power density too high, localized temperatures vaporize metal in affected region
- There is a practical range of values for heat power density within which welding can be performed

Comparisons Among Welding Processes

- Oxyfuel gas welding (OFW) develops large amounts of heat, but power density is relatively low because heat is spread over a large area
  - Oxyacetylene gas, the hottest OFW fuel, burns at a top temperature of around 3500°C (6300°F)
- Arc welding produces high power density over a smaller area, resulting in local temperatures of 5500° to 6600°C (10,000° to 12,000°F)

Power Densities for Welding Processes

Welding process	W/mm^2	$(Btu/sec\text{-}in^2)$
Oxyfuel	10	(6)
Arc	50	(30)
Resistance	1,000	(600)
Laser beam	9,000	(5,000)
Electron beam	10,000	(6,000)

Power Density

- Power entering surface divided by corresponding surface area:

$$PD = \frac{P}{A}$$

where PD = power density, W/mm^2 (Btu/sec-in^2); P = power entering surface, W (Btu/sec); and A = surface area over which energy is entering, mm^2 (in^2)

Example 29.1 Power Density in Welding

A heat source transfers 3000 W to the surface of a metal part. The heat impinges the surface in a circular area, with intensities varying inside the circle. The distribution is as follows: 70% of the power is transferred within a circle of diameter = 5 mm, and 90% is transferred within a concentric circle of diameter = 12 mm. What are the power densities in (a) the 5-mm diameter inner circle and (b) the 12-mm-diameter ring that lies around the inner circle?

Solution: (a) The inner circle has an area $A = \dfrac{\pi(5)^2}{4} = 19.63\ \text{mm}^2$.

The power inside this area $P = 0.70 \times 3000 = 2100$ W.

Thus the power density $PD = \dfrac{2100}{19.63} = 107\ \text{W/mm}^2$.

(b) The area of the ring outside the inner circle is $A = \dfrac{\pi(12^2 - 5^2)}{4} = 93.4\ \text{mm}^2$.

The power in this region $P = 0.9\,(3000) - 2100 = 600$ W.

The power density is therefore $PD \dfrac{600}{93.4} = 6.4\ \text{W/mm}^2$.

Observation: The power density seems high enough for melting in the inner circle, but probably not sufficient in the ring that lies outside this inner circle.

Unit Energy for Melting

Quantity of heat required to melt a unit volume of metal

- U_m is the sum of:
  - Heat to raise temperature of solid metal to melting point
    - Depends on volumetric specific heat
  - Heat to transform metal from solid to liquid phase at melting point
    - Depends on heat of fusion
    - Melting point

TABLE 29.2 Melting temperatures on the absolute temperature scale for selected metals.

Metal	Melting Temperature °K[a]	Melting Temperature °R[b]	Metal	Melting Temperature °K[a]	Melting Temperature °R[b]
Aluminum alloys	930	1680	Steels		
Cast iron	1530	2760	Low carbon	1760	3160
Copper and alloys			Medium carbon	1700	3060
Pure	1350	2440	High carbon	1650	2960
Brass, navy	1160	2090	Low alloy	1700	3060
Bronze (90 Cu–10 Sn)	1120	2010	Stainless steels		
Inconel	1660	3000	Austenitic	1670	3010
Magnesium	940	1700	Martensitic	1700	3060
Nickel	1720	3110	Titanium	2070	3730

Based on values in [2].
[a]Kelvin scale = Centigrade (Celsius) temperature + 273.
[b]Rankine scale = Fahrenheit temperature + 460.

The quantity of heat for melting can be estimated by the following equation:

$$U_m = KT_m^2 \tag{29.2}$$

where U_m = the unit energy for melting (i.e., the quantity of heat required to melt a unit volume of metal starting from room temperature), J/mm^3 (Btu/in^3); T_m = melting point of the metal on an absolute temperature scale, °K (°R); and K = constant whose value is 3.33×10^{-6} when the Kelvin scale is used (and $K = 1.467 \times 10^{-5}$ for the Rankine temperature scale). Absolute melting temperatures for selected metals are presented in Table 29.2.

Heat Transfer Mechanisms in Welding

- Not all of the input energy is used to melt the weld metal

1. Heat transfer efficiency f_1 - actual heat received by workpiece divided by total heat generated at source
2. Melting efficiency f_2 - proportion of heat received at work surface used for melting
    - The rest is conducted into work metal

Figure clarify heat transfer mechanisms in fusion welding

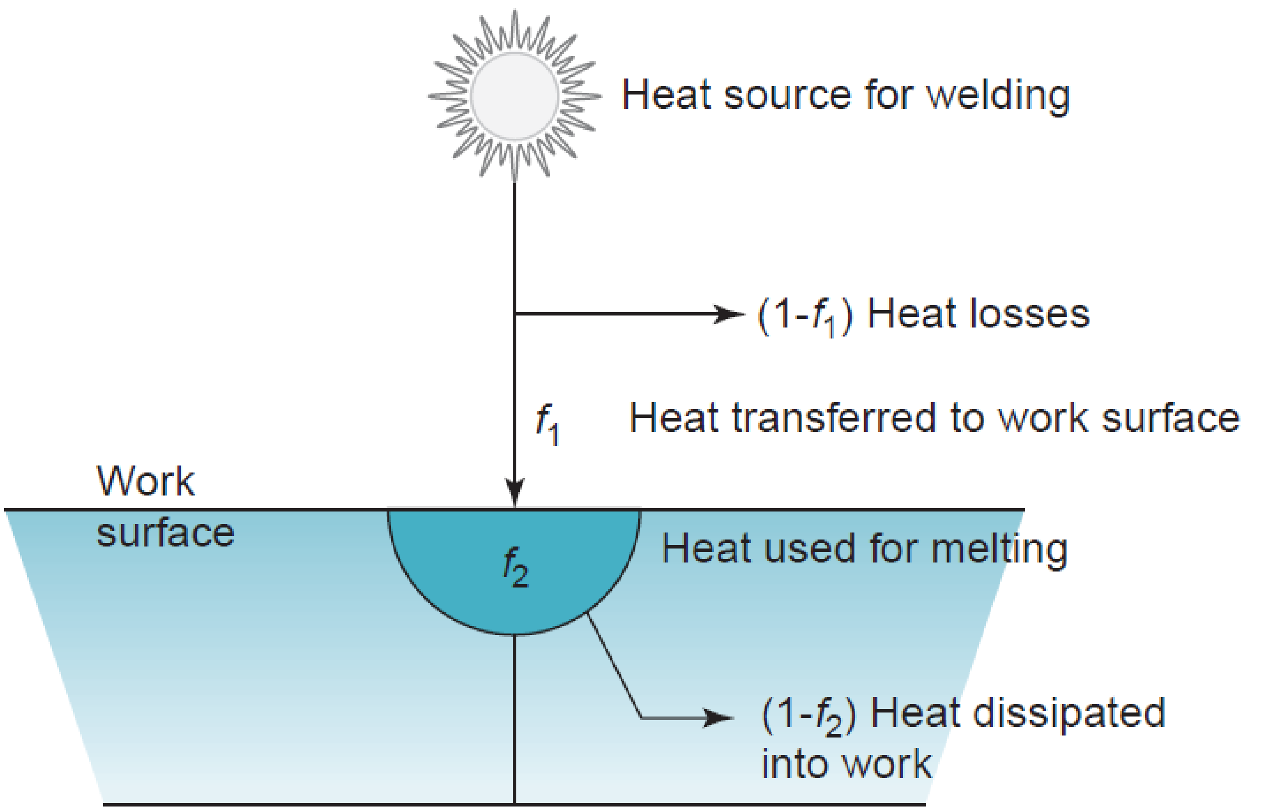


FIGURE 29.8 Heat transfer mechanisms in fusion welding.

Heat Available for Welding

$$H_w = f_1 f_2 H$$

where H_w = net heat available for welding; f_1 = heat transfer efficiency; f_2 = melting efficiency; and H = total heat generated by welding process

Heat Transfer Efficiency f_1

Proportion of heat received at work surface relative to total heat generated at source

- Depends on welding process and capacity to convert power source (e.g., electrical energy) into usable heat at work surface
    - Oxyfuel gas welding processes are relatively inefficient
    - Arc welding processes are relatively efficient

Melting Efficiency f_2

Proportion of heat received at work surface used for melting; the rest is conducted into the work

- Depends on welding process but also thermal properties of metal, joint shape, and work thickness
  - Metals with high thermal conductivity, such as aluminum and copper, present a problem in welding because of the rapid dissipation of heat away from the heat contact area

Energy Balance Equation

- Net heat energy into welding operation equals heat energy required to melt the volume of metal welded

$$H_w = U_m V$$

where H_w = net heat energy delivered to operation, J (Btu); U_m = unit energy required to melt the metal, J/mm^3 (Btu/in^3); and V = volume of metal melted, mm^3 (in^3)

Rate Balance Equation

Most welding operations are rate processes; that is, the net heat energy H_w is delivered at a given rate, and the weld bead is made at a certain travel velocity. It is therefore appropriate to express a rate balance equation as:

$$R_{Hw} = U_m R_{WV} \tag{29.5}$$

where R_{Hw} = rate of heat energy delivered to the operation for welding, J/s = W (Btu/min); and R_{WV} = volume rate of metal welded, mm^3/s (in^3/min). In the welding of a continuous bead, the volume rate of metal welded is the product of weld area A_w and travel velocity v. Substituting these terms into the above equation, the rate balance equation can now be expressed as

$$R_{Hw} = f_1 f_2 R_H = U_m A_w v \tag{29.6}$$

where f_1 and f_2 are the heat transfer and melting factors; R_H = rate of input energy generated by the welding power source, W (Btu/min); A_w = weld cross-sectional area, mm^2 (in^2); and v = the travel velocity of the welding operation, mm/s (in/min). In Chapter 30, we examine how the power density in Eq. (29.1) and the input energy rate for Eq. (29.6) are generated for some of the individual welding processes.

Example 29.2
Welding Travel Speed

The power source in a particular welding setup generates 3500 W that can be transferred to the work surface with a heat transfer factor = 0.7. The metal to be welded is low carbon steel, whose melting temperature, from Table 29.2, is 1760°K. The melting factor in the operation is 0.5. A continuous fillet weld is to be made with a cross-sectional area = 20 mm^2. Determine the travel speed at which the welding operation can be accomplished.

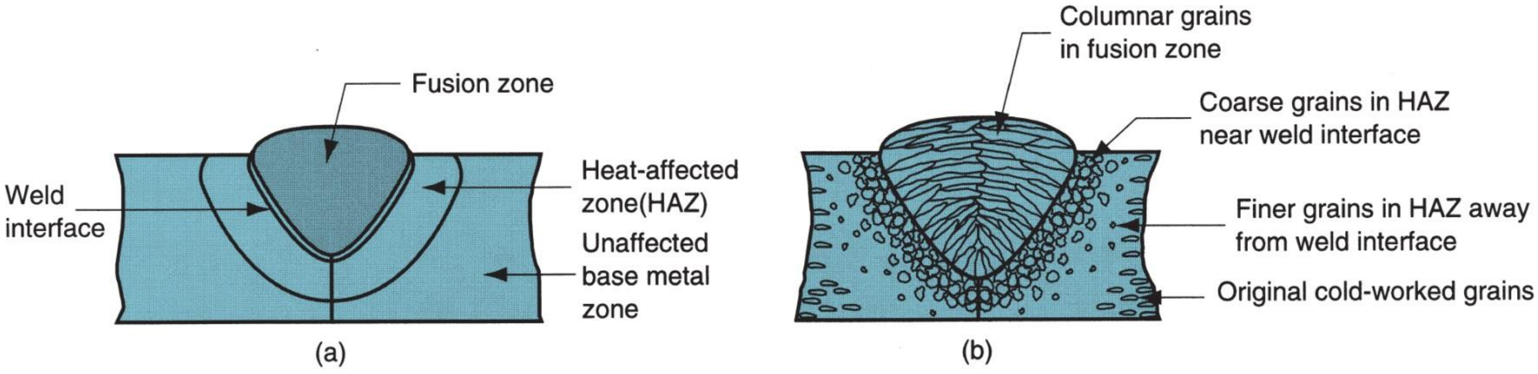
Solution: Let us first find the unit energy required to melt the metal U_m from Eq. (29.2).

$$U_m = 3.33(10^{-6}) \times 1760^2 = 10.3 \text{ J/mm}^3$$

Rearranging Eq. (29.6) to solve for travel velocity, we have $v = \frac{f_1 f_2 R_H}{U_m A_w}$, and solving for the conditions of the problem, $v = \frac{0.7\,(0.5)\,(3500)}{10.3\,(20)} = 5.95$ mm/s. ■

Typical Fusion Welded Joint

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



Features of 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

Heat Affected Zone

Metal has experienced temperatures below melting point, but high enough to cause microstructural changes in the solid metal

- Chemical composition same as base metal, but this region has been heat treated so that its properties and structure have been altered
  - Effect on mechanical properties in HAZ is usually negative
    - It is here that welding failures often occur