Introduction

- Welding processes is divided into two major categories:

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  - ***Fusion Welding***: coalescence is accomplished **by melting the two parts to be joined, in some cases adding filler metal to the joint.**
  - ***Solid-State Welding***: heat and/or pressure are used to achieve coalescence, **but no melting of the base metals occurs and no filler metal is added.**

- Fusion welding is the most important category. It includes:
  - ***Arc Welding***.
  - ***Resistance Welding***.
  - ***Oxyfuel Gas Welding***.
  - ***Other Fusion Welding Processes***.

Arc Welding

- ***Arc Welding*** (AW): a fusion-welding process in which coalescence of the metals is achieved by the heat of an electric arc between an electrode and the work.
  - **Electric arc: discharge of electric current across a gap in a circuit.**
  - Sustained by the presence of a thermally ionized column of gas (called a plasma) through which current flows.
  - To initiate the arc**, the electrode is brought into contact with the work and then quickly separated from it by a short distance**. **2-3 mm**
  - The electric energy from the arc formed produces temperatures of **5500 ºC or higher.**
  - A pool of molten metal, consisting of base and filler metal (if one is used) **is formed near the tip of the electrode, and solidifies as the electrode is moved along the joint.**

Arc Welding

- ***Arc Welding*** (AW).

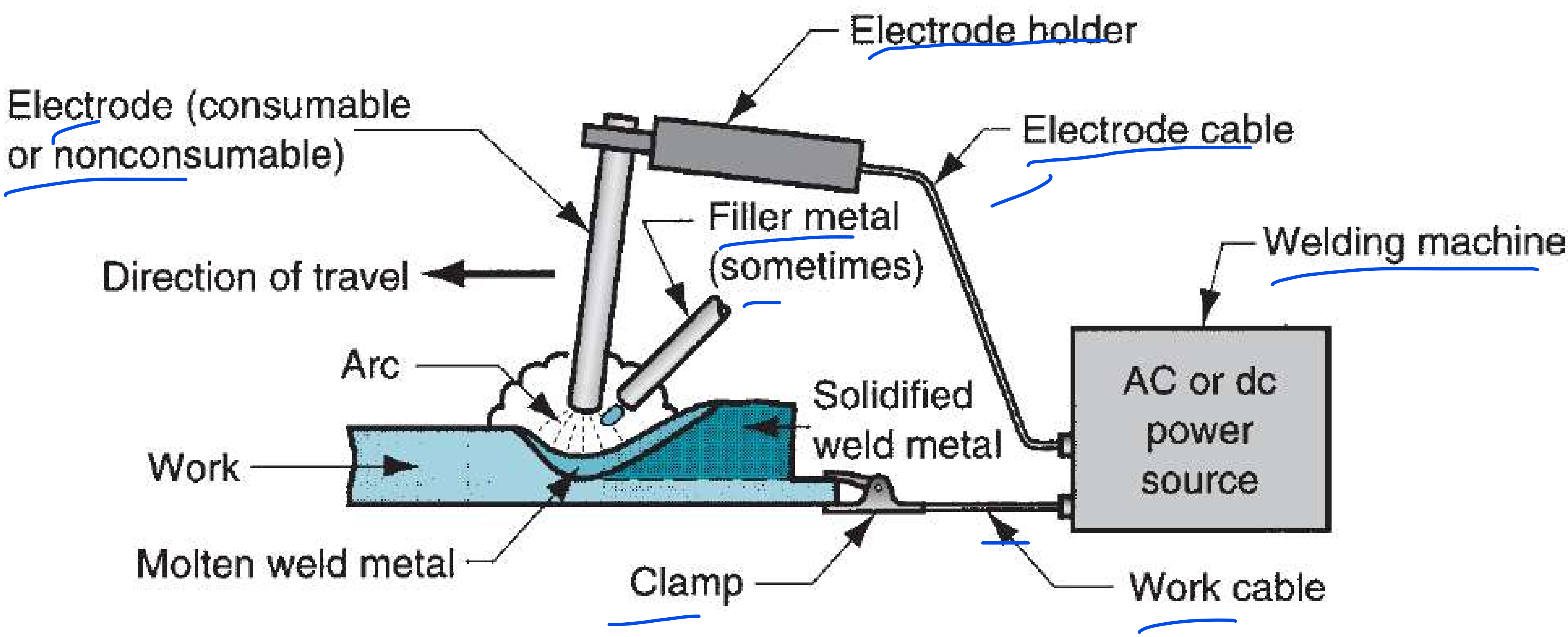


Fig. 26-1 The basic configuration and electrical circuit of an arc welding process.

Arc Welding
General Technology of AW

- Some technical issues related to AW processes should be addressed. These include***: Electrodes, Arc Shielding and Power Source in Arc Welding***.

  – ***Electrodes***: classified **as consumable or nonconsumable.**

    - Consumable Electrodes: provide the source of the filler metal in AW.
    - Available in two principal forms: 1 rods (also **called sticks**, **225 to 450 mm in length and 9.5 mm or less in diameter) and wire.** 2
    - **The problem in weld rods is that they must be changed periodically, reducing arc time of the welder.**
    - **This problem is avoided using consumable weld wire as it can be continuously fed.**
    - **In both forms, the electrode is consumed by the arc during the welding process and added to the weld joint as filler metal.**

Arc Welding
General Technology of AW

– ***Electrodes***: classified as consumable or nonconsumable.

- Nonconsumable Electrodes: **made of tungsten (or carbon, rarely), which resists melting by the arc.**
- Despite its name, a nonconsumable electrode is **gradually depleted during the welding process (vaporization is the principal mechanism).**
- Filler metal used in the **operation must be supplied by means of a separate wire that is fed into the weld pool.**

Arc Welding
General Technology of AW

– ***Arc Shielding***: the process of shielding the arc from the surrounding area **to prevent chemical reactions, between the metals being joined and gases such as nitrogen, oxygen and hydrogen, that are accelerated at high temperatures.**

- Done by covering **the electrode tip, arc, and molten weld pool with a blanket of gas and/or flux that inhibit exposure of the metal to air.**
- ***Shielding gases***: **argon and helium, both of which are inert.**
- ***Flux***: a substance used to **prevent the formation of oxides and other unwanted contaminants, or to dissolve them and facilitate removal**.
- **During welding, the flux melts and becomes a liquid slag, covering** the operation and protecting the molten weld metal.
- The **slag hardens upon cooling and must be removed later**.
- **Flux additional functions: stabilize the arc, and reduce spattering.**

Arc Welding
General Technology of AW

– ***Power Source in AW***: both direct current (DC) and alternating current (AC) are used in AW. **DC machines are more popular.**

- In all AW processes, power to drive the operation is the product of the current I passing through the arc and the voltage E across it.
- The power is converted into heat, but not all of the heat is transferred to the surface of the work, due to losses that reduce the amount of usable heat (conduction, radiation, etc).
- Heat transfer efficiency is greater for AW processes that use consumable electrodes because most of the heat consumed in melting the electrode is subsequently transferred to the work as molten metal.
- The process with the lowest heat transfer efficiency is gas tungsten AW, which uses a nonconsumable electrode.

AW Processes
Consumable Electrodes

(1) Shielded Metal Arc Welding (SMAW): **uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding.**

- **The filler metal used has a composition usually being very close to that of the base metal.**
- The coating consists of **powdered cellulose (i.e., cotton and wood powders) mixed with oxides, carbonates, and other ingredients, held together by a silicate binder.**
- The heat of the welding process **melts the coating to provide a protective atmosphere and slag for the welding operation.**
- During operation the bare metal end of the welding stick **(opposite the welding tip) is clamped in an electrode holder that is connected to the power source.**

AW Processes
Consumable Electrodes

(1) Shielded Metal Arc Welding (SMAW): uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding.

- **Currents typically used in SMAW range between 30 and 300 A at voltages from 15 to 45 V.**
- Common applications: **construction, pipelines, etc.**
- The equipment is portable, low cost and produce high power density, making SMAW the **most widely used of the AW processes.**
- Base metals **include iron alloys, and certain nonferrous alloys.** It is not used or seldom used **for aluminum and its alloys, copper alloys, and titanium.**

AW Processes
Consumable Electrodes

(1) Shielded Metal Arc Welding (SMAW).

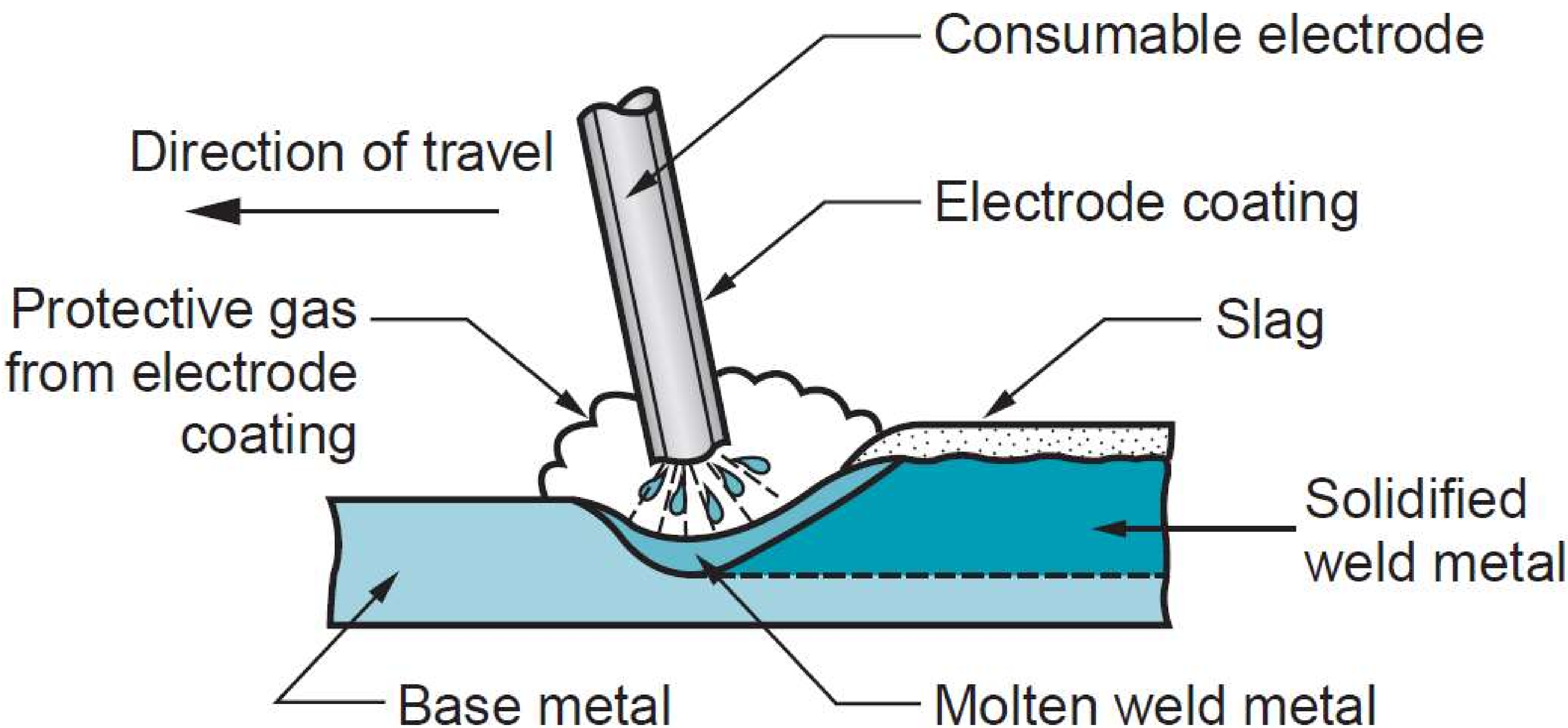


Fig. 26-2 Shielded metal arc welding (SMAW).

AW Processes
Consumable Electrodes

(2) Gas Metal Arc Welding (GMAW): the electrode is a consumable bare metal wire, and shielding is accomplished by flooding the arc with gas. The wire (0.8 to 6.5 mm in D) is fed directly from spool.

- Shielding gases **include argon and helium (for welding Al and stainless steel),** and **active gases such as carbon dioxide (for welding low and medium carbon steels).**

- As the electrode is bare metal, no slag forms and thus cleaning and grinding of slag is not needed.

- ***Metal Inert Gas (MIG) Welding***: **applied to the welding of aluminum using inert gas (argon) for arc shielding.**

- ***CO_2 Welding***: **gas used is CO_2 instead of the expensive argon, specially for steels.**

- **Advantages: no slag, no interruptions during welding (wire is used instead of stick), high deposition rates, etc.**

AW Processes
Consumable Electrodes

(2) Gas Metal Arc Welding (GMAW).

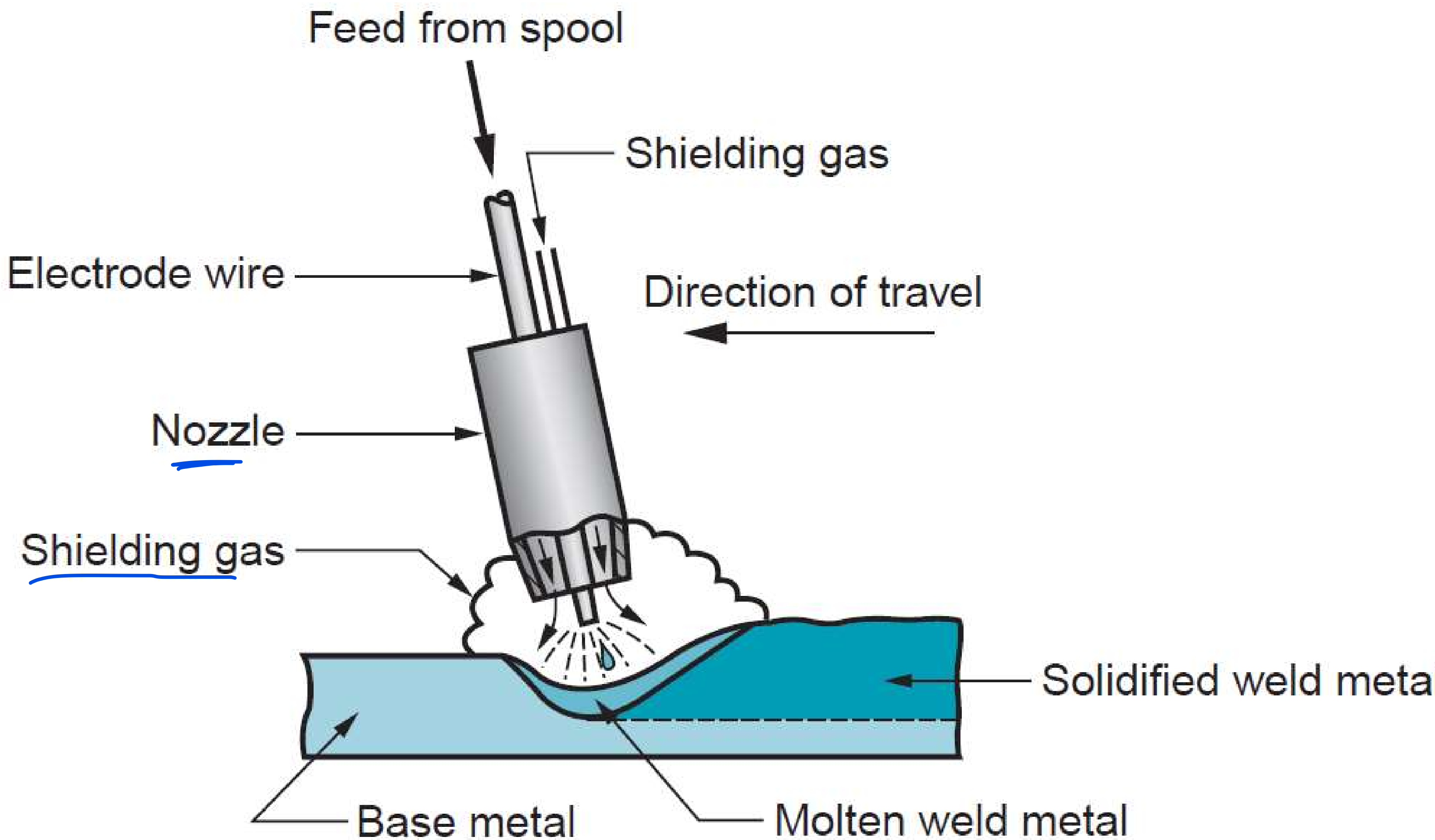


Fig. 26-3 Gas metal arc welding (GMAW).

AW Processes
Nonconsumable Electrodes

(1) Gas Tungsten Arc Welding (GTAW): uses a nonconsumable tungsten electrode and an inert gas for arc shielding. **The term *TIG* welding (tungsten inert gas welding) is often applied to this process**

- **When a filler metal is used (sometimes not used), it is added to the weld pool from a separate rod or wire**.

- **Tungsten is a good electrode material (melting point = 3410 ^{o}C). Shielding gases include argon, helium, or a mixture.**

- Applicable to all metals in a wide range of thicknesses. **Also used for joining dissimilar metals. Mostly used for Al and steels.**

- **Advantages include: high-quality welds, and little or no post weld cleaning because no flux is used.**

AW Processes
Nonconsumable Electrodes

(1) Gas Tungsten Arc Welding (GTAW).

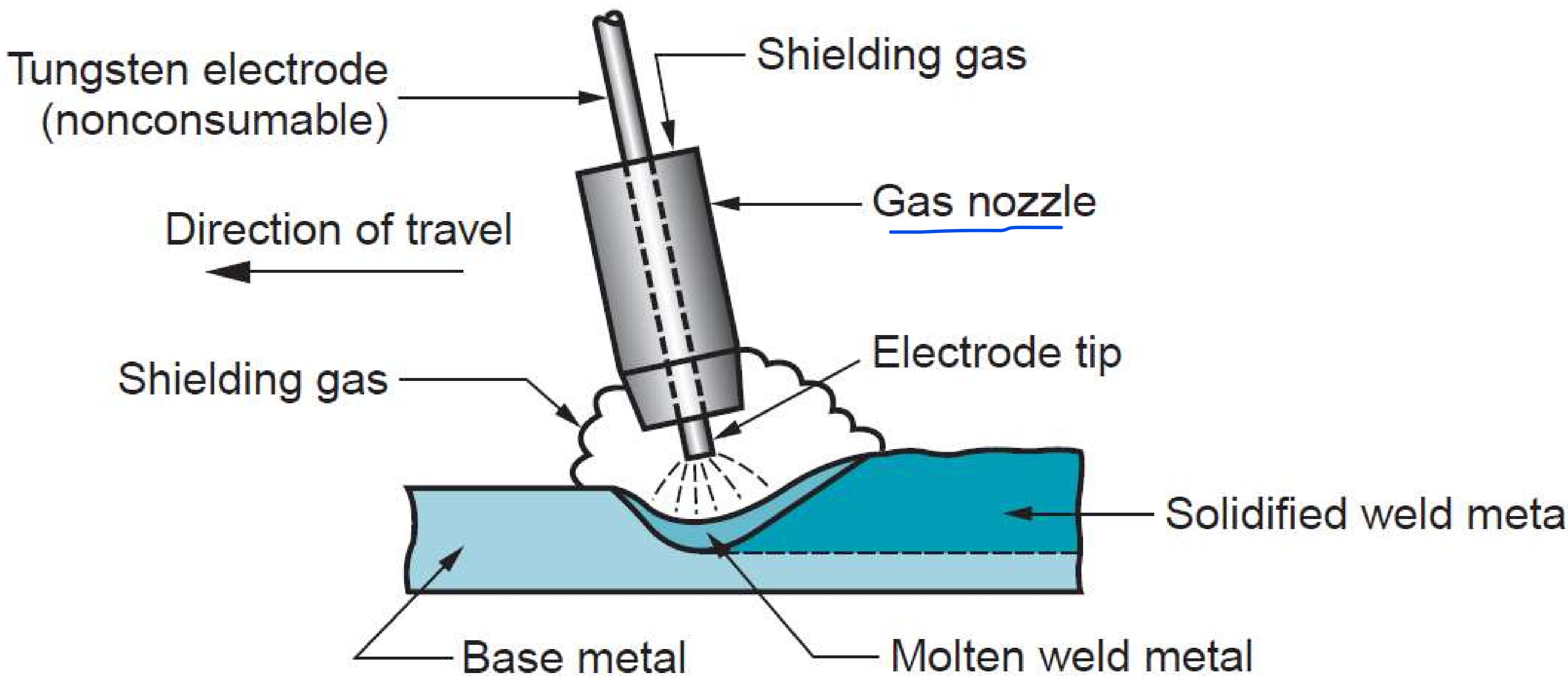


Fig. 26-6 Gas tungsten arc welding (GTAW).

Resistance Welding

Resistance Welding (RW): a group of fusion-welding processes that uses a combination of heat and pressure to accomplish coalescence, the heat being generated by electrical resistance to current flow at the junction to be welded.

- The components in RW include workparts to be welded (usually sheet metal parts), two opposing electrodes, a mean of applying pressure to squeeze the parts between the electrodes, and an AC power supply from which a controlled current can be applied.
- The operation results in a fused zone between the two parts, called a ***weld nugget*** in spot welding.
- **Uses no shielding gases, flux, or filler metal; and the electrodes that conduct electrical power to the process are nonconsumable.**
- **Classified as fusion welding because the applied heat almost always causes melting of the contact surfaces.**

Resistance Welding

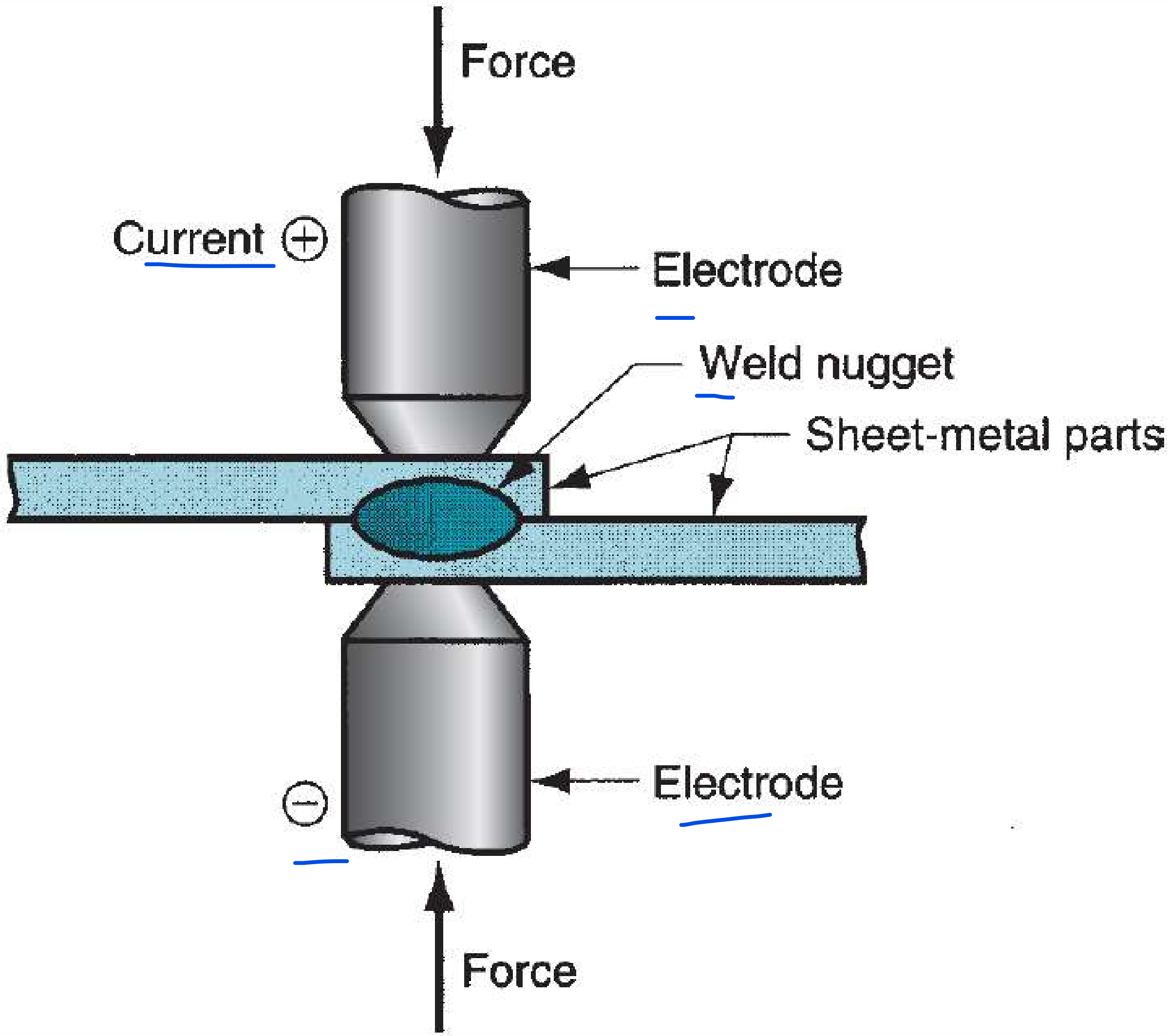


Fig. 26-8 Resistance welding (RW), showing the components in spot welding, the predominant process in the RW group.

Resistance Welding
Power Sources in RW

- The heat energy supplied to the welding operation depends on current flow, resistance of the circuit, and length of time the current is applied:

$$H = I^2 R t$$

where H = heat generated, J; I = current, A; R = electrical resistance, Ω; and t = time, s.

- ***I* used in resistance welding operations is very high (5000 to 20,000 A, typically, for short periods (0.1 to 0.4 s)), and low *E* is relatively (below 10 V).**

- The current in RW is very high because the resistance is very low ($\sim 1 \times 10^{-4} \Omega$).

- Resistance in the welding circuit is the sum of (1) resistance of the electrodes, (2) resistances of the workparts, (3) contact resistances between electrodes and workparts, and (4) contact resistance of the faying surfaces (should be largest). Thus, heat is generated in all of these regions of electrical resistance.

Resistance Welding
Power Sources in RW

- Advantages of RW:
  - No filler metal is required.
  - High production rates
  - Can be mechanized.
  - Operator skill level is lower than that required for arc welding
  - Good repeatability and reliability.
- Drawbacks of RW:
  - Equipment cost is high.
  - Limited to lap joints for most RW processes.

Resistance-Welding Processes

- <u>Resistance welding can be classified into three major types; ***Spot***, ***Seam*** and ***Projection Welding***.</u>
  - <u>***Resistance Spot Welding***:</u>
    - **<u>By far the predominant process in this group.</u>**
    - **<u>Widely used in mass production of automobiles, appliances, metal furniture, and other products made of sheet metal.</u>**
    - If one considers that a typical car body has approximately **<u>10,000 individual spot welds, and that the annual production of automobiles</u>** throughout the world is measured in tens of millions of units, the economic importance of resistance spot welding can be appreciated.

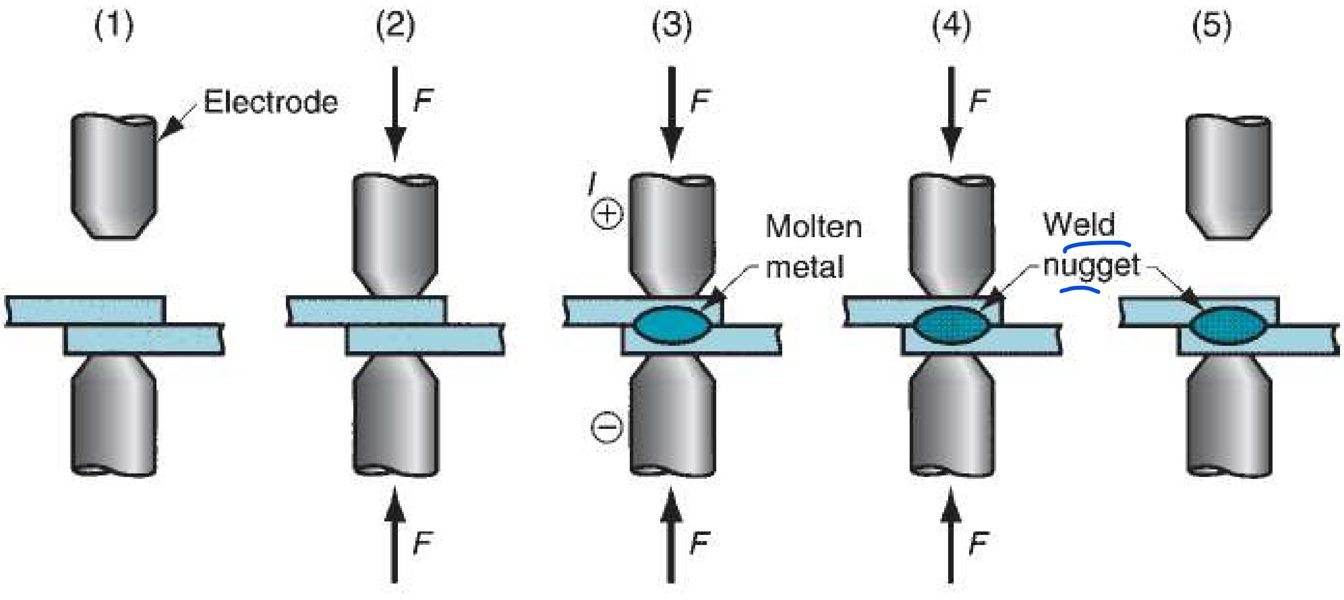
Resistance-Welding Processes

– ***Resistance Spot Welding***: **a RW process in which fusion of the faying surfaces of a lap joint is achieved at one location by opposing electrodes.**

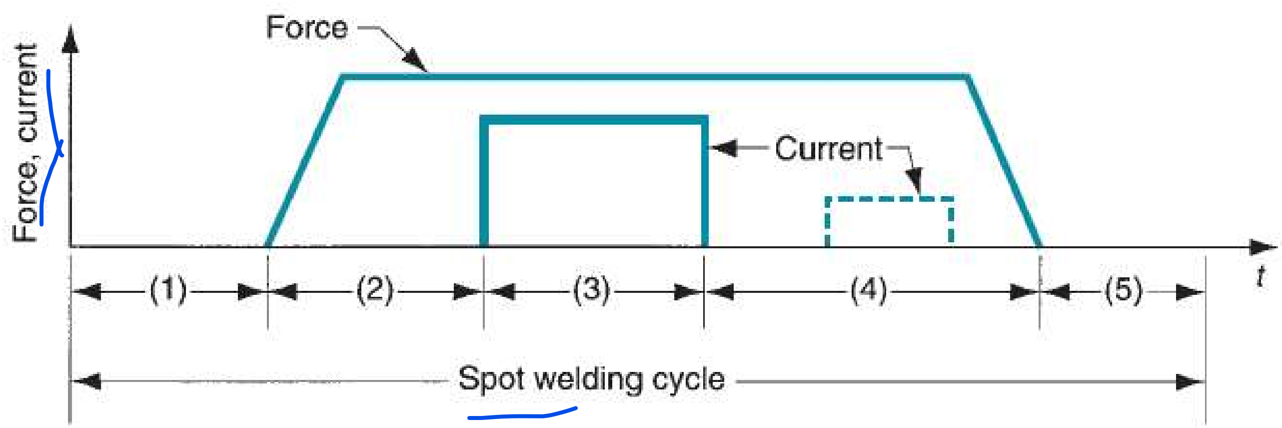
- Used to join sheet-metal parts of **thickness 3 mm or less**, using a series of spot welds.
- Size and shape of the weld spot is determined by the electrode tip (usually round).
- The resulting weld nugget is typically 5 to 10 mm in diameter, with a HAZ extending slightly beyond the nugget into the base metals.
- If the weld is made properly, its strength will be comparable to that of the surrounding metal.

Resistance-Welding Processes

Fig. 26-9 (a) Steps in a spot-welding cycle, and (b) plot of squeezing force and current during cycle. The sequence is: (1) parts inserted between open electrodes, (2) electrodes close and force is applied, (3) **weld time—current is switched on**, (4) **current is turned off but force is maintained or increased,** and (5) electrodes are opened, and the welded assembly is removed.



(a)



(b)

Resistance-Welding Processes

- **Materials used for RSW electrodes consist of two main groups:**
  - **Copper-based alloys.**
  - **Refractory metal compositions; e.g. copper and tungsten combinations: noted for superior wear resistance.**
- The tooling in spot welding gradually wears out as it is used.
- Whenever practical, the electrodes are designed with internal passageways for water cooling.

Resistance-Welding Processes

– ***Resistance Seam Welding*** (RSEW): the stick-shaped electrodes in spot welding are replaced by rotating wheels.

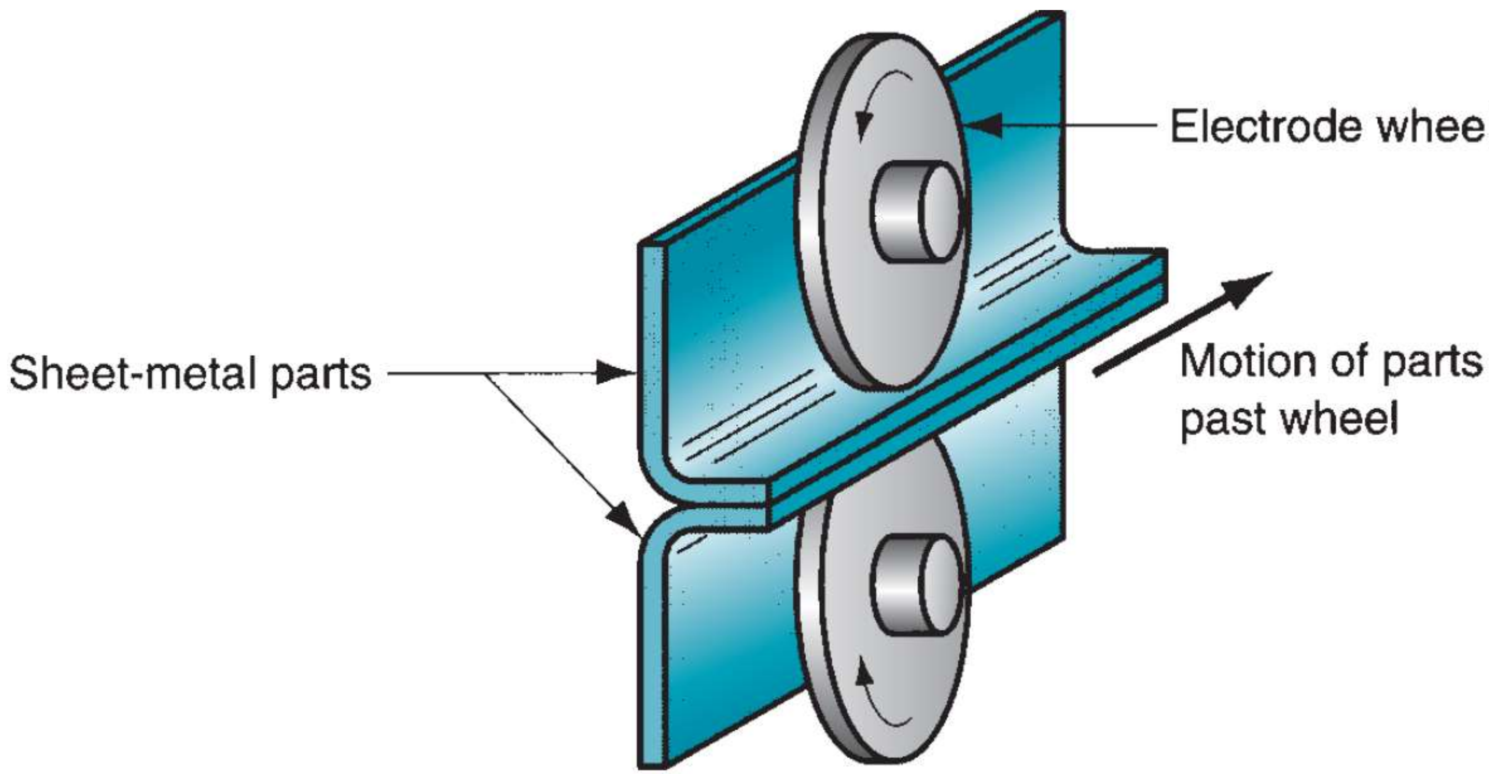


Fig. 26-10 Resistance seam welding (RSWE).

Resistance-Welding Processes

– ***Resistance Seam Welding*** (RSEW): seams have different types.

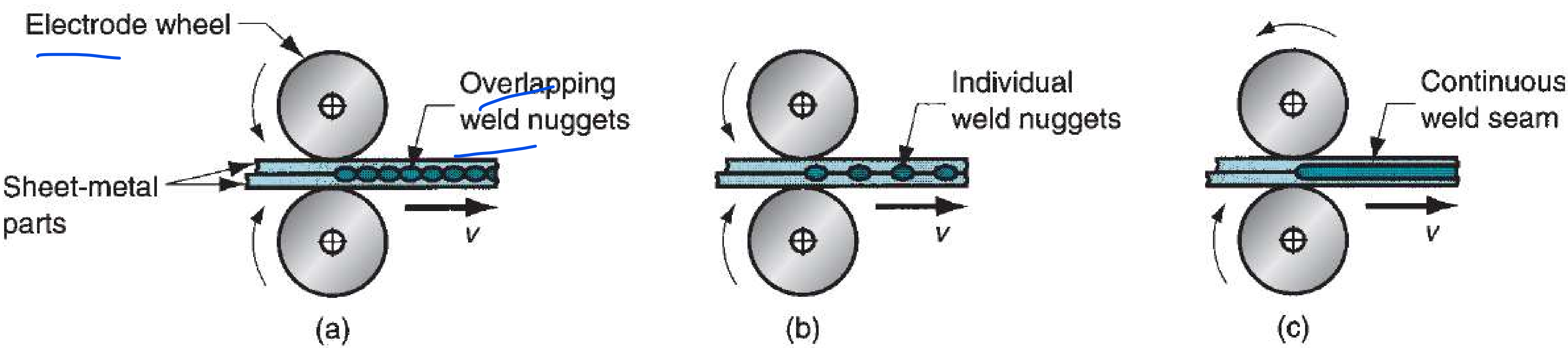


Fig. 26-11 Different types of seams produced by electrode wheels: (a) conventional resistance seam welding, in which overlapping spots are produced; (b) roll spot welding; and (c) continuous resistance seam.

Oxyfuel Gas Welding

- ***Oxyfuel Gas Welding*** (OFW): the term used to describe the group of FW operations that burn various fuels mixed with oxygen to perform welding.
  - The OFW processes employ several types of gases, which is the primary distinction among the members of this group.
  - Oxyfuel gas is also commonly used in cutting torches to cut and separate metal plates and other parts.
  - The most important OFW process is oxyacetylene welding.

Oxyfuel Gas Welding
Oxyacetylene Welding

- ***Oxyacetylene Welding*** (OAW): a fusion-welding process performed by a high-temperature flame from combustion of acetylene and oxygen.
  - **<u>The flame is directed by a welding torch.</u>**
  - A filler metal is sometimes added, and pressure is occasionally applied in OAW between the contacting part surfaces.
  - Composition of the filler (often coated with a flux) must be similar to that of the base metals. Flux helps to clean the surfaces and prevent oxidation.
  - **<u>Acetylene (C_2H_2) is the most popular fuel among the OFW group because it is capable of higher temperatures than any of the others—up to 3480 ^{o}C.</u>**

Oxyfuel Gas Welding
Oxyacetylene Welding

- ***Oxyacetylene Welding*** (OAW)

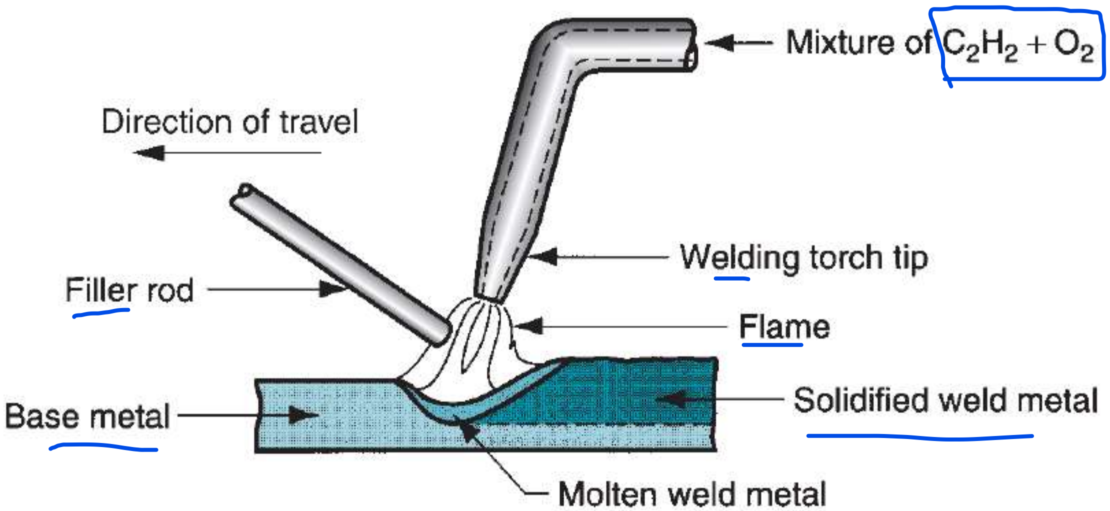


Fig. 26-12 A typical oxyacetylene welding operation (OAW).

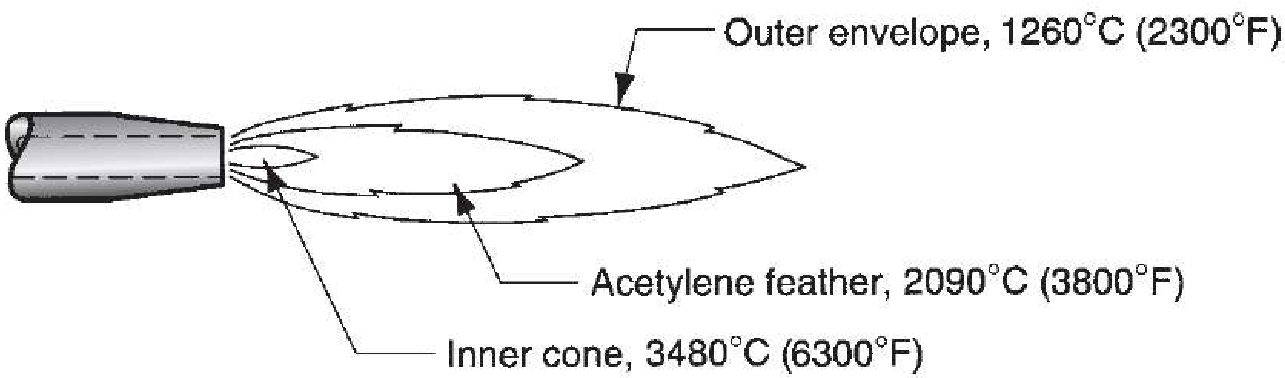


Fig. 26-13 The neutral flame (acetylene and oxygen 1 : 1) from an oxyacetylene torch, indicating temperatures achieved.

Weld Quality

- <u>**The purpose of any welding process is to join two or more components into a single structure.**</u>

- The physical integrity of the structure thus formed depends on the quality of the weld.

- The Arc Welding (AW) process is the one for which the quality issue is the most critical and complex.

Weld Quality
Residual Stresses and Distortion

- The sudden temperature changes in localized regions of the work during fusion welding result in thermal expansion and contraction that cause residual stresses in the weldment.

- These stresses can cause distortion and warping of the welded assembly.

- **The situation in welding is complicated because:**
  - **Heating is very localized.**
  - **Melting of the base metals occurs in these local regions.**
  - **Location of heating and melting is in motion.**

Weld Quality
Residual Stresses and Distortion

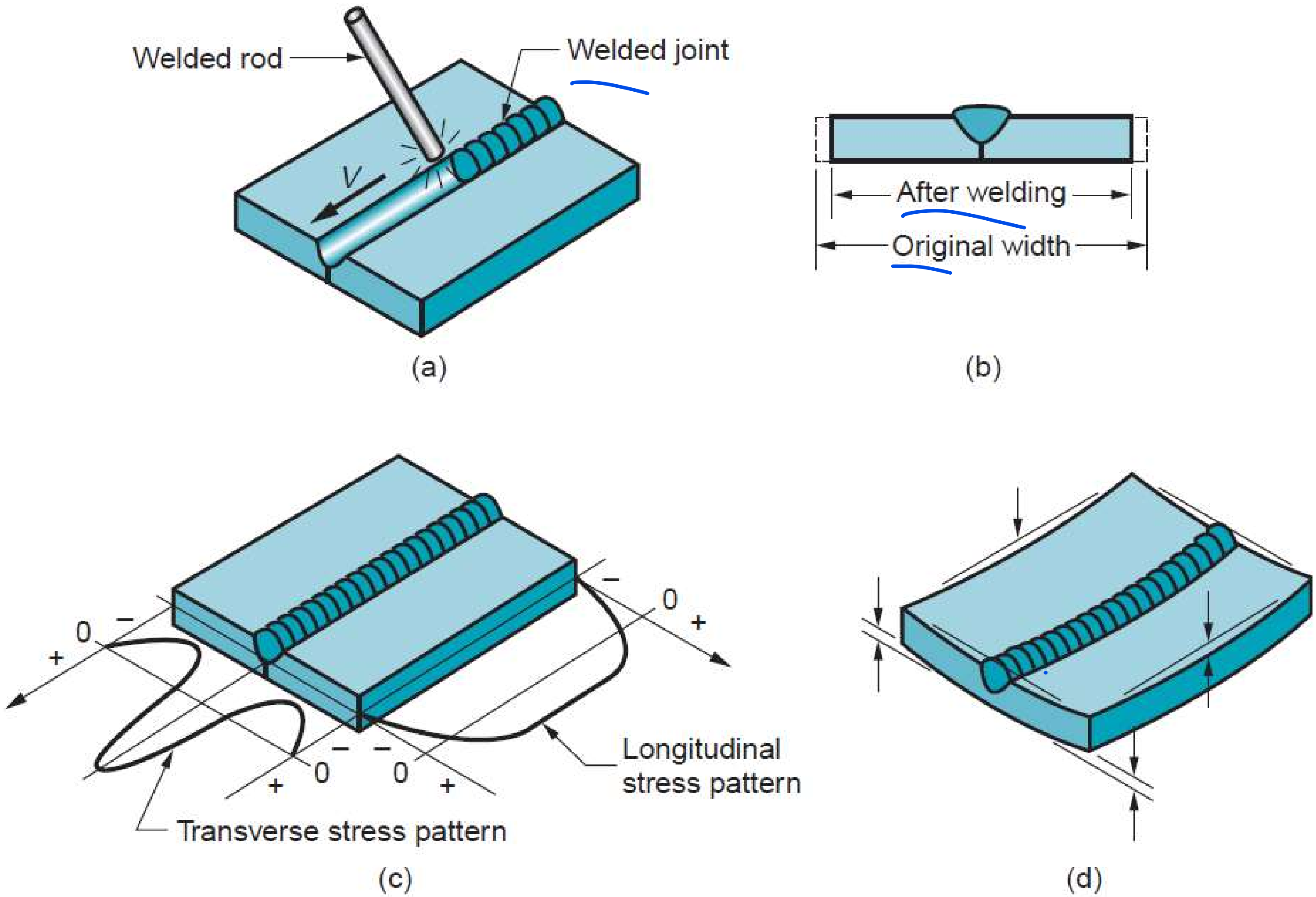


Fig. 26-18 (a) Butt welding two plates; (b) shrinkage across the width of the welded assembly; (c) transverse and longitudinal residual stress pattern; and (d) likely warping in the welded assembly.

Weld Quality
Residual Stresses and Distortion

- As welding proceeds, a molten pool is formed from the base metal that quickly solidifies behind the moving arc.

- The portions of the work immediately adjacent to the weld bead become extremely hot and expand, while portions removed from the weld remain relatively cool.

- **<u>The weld pool quickly solidifies, and as it and the surrounding metal cool and contract, shrinkage occurs across the width of the weldment.</u>**

- The weld seam is left in residual tension, and reactionary compressive stresses are set up in regions of the parts away from the weld.

- <u>Residual stresses and shrinkage also occur along the length of the weld bead.</u>

Weld Quality
Residual Stresses and Distortion

- Since the outer regions of the base parts have remained relatively cool and dimensionally unchanged, while the weld bead has solidified from very high temperatures and then contracted, residual tensile stresses remain longitudinally in the weld bead.

- The net result of these residual stresses, transversely and longitudinally, is likely to cause warping in the welded assembly.

Weld Quality
Welding Defects

- Defects other than residual stresses and distortion can appear in welding:

  - *Cracks*: **fracture-type interruptions either in the weld itself or in the base metal adjacent to the weld.**

    - Most serious welding defect because it constitutes a discontinuity in the metal that significantly reduces weld strength.

    - Caused by embrittlement or low ductility of the weld and/or base metal combined with high restraint during contraction.

    - Generally, this defect must be repaired.

Weld Quality
Welding Defects

– ***Cracks***.

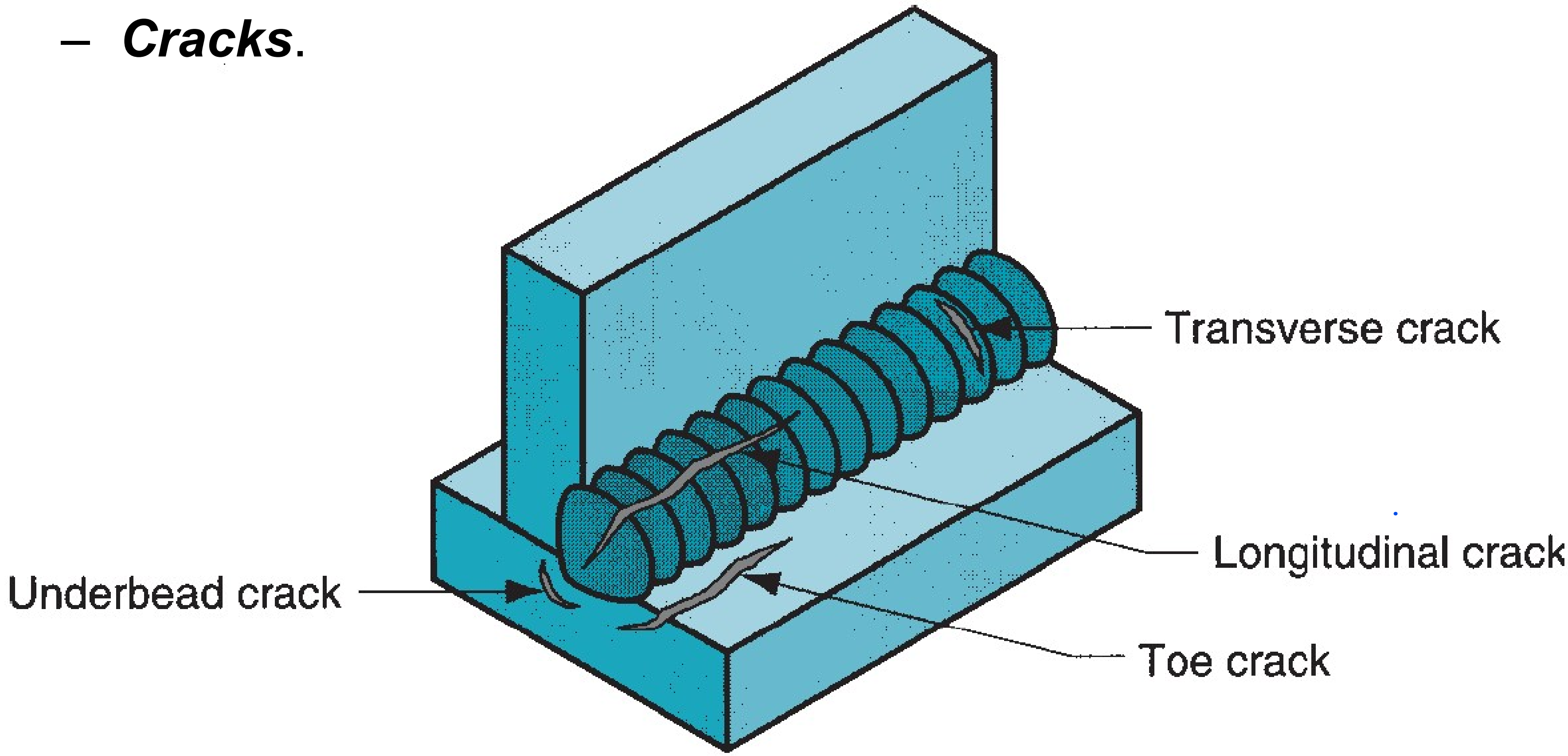


Fig. 26-19 Various forms of welding cracks.

Weld Quality
Welding Defects

– ***Cavities***: include various porosity and shrinkage voids.

  - ***Porosity*****: consists of small voids in the weld metal formed by gases entrapped during solidification. Porosity usually results from inclusion of atmospheric gases, sulfur in the weld metal, or contaminants on the surfaces.**

  - ***Shrinkage Voids*****: cavities formed by shrinkage during solidification. Both of these cavity-type defects are similar to defects found in casting.**

Weld Quality
Welding Defects

- ***Incomplete Fusion***: a weld bead in which fusion has not occurred throughout the entire cross section of the joint.

    - ***Lack of Penetration*: a related defect, which means that fusion has not penetrated deeply enough into the root of the joint.**

- ***Imperfect Shape*** or ***Unacceptable Contour***: weld should have a certain desired profile for maximum strength for a single V-groove weld.

    - This profile maximizes the strength of the welded joint and avoids incomplete fusion and lack of penetration.

Weld Quality
Welding Defects

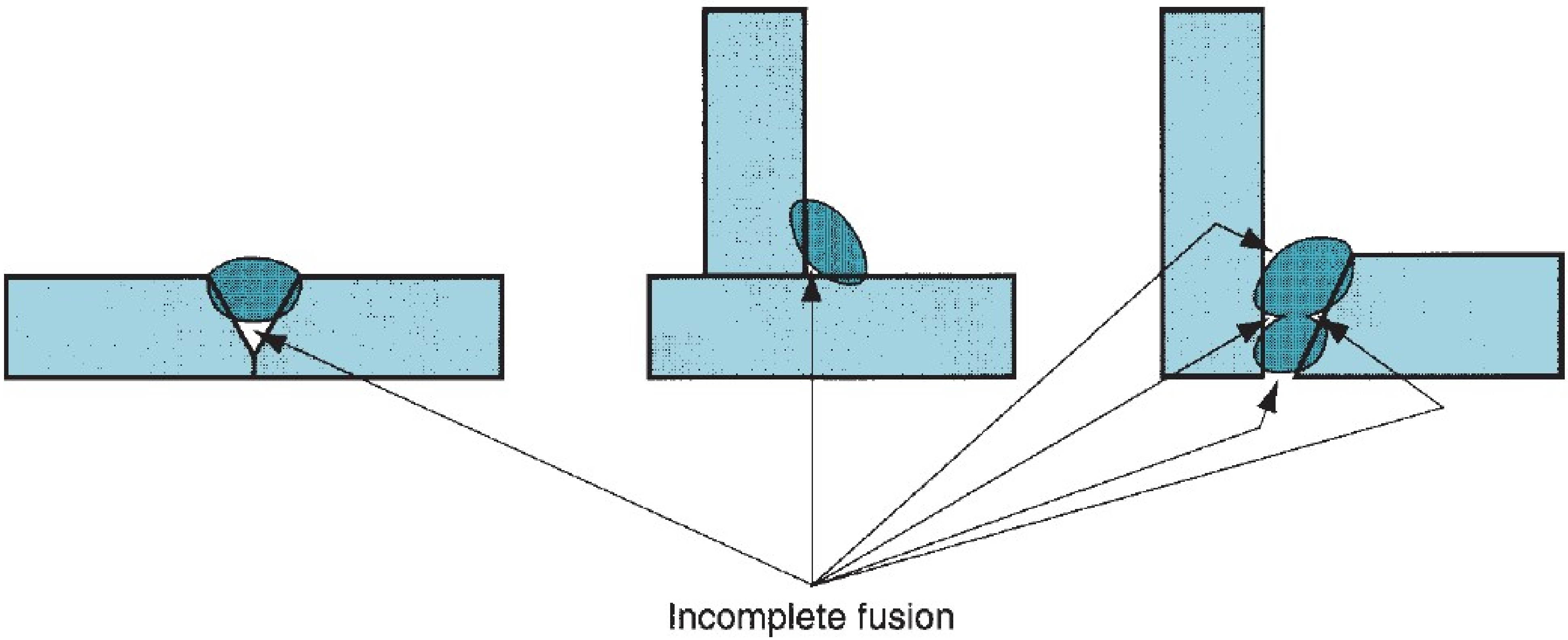


Fig. 26-20 Several forms of incomplete fusion.

Weld Quality
Welding Defects

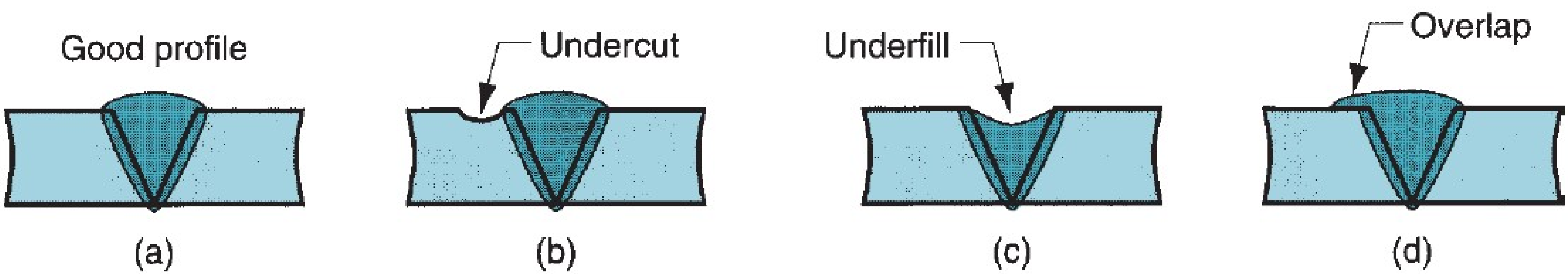


Fig. 26-21 (a) Desired weld profile for single V-groove weld joint. Same joint but with several weld defects: (b) ***undercut***, in which a portion of the base metal part is melted away; (c) ***underfill***, a depression in the weld below the level of the adjacent base metal surface; and (d) ***overlap***, in which the weld metal spills beyond the joint onto the surface of the base part but no fusion occurs.

Weldability

- ***Weldability***: the capacity of a metal or combination of metals to be welded into a suitably designed structure, and for the resulting weld joint(s) to possess the required metallurgical properties to perform satisfactorily in the intended service.

- <u>**Good weldability is characterized by:**</u>

  – <u>**The ease with which the welding process is accomplished.**</u>

  – <u>**Absence of weld defects, and acceptable strength.**</u>

  – <u>**Ductility, and toughness in the welded joint.**</u>

Weldability

- Factors affecting weldability:
  - ***Welding Process*: some metals or metal combinations that can be readily welded by one process are difficult to weld by others; e.g. stainless steel can be readily welded by most AW processes, but is considered a difficult metal for oxyfuel welding.**
  - ***Base Metal Properties*: such as melting point, thermal conductivity, and coefficient of thermal expansion.**
    - Too low melting point: means that such metals melt too easily for good welding; e.g. aluminum.
    - Too high thermal conductivities: such metals tend to transfer heat away from the weld zone, which can make them hard to weld (e.g., copper).

Weldability

- Factors affecting weldability:
  - ***Filler Metal*****: must be compatible with the base metal(s).**
  - ***Surface Conditions*****: adversely affect the operation; e.g. moisture can result in porosity in the fusion zone. Oxides and other solid films on the metal surfaces can prevent adequate contact and fusion from occurring**.

Design Considerations in Welding

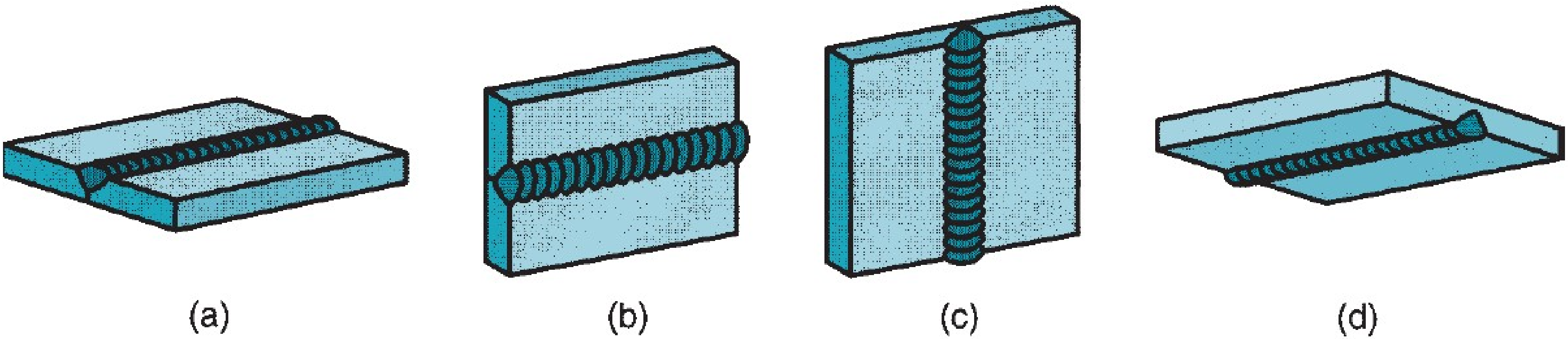


Fig. 26-23 Welding positions (defined here for groove welds): (a) flat, (b) horizontal, (c) vertical, and (d) overhead.