Weld Quality

Residual Stresses and Distortion

- The rapid heating and cooling in localized regions of the w.p. during fusion welding, especially arc welding, result in thermal expansion and contraction that cause residual stresses in the weldment.
- These stresses, in turn, can cause distortion and warping of the welded assembly.
- **The situation in welding is complicated because:**

(1) heating is very localized,
(2) melting of the base metals occurs in these local regions, and
(3) the location of heating and melting is in motion (at least in arc welding).

- Consider, for example, butt welding of two plates by arc-welding as shown in Figure (5-37a).
- The operation begins at one end and travels to the opposite end.
- As it proceeds, a molten pool is formed from the base metal (and filler metal, if used) that quickly solidifies behind the moving arc.
- The portions of the w.p. immediately adjacent to the weld bead become extremely hot and expand, while portions removed from the weld remain relatively cool.
- The weld pool quickly solidifies in the cavity between the two parts, and as it and the surrounding metal cool and contract, shrinkage occurs across the width of the weldment, as seen in Figure (5-37b).
- The weld seam is left in residual tension, and reactionary compressive stresses are set up in regions of the parts away from the weld.
- Residual stresses and shrinkage also occur along the length of the weld bead.
- 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.
- These transverse and longitudinal stress patterns are depicted in Figure (5-37c).
- The net result of these residual stresses, transversely and longitudinally, is likely to cause warping in the welded assembly as shown in Figure (5-37d).

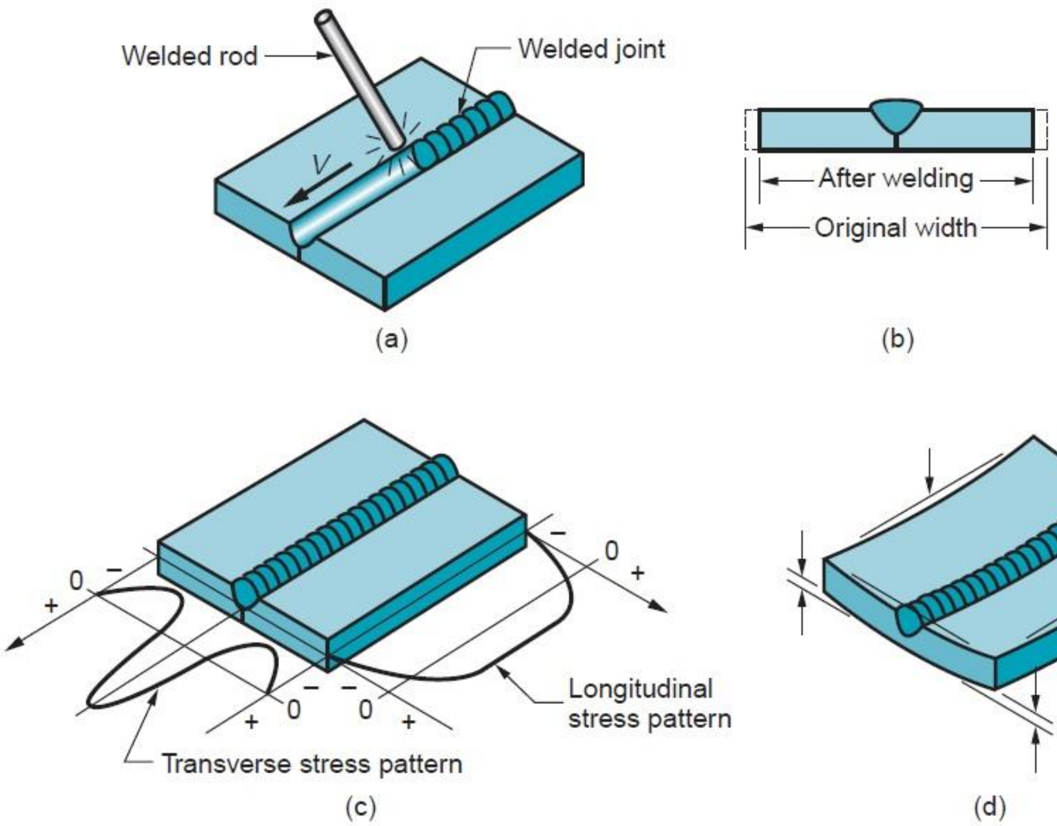

Figure (5-37) (a) Butt welding two plates; (b) shrinkage across the width of the welded assembly; (c) transverse and longitudinal residual stress pattern; and (d) likely warping in the welded assembly.

- Thermally induced residual stresses and the accompanying distortion are a potential problem in nearly all fusion-welding processes and in certain solid-state welding operations in which significant heating takes place.
- **Some techniques to minimize warping in a weldment:**

(1) Welding fixtures can be used to physically restrain movement of the parts during welding.
(2) Heat sinks can be used to rapidly remove heat from sections of the welded parts to reduce distortion.
(3) Tack welding at multiple points along the joint can create a rigid structure prior to continuous seam welding.
(4) Welding conditions (speed, amount of filler metal used, etc.) can be selected to reduce warping.
(5) The base parts can be preheated to reduce the level of thermal stresses experienced by the parts.
(6) Stress relief heat treatment can be performed on the welded assembly, either in a furnace for small weldments, or using methods that can be used in the field for large structures.
(7) Proper design of the weldment itself can reduce the degree of warping.

Welding Defects

In addition to residual stresses and distortion in the final assembly, other defects can occur in welding. Following is a brief description of each of the major categories:

(1) Cracks:

- They are fracture-type interruptions either in the weld itself or in the base metal adjacent to the weld.
- This is perhaps the most serious welding defect because it constitutes a discontinuity in the metal that significant reduces weld strength.
- Several forms are defined in Figure (5-38).
- Welding cracks are caused by embrittlement or low ductility of the weld and/or base metal combined with high restraint during contraction.

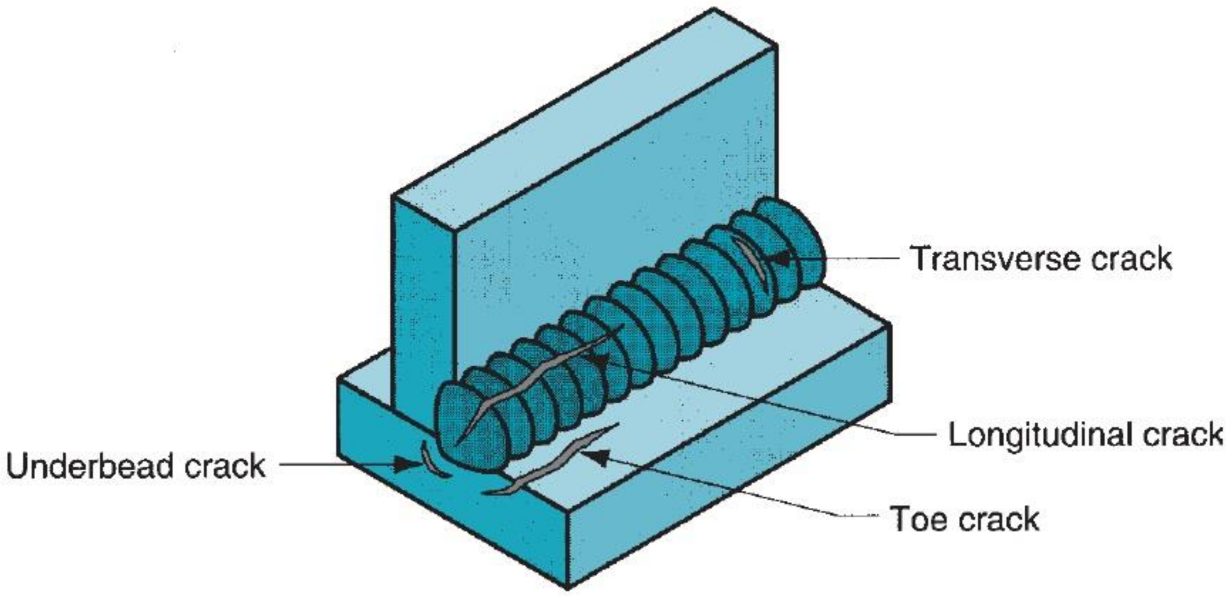

Figure (5-38) Various forms of welding cracks.

(2) Cavities:

- These include various porosity and shrinkage voids.
- Porosity consists of small voids in the weld metal formed by gases entrapped during solidification.
- The shapes of the voids vary between spherical (blow holes) to elongated (worm holes).
- Porosity usually results from inclusion of atmospheric gases, sulfur in the weld metal, or contaminants on the surfaces.
- Shrinkage voids are cavities formed by shrinkage during solidification.

- Both of these cavity-type defects are similar to defects found in castings and emphasize the close kinship between casting and welding.

(3) Solid Inclusions:
- These are nonmetallic solid materials trapped inside the weld metal.
- The most common form is slag inclusions generated during arc-welding processes that use flux.
- Instead of floating to the top of the weld pool, globules of slag become encased during solidification of the metal.
- Another form of inclusion is metallic oxides that form during the welding of metals such as aluminum, which normally has a surface coating of Al_2O_3.

(4) Incomplete Fusion:
- Several forms of this defect are illustrated in Figure (5-39).
- Also known as lack of fusion, it is simply a weld bead in which fusion has not occurred throughout the entire cross section of the joint.
- A related defect is lack of penetration which means that fusion has not penetrated deeply enough into the root of the joint.

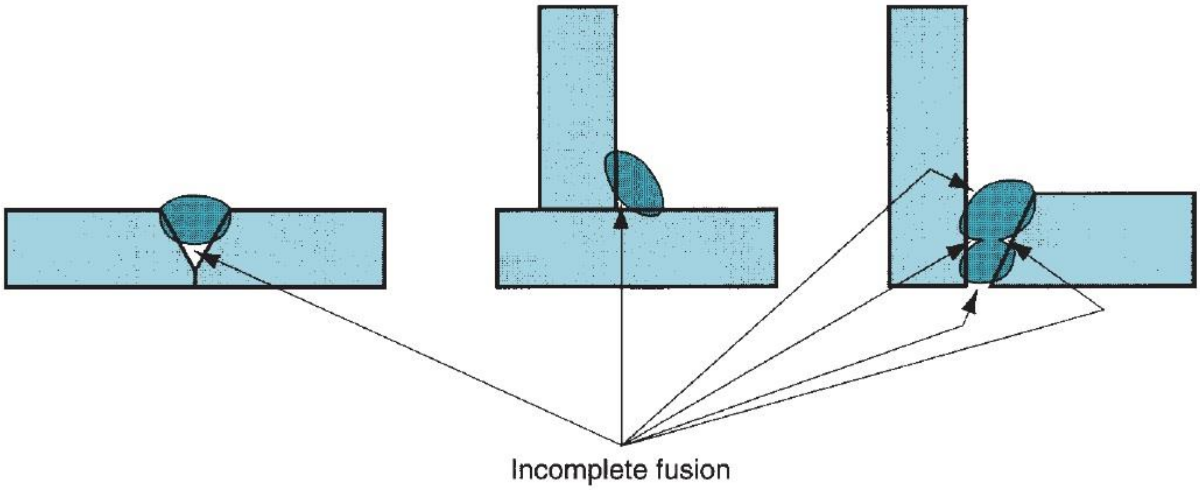

Figure (5-39) Several forms of incomplete fusion.

(5) Imperfect Shape or Unacceptable Contour:

- The weld should have a certain desired profile for maximum strength, as indicated in Figure (5-40a) for a single V-groove weld.
- This weld profile maximizes the strength of the welded joint and avoids incomplete fusion and lack of penetration.
- Some of the common defects in weld shape and contour are illustrated in Figure (5-40).

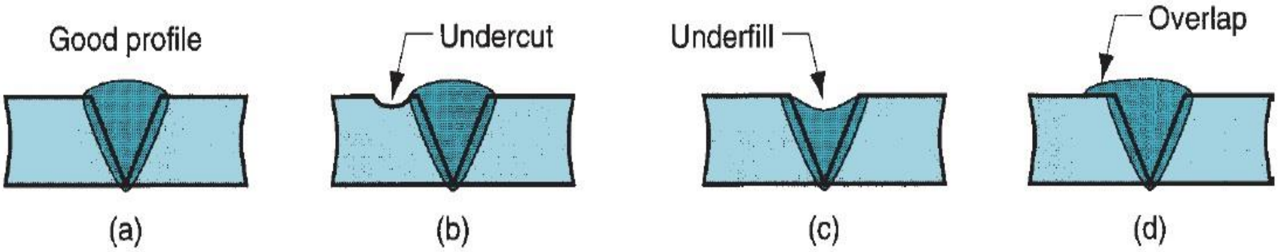

Figure (5-40) (a) Desired weld profile for single V-groove weld joint. Same joint but with several weld defects: (b) **undercut**, in which a portion of the base metal part is melted away; (c) **underfill**, a depression in the weld below the level of the adjacent base metal surface; and (d) **overlap**, in which the weld metal spills beyond the joint on to the surface of the base part but no fusion occurs.

(6) Miscellaneous Defects:

- This category includes ***arc strikes***, in which the welder accidentally allows the electrode to touch the base metal next to the joint, leaving a scar on the surface; and ***excessive spatter***, in which drops of molten weld metal splash onto the surface of the base parts.

Inspection and Testing Methods

- A variety of inspection and testing methods are available to check the quality of the welded joint.
- Standardized procedures have been developed and specified over the years by engineering and trade societies such as the American Welding Society (AWS).
- For purposes of discussion, these inspection and testing procedures can be divided into three categories: (1) visual, (2) nondestructive, and (3) destructive.

(1) Visual inspection

- It is no doubt the most widely used welding inspection method.
- An inspector visually examines the weldment for (1) conformance to dimensional specifications on the part drawing, (2) warping, and (3) cracks, cavities, incomplete fusion, and other visible defects.
- The welding inspector also determines if additional tests are warranted, usually in the nondestructive category.
- The limitation of visual inspection is that only surface defects are detectable; internal defects cannot be discovered by visual methods.

(2) Nondestructive evaluation (NDE)

- It includes various methods that do not damage the specimen being inspected.
- Dye-penetrant and fluorescent-penetrant tests are methods for detecting small defects such as cracks and cavities that are open to the surface.
- Fluorescent penetrants are highly visible when exposed to ultraviolet light, and their use is therefore more sensitive than dyes.

Magnetic Particle Testing

- It is limited to ferromagnetic materials.
- A magnetic field is established in the subject part, and magnetic particles (e.g., iron filings) are sprinkled on the surface.
- Subsurface defects such as cracks and inclusions reveal themselves by distorting the magnetic field, causing the particles to be concentrated in certain regions on the surface.

Ultrasonic testing

- It involves the use of high-frequency sound waves (>20 kH_z) directed through the specimen.
- Discontinuities (e.g., cracks, inclusions, porosity) are detected by losses in sound transmission.

Radiographic testing

- It uses X-rays or gamma radiation to detect flaws internal to the weld metal.
- It provides a photographic film record of any defects.

(3) Destructive testing

- It is a method in which the weld is destroyed either during the test or to prepare the test specimen.
- They include mechanical and metallurgical tests.

Mechanical tests

- They are similar in purpose to conventional testing methods such as tensile tests and shear tests.
- The difference is that the test specimen is a weld joint.
- Figure (5-41) presents a sampling of the mechanical tests used in welding.

Metallurgical tests

- They involve the preparation of metallurgical specimens of the weldment to examine such features as metallic structure, defects, extent and condition of heat-affected zone, presence of other elements, and similar phenomena.

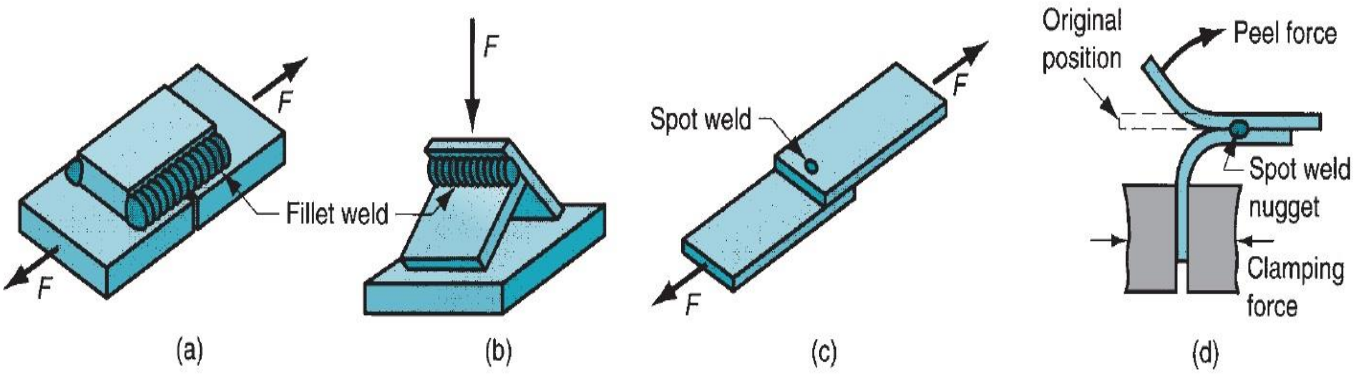

Figure (5-41) Mechanical tests used in welding: (a) tension–shear test of arc weldment, (b) fillet break test, (c) tension–shear test of spot weld, (d) peel test for spot weld.

Weldability

- Weldability is 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.

- **Good weldability is characterized by:**
  (1) the ease with which the welding process is accomplished,
  (2) absence of weld defects, and
  (3) acceptable strength, ductility, and toughness in the welded joint.

- **Factors that affect weldability include:**

(1) Welding Process:
- Some metals or metal combinations that can be readily welded by one process are difficult to weld by others.
- For example, stainless steel can be readily welded by most AW processes, but is considered a difficult metal for oxyfuel welding.

(2) Base Metal Properties:
- Properties of the base metal affect welding performance.
- Important properties include melting point, thermal conductivity, and coefficient of thermal expansion.
- One might think that a lower melting point would mean easier welding.
- However, some metals melt too easily for good welding (e.g., aluminum).
- Metals with high thermal conductivity tend to transfer heat away from the weld zone, which can make them hard to weld (e.g., copper).
- High thermal expansion and contraction in the metal causes distortion problems in the welded assembly.
- Dissimilar metals pose special problems in welding when their physical and/or mechanical properties are substantially different.
- Differences in melting temperature are an obvious problem.
- Differences in strength or coefficient of thermal expansion may result in high residual stresses that can lead to cracking.

(3) Filler Metal:
- If a filler metal is used, it must be compatible with the base metal(s).
- In general, elements mixed in the liquid state that form a solid solution upon solidification will not cause a problem.
- Embrittlement in the weld joint may occur if the solubility limits are exceeded.

(4) Surface Conditions:

- Surface conditions of the base metals can adversely affect the operation.
- For example, 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 Consideration in Welding

- If an assembly is to be permanently welded, the designer should follow certain guidelines:

- **Design for Welding:**
- The most basic guideline is that the product should be designed from the start as a welded assembly, and not as a casting or forging or other formed shape.
- **Minimum Parts:**
- Welded assemblies should consist of the fewest number of parts possible.
- For example, it is usually more cost efficient to perform simple bending operations on a part than to weld an assembly from flat plates and sheets.

The following guidelines apply to arc welding:

(1) Good fit-up of parts to be welded is important to maintain dimensional control and minimize distortion. Machining is sometimes required to achieve satisfactory fit-up.

(2) The assembly must provide access room to allow the welding gun to reach the welding area.

(3) Whenever possible, design of the assembly should allow flat welding to be performed, since this is the fastest and most convenient welding position. The possible welding positions are defined in Figure (5-42). The overhead position is the most difficult.

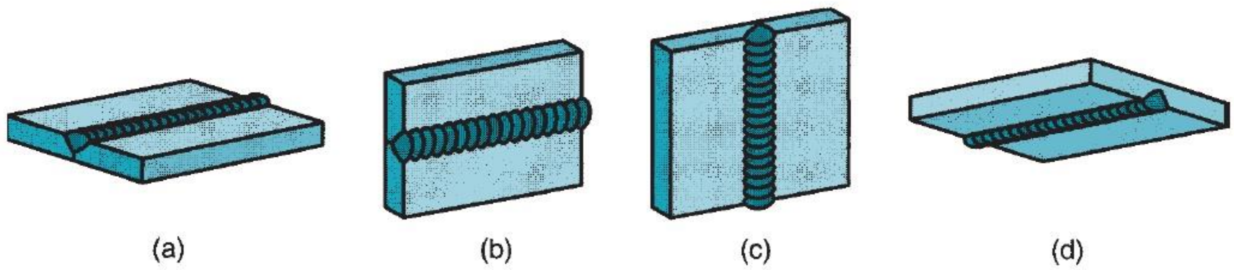

Figure (5-42) Welding positions (defined here for groove welds): (a) flat, (b)horizontal, (c) vertical, and (d) overhead.

The following design guidelines apply to resistance spot welding:

(1) Low-carbon sheet steel up to 3.2 mm is the ideal metal for resistance spot welding.
(2) Additional strength and stiffness can be obtained in large flat sheet metal components by: (1) spot welding reinforcing parts into them, or (2) forming flanges and embossments into them.
(3) The spot-welded assembly must provide access for the electrodes to reach the welding area.
(4) Sufficient overlap of the sheet-metal parts is required for the electrode tip to make proper contact in spot welding. For example, for low-carbon sheet steel, the overlap distance should range from about six times stock thickness for thick sheets of 3.2 mm to about 20 times thickness for thin sheets, such as 0.5 mm.