## (B) Solid-State Welding

- In solid state-welding, coalescence of the part surfaces is achieved by:

(1) pressure alone, or (2) heat and pressure.

- For some solid-state processes, time is also a factor.
- If both heat and pressure are used, the amount of heat by itself is not sufficient to cause melting of the work surfaces.
- In other words, fusion of the parts would not occur using only the heat that is externally applied in these processes.
- In some cases, the combination of heat and pressure, or the particular manner in which pressure alone is applied, generates sufficient energy to cause localized melting of the faying surfaces.
- Filler metal is not added in solid-state welding.

## General Considerations in Solid-State Welding

- In most of the solid-state processes, a metallurgical bond is created with little or no melting of the base metals.
- To metallurgically bond two similar or dissimilar metals, the two metals must be brought into intimate contact so that their cohesive atomic forces attract each other.
- In normal physical contact between two surfaces, such intimate contact is prohibited by the presence of chemical films, gases, oils, and so on.
- In order for atomic bonding to succeed, these films and other substances must be removed.
- In fusion welding (as well as other joining processes such as brazing and soldering), the films are dissolved or burned away by high temperatures, and atomic bonding is established.
- But in solid-state welding, the films and other contaminants must be removed by other means to allow metallurgical bonding to take place.
- In some cases, a thorough cleaning of the surfaces is done just before the welding process; while in other cases, the cleaning action is accomplished as an integral part of bringing the part surfaces together.
- To summarize, the essential ingredients for a successful solid-state weld are:

(1) that the two surfaces must be very clean, and

(2) they must be brought into very close physical contact with each other to permit atomic bonding.

**Advantages of Solid-State Welding:**

(1) If no melting occurs, then there is no heat-affected zone, and so the metal surrounding the joint retains its original properties.

(2) Many of these processes produce welded joints that comprise the entire contact interface between the two parts, rather than at distinct spots or seams, as in most fusion-welding operations.

(3) Some of these processes are quite applicable to bonding dissimilar metals, without concerns about relative thermal expansions, conductivities, and other problems that usually arise when dissimilar metals are melted and then solidified during joining.

## Solid State-Welding Processes

### (a) Forge Welding

- Forge welding is a welding process in which the components to be joined are heated to hot working temperatures and then forged together by hammer or other means.
- Considerable skill was required by the craftsmen who practiced it in order to achieve a good weld by present-day standards.
- The process may be of historic interest; however, it is of minor commercial importance today.

### (b) Cold Welding (CW)

- Cold welding (CW) is a solid-state welding process accomplished by applying high pressure between clean contacting surfaces at room temperature.
- The faying surfaces must be exceptionally clean for CW to work, and cleaning is usually done by degreasing and wire brushing immediately before joining.
- Also, at least one of the metals to be welded, and preferably both, must be very ductile and free of work hardening.
- Metals such as soft aluminum and copper can be readily cold welded.
- The applied compression forces in the process result in coldworking of the metal parts, reducing thickness by as much as 50%; but they also cause localized plastic deformation at the contacting surfaces, resulting in coalescence.
- For small parts, the forces may be applied by simple hand-operated tools.
- For heavier w.p., powered presses are required to exert the necessary force.
- No heat is applied from external sources in CW, but the deformation process raises the temperature of the w.p. somewhat.
- Applications of CW include making electrical connections.

### (c) Roll Welding

- Roll welding is a variation of either forge welding or cold welding, depending on whether external heating of the w.ps. is accomplished prior to the process.
- Roll welding (ROW) is a solid-state welding process in which pressure sufficient to cause coalescence is applied by means of rolls, either with or without external application of heat.
- The process is illustrated in Figure (5-32).
- If no external heat is supplied, the process is called cold-roll welding; if heat is supplied, the term hot-roll welding is used.
- Applications of roll welding include cladding stainless steel to mild or low alloy steel for corrosion resistance, making bimetallic strips for measuring temperature, and producing ‘‘sandwich’’ coins.

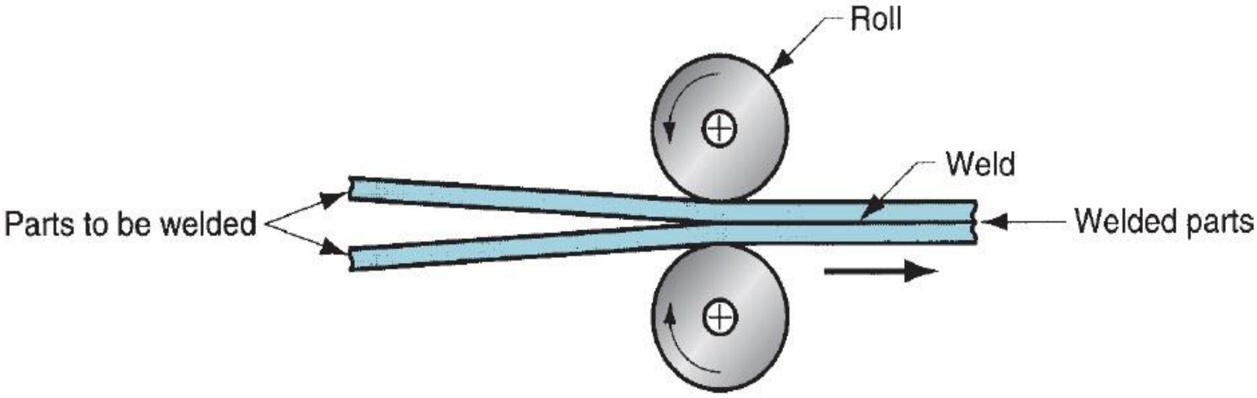


Figure (5-32) Roll Welding (ROW).

### (d) Hot Pressure Welding (HPW)

- Hot pressure welding (HPW) is another variation of forge welding in which coalescence occurs from the application of heat and pressure sufficient to cause considerable deformation of the base metals.
- The deformation disrupts the surface oxide film, thus leaving clean metal to establish a good bond between the two parts.
- Time must be allowed for diffusion to occur across the faying surfaces.
- The operation is usually carried out in a vacuum chamber or in the presence of a shielding medium.
- Principal applications of HPW are in the aerospace industry.

### (e) Diffusion Welding (DFW)

- Diffusion welding (DFW) is a solid-state welding process that results from the application of heat and pressure, usually in a controlled atmosphere, with sufficient time allowed for diffusion and coalescence to occur.
- Temperatures are well below the melting points of the metals (about 0.5 $T_m$ is the maximum), and plastic deformation at the surfaces is minimal.
- The primary mechanism of coalescence is solid state diffusion, which involves migration of atoms across the interface between contacting surfaces.
- The time for diffusion to occur between the faying surfaces can be significant, requiring more than an hour in some applications.

**Applications of DFW**

(1) joining of high-strength and refractory metals in the aerospace and nuclear industries.

(2) The process is used to join both similar and dissimilar metals, and in the latter case a filler layer of a different metal is often sandwiched between the two base metals to promote diffusion.

### (f) Explosion Welding (EXW)

- Explosion welding (EXW) is a solid-state welding process in which rapid coalescence of two metallic surfaces is caused by the energy of a detonated explosive.
- It is commonly used to bond two dissimilar metals, in particular to clad one metal on top of a base metal over large areas.
- The term explosion cladding is used in this context.
- **EXW Applications**
- include production of corrosion-resistant sheet and plate stock for making processing equipment in the chemical and petroleum industries.
- **EXW Advantages**

(1) No filler metal is used in EXW, and no external heat is applied.

(2) Also, no diffusion occurs during the process (the time is too short).

(3) The nature of the bond is metallurgical, in many cases combined with a mechanical interlocking that results from a rippled or wavy interface between the metals.

- The process for cladding one metal plate on another can be described with reference to Figure (5-33).
- In this setup, the two plates are in a parallel configuration, separated by a certain gap distance, with the explosive charge above the upper plate, called the flyer plate.

- A buffer layer (e.g., rubber, plastic) is often used between the explosive and the flyer plate to protect its surface.
- The lower plate, called the backer metal, rests on an anvil for support.
- When detonation is initiated, the explosive charge propagates from one end of the flyer plate to the other, caught in the stop-action view shown in Figure (5-33)(2).

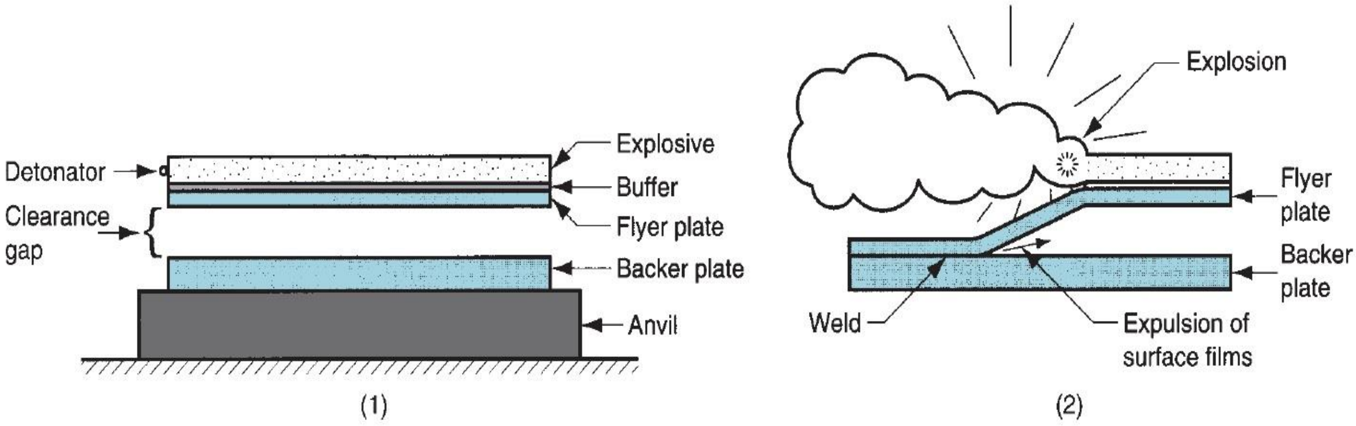


Figure (5-33) Explosive welding (EXW): (1) setup in the parallel configuration, and (2) during detonation of the explosive charge.

- One of the difficulties in comprehending what happens in EXW is the common misconception that an explosion occurs instantaneously; it is actually a progressive reaction, although admittedly very rapid—propagating at rates as high as 8500m/s.
- The resulting high-pressure zone propels the flyer plate to collide with the backer metal progressively at high velocity, so that it takes on an angular shape as the explosion advances, as illustrated in Figure (5-33).
- The upper plate remains in position in the region where the explosive has not yet detonated.
- The high-speed collision, occurring in a progressive and angular fashion as it does, causes the surfaces at the point of contact to become fluid, and any surface films are expelled forward from the apex of the angle.
- The colliding surfaces are thus chemically clean, and the fluid behavior of the metal, which involves some interfacial melting, provides intimate contact between the surfaces, leading to metallurgical bonding.
- Variations in collision velocity and impact angle during the process can result in a wavy or rippled interface between the two metals.
- This kind of interface strengthens the bond because it increases the contact area and tends to mechanically interlock the two surfaces.

### (g) Friction Welding (FRW)

- Friction welding (FRW) is a solid-state welding process in which coalescence is achieved by frictional heat combined with pressure.
- The friction is induced by mechanical rubbing between the two surfaces, usually by rotation of one part relative to the other, to raise the temperature at the joint interface to the hot working range for the metals involved.
- Then the parts are driven toward each other with sufficient force to form a metallurgical bond.
- The sequence is portrayed in Figure (5-34) for welding two cylindrical parts, the typical application.

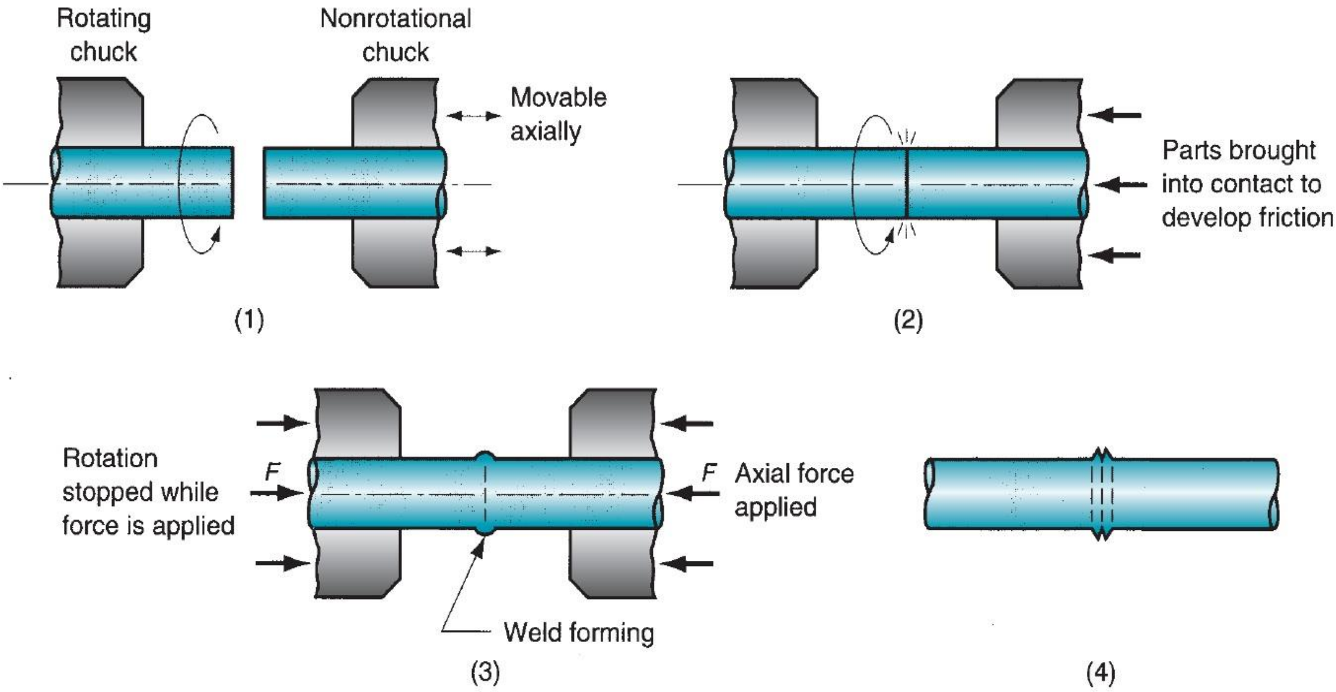


Figure (5-34) Friction welding (FRW): (1) rotating part, no contact; (2) parts brought into contact to generate friction heat; (3) rotation stopped and axial pressure applied; and (4) weld created.

- The axial compression force upsets the parts, and a flash is produced by the material displaced.
- Any surface films that may have been on the contacting surfaces are expunged during the process.
- The flash must be subsequently trimmed (e.g., by turning) to provide a smooth surface in the weld region.
- **<u>FRW Advantages</u>**

(1) When properly carried out, no melting occurs at the faying surfaces.
(2) No filler metal, flux, or shielding gases are normally used.

- Nearly all FRW operations use rotation to develop the frictional heat for welding.
- **There are two principal drive systems, distinguishing two types of FRW:**

(1) continuous drive friction welding, and
(2) inertia friction welding.

- **Continuous-drive friction welding:**

(1) One part is driven at a constant rotational speed and forced into contact with the stationary part at a certain force level so that friction heat is generated at the interface.
(2) When the proper hot working temperature has been reached, braking is applied to stop the rotation abruptly, and simultaneously the pieces are forced together at forging pressures.

- **Inertia friction welding:**

(1) The rotating part is connected to a flywheel, which is brought up to a predetermined speed.
(2) Then the flywheel is disengaged from the drive motor, and the parts are forced together.
(3) The kinetic energy stored in the flywheel is dissipated in the form of friction heat to cause coalescence at the abutting surfaces. The total cycle for these operations is about 20 seconds.

- Machines used for friction welding have the appearance of an engine lathe.
- They require a powered spindle to turn one part at high speed, and a means of applying an axial force between the rotating part and the nonrotating part.
- With its short cycle times, the process lends itself to mass production.
- The process yields a narrow heat-affected zone and can be used to join dissimilar metals.
- However, at least one of the parts must be rotational, flash must usually be removed, and upsetting reduces the part lengths (which must be taken into consideration in product design).
- A more recent version of the process is ***linear friction welding***, in which a linear reciprocating motion is used to generate friction heat between the parts.
- This eliminates the requirement for at least one of the parts to be rotational (e.g., cylindrical, tubular).
- **FRW Applications**
- It is applied in the welding of various shafts and tubular parts in industries such as automotive, aircraft, farm equipment, petroleum, and natural gas.

### (h) Friction Stir Welding (FSW)

- Friction stir welding (FSW), illustrated in Figure (5-35), is a solid state welding process in which a rotating tool is fed along the joint line between two workpieces, generating friction heat and mechanically stirring the metal to form the weld seam.
- The process derives its name from this stirring or mixing action.
- FSW is distinguished from conventional FRW by the fact that friction heat is generated by a separate wear-resistant tool rather than by the parts themselves.
- The rotating tool is stepped, consisting of a cylindrical shoulder and a smaller probe projecting beneath it.
- During welding, the shoulder rubs against the top surfaces of the two parts, developing much of the friction heat, while the probe generates additional heat by mechanically mixing the metal along the butt surfaces.
- The probe has a geometry designed to facilitate the mixing action.
- The heat produced by the combination of friction and mixing does not melt the metal but softens it to a highly plastic condition.
- As the tool is fed forward along the joint, the leading surface of the rotating probe forces the metal around it and into its wake, developing forces that forge the metal into a weld seam.
- The shoulder serves to constrain the plasticized metal flowing around the probe.
- **<u>FSW Applications</u>**
- It is used in the aerospace, automotive, railway, and shipbuilding industries.
- Typical applications are butt joints on large aluminum parts.
- Other metals, including steel, copper, and titanium, as well as polymers and composites have also been joined using FSW.
- **<u>FSW Advantages</u>**

(1) good mechanical properties of the weld joint,
(2) avoidance of toxic fumes, warping, shielding issues, and other problems associated with arc welding,
(3) little distortion or shrinkage, and
(4) good weld appearance.

- **<u>FSW Disadvantages</u>**

(1) an exit hole is produced when the tool is withdrawn from the work, and
(2) heavy-duty clamping of the parts is required.

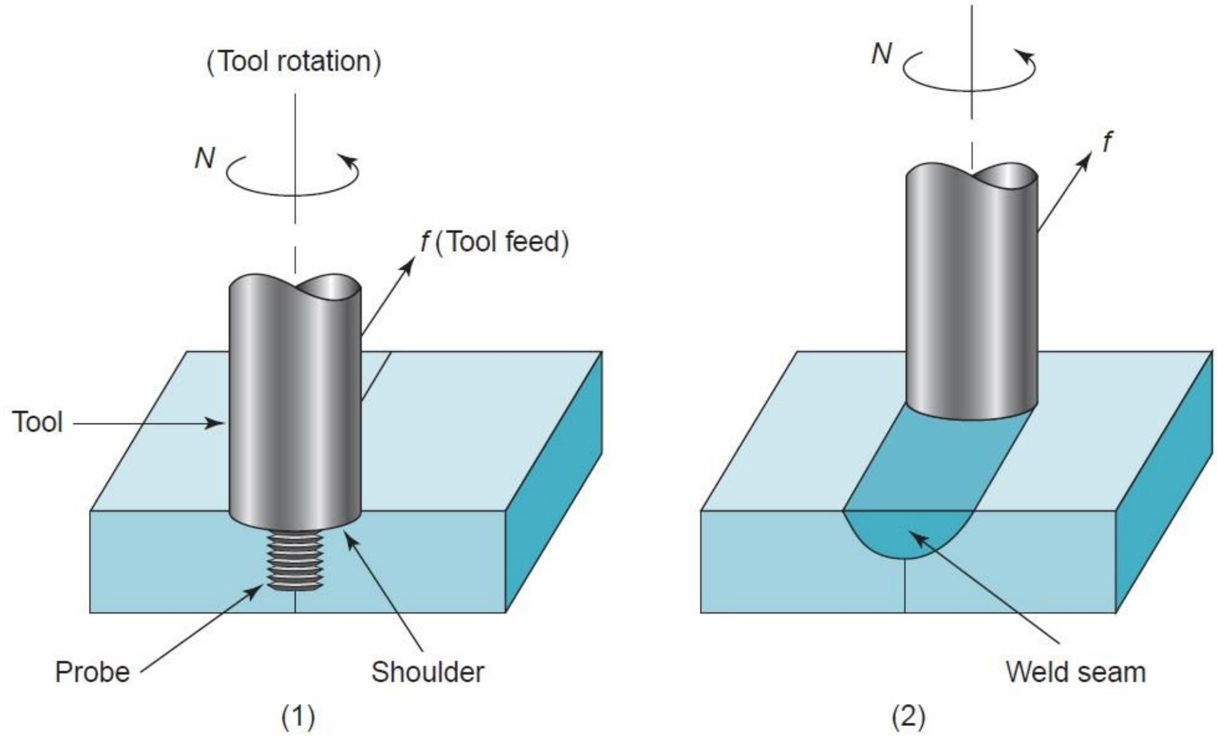


Figure (5-35) Friction stir welding (FSW): (1) rotating tool just prior to feeding into joint and (2) partially completed weld seam. N = tool rotation, f = tool feed.

### (i)Ultrasonic Welding (USW)

- Ultrasonic welding (USW) is a solid-state welding process in which two components are held together under modest clamping force, and oscillatory shear stresses of ultrasonic frequency are applied to the interface to cause coalescence.
- The operation is illustrated in Figure (5-36) for lap welding, the typical application.

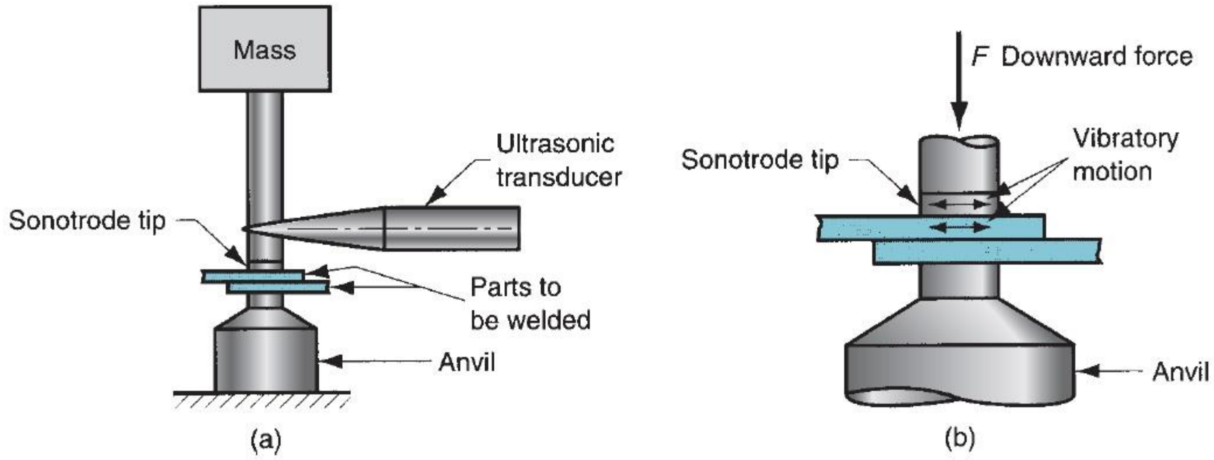


Figure (5-36) Ultrasonic welding (USW): (a) general setup for a lap joint; and (b) close-up of weld area.

- The oscillatory motion between the two parts breaks down any surface films to allow intimate contact and strong metallurgical bonding between the surfaces.
- Although heating of the contacting surfaces occurs due to interfacial rubbing and plastic deformation, the resulting temperatures are well below the melting point.
- No filler metals, fluxes, or shielding gases are required in USW.
- The oscillatory motion is transmitted to the upper w.p. by means of a sonotrode, which is coupled to an ultrasonic transducer.
- This device converts electrical power into high-frequency vibratory motion.
- Typical frequencies used in USW are 15 to 75 kHz, with amplitudes of 0.018 to 0.13mm.
- Clamping pressures are well below those used in cold welding and produce no significant plastic deformation between the surfaces.
- Welding times under these conditions are less than 1 sec.
- Welding harder materials causes rapid wear of the sonotrode contacting the upper w.p.
- W.ps. should be relatively small, and welding thicknesses less than 3 mm is the typical case.
- **USW Applications**

(1) wire terminations and splicing in electrical and electronics industries (eliminates the need for soldering),

(2) assembly of aluminum sheet-metal panels,

(3) welding of tubes to sheets in solar panels, and other tasks in small parts assembly.

(4) USW operations are generally limited to lap joints on soft materials such as aluminum and copper.