2- Solid state welding

There are few welding techniques in which material coalescence at the faying surfaces does take place in the solid state itself contrary to the molten state in most of the conventional welding methods. Thus, a conventional heating source is not required in such techniques. If two parts with very clean surfaces are brought together, the atoms in the lattices at the interface tend to create new bonds across the surfaces – creating a weld. This type of weld does not melt the material, so it is called a solid state weld. Two important properties that facilitate solid state welding are (a) surfaces must be very clean, and (b) high pressure and temperature improve the diffusion process. Few popular solid state techniques are briefly presented in the following sections.

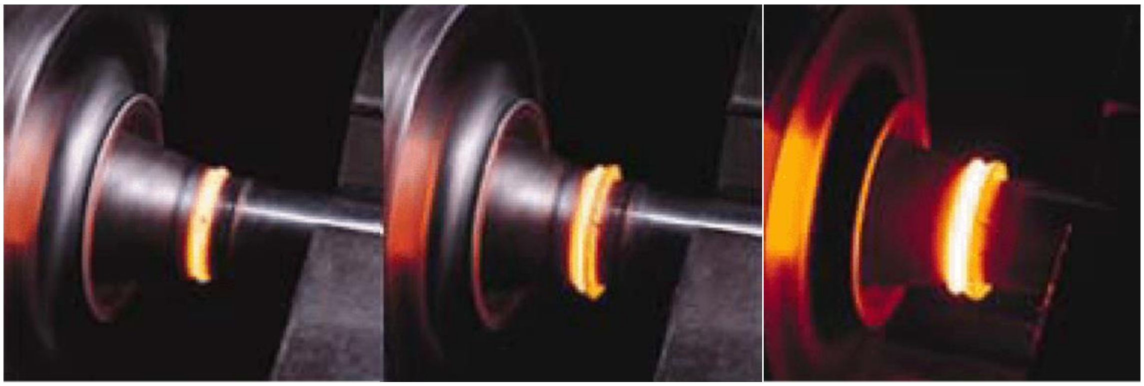
2-1 Friction Welding (FRW) (Inertia Welding)

Principles:

Friction Welding (FRW) is a solid state welding process which produces welds due to the compressive force contact of workpieces which are either rotating or moving relative to one another. Heat is produced due to the mechanical friction between two contacting pieces of metal that are held together while one rotates and the other is held stationary which displaces material plastically from the faying surfaces friction.

- No material is melted.
- Simple and rapid process (cycle time for a weld is usually less than 25 seconds).
- Since all of the energy used is converted into heat, the process is very efficient.
- The strength of the weld is almost the same as the base metal.
- Dissimilar materials can be welded.
- Surface impurities are displaced radially into a small flash that can be removed after welding, if desired.

- Restricted to joining round bars and tubes of the same size, or to joining bars and tubes to flat surfaces.
- Before the process, the ends of the workpieces must be cut true and fairly smooth.



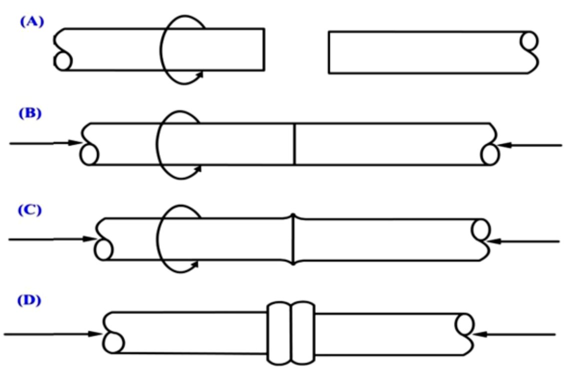
The basic steps explaining the friction welding process are shown in Figure (1).

In friction welding the heat required to produce the joint is generated by friction heating at the interface. The components to be joined are first prepared to have smooth, square cut surfaces. One piece is held stationary while the other is mounted in a motor driven chuck or collet and rotated against it at high speed. A low contact pressure may be applied initially to permit cleaning of the surfaces by a burnishing action. This pressure is then increased and contacting friction quickly generates enough heat to raise the abutting surfaces to the welding temperature.

As soon as this temperature is reached, rotation is stopped and the pressure is maintained or increased to complete the weld. The softened material is squeezed out to form a flash. A forged structure is formed in the joint. If desired, the flash can be removed by subsequent machining action. Friction welding has been used to join steel bars upto 100 mms in diameter and tubes with outer diameter upto 100 mm.

Inertia welding is a modified form of friction welding, where the moving

piece is attached to a rotating flywheel. The flywheel is brought to a specified rotational speed and is then separated from the driving motor. The rotating assembly is then pressed against the stationary member and the kinetic energy of the flywheel is converted into frictional heat. The weld is formed when the flywheel stops its motion and the pieces remain pressed together. Since the conditions of the inertia welding are easily duplicated, welds of consistent quality can be produced and the process can be easily automated. The heat affected zones are usually narrow, since the time period is very short for heating and cooling. The radial and orbital FRW are as shown in Figs. 4.4.2 and 4.4.3 respectively.



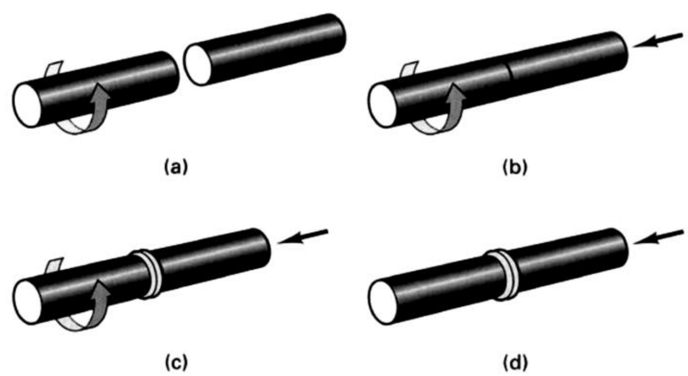
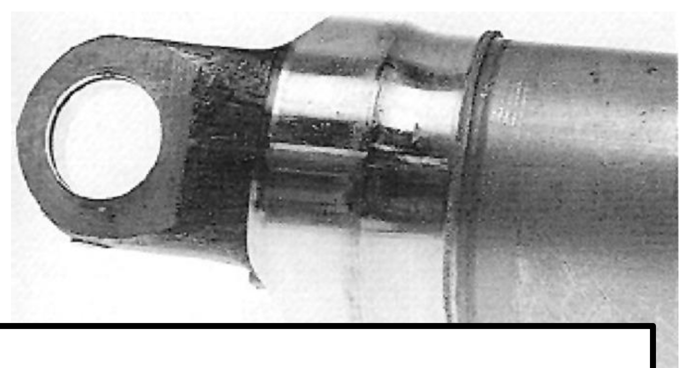
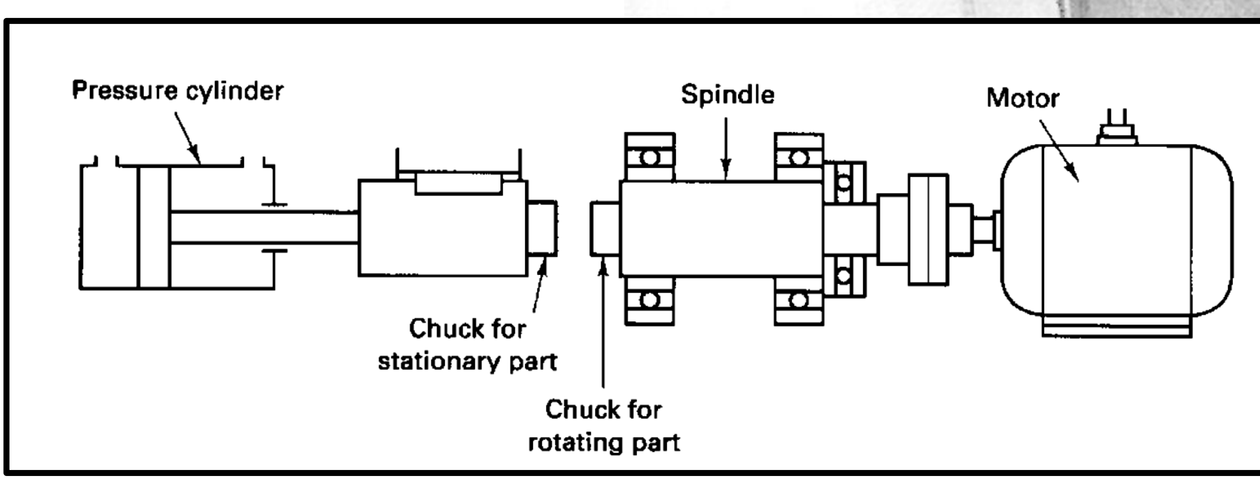


Figure (1): **Basic Steps in Friction welding**





Advantages of Friction Welding:

- No filler material, flux or shielding gases are needed.
- It is an environment-friendly process without generation of smoke, fumes or gases.
- No material is melted so the process is in solid state with narrow heat affected zone (HAZ).
- Oxides can be removed after the welding process.
- In most cases, the weld strength is stronger than the weaker of the two materials being joined.
- The process can be easily automated for mass production.
- The process is very efficient and comparatively very rapid welds are made.
- Plant requirements are minimal and wide variety of metals and combinations can be welded.

Limitations of Friction Welding:

- The process is restricted to joining round bars or tubes of same diameter (or bars tubes to flat surfaces), i.e. capable of being rotated about the axis.
- Dry bearing and non-forgeable materials cannot be welded, i.e. one of the component must be ductile when hot, to permit deformations.

Applications of Friction Welding:

- Friction welded parts in production applications span over wide products for aerospace, agricultural, automotive, defense, marine and oil industries.
- Right from tong holds to critical aircraft engine components are friction welded in production.
- Automotive parts that are friction welded include gears, engine valves, axle tubes, driveline components, strut rods and shock absorbers.
- Hydraulic piston rods, track rollers, gears, bushings, axles and similar parts are commonly friction welded by the manufacturers of agricultural equipment.

- Friction welded aluminum/copper joints are in wide usage in the electrical industry.
- Stainless steels are friction welded to carbon steels in various sizes for use in marine systems and water pumps for home and industrial use.
- Friction welded assemblies are often used to replace expensive casting and forgings.

FRICTION STIR WELDING (FSW) :

Friction Stir Welding (FSW) is another variant process of friction welding.

The necessity and advent of Friction Stir Welding:

The basic problems with fusion welding of aluminum and its alloys are that they possess:

- Cast brittle dendritic structure,
- Micro porosity,
- Inferior mechanical and fatigue properties,
- Loss of strength in heat affected zone,
- Solidification and liquation cracking,
- Loss of alloying elements from the weld pool.

The following alternate techniques are being used for joining of aluminium and its alloys:

- Electron beam welding (EBW),
- Laser beam welding (LBW),
- Variable polarity plasma arc welding (VPPAW),
- Friction stir welding (FSW).

The basic terminologies and process sequence of FSW process is as shown in Figure (2).

Unique advantages of FSW:

- Solid state process.
- Routinely used to join difficult to fusion weld alloys (e.g., 2xxx & 7xxx aluminum alloys).
- Fine grained, re-crystallized microstructure can be obtained.

- No significant alteration of chemical composition.
- Eliminates fusion welding problems.
- Lower power consumption, user friendly and environment friendly process.

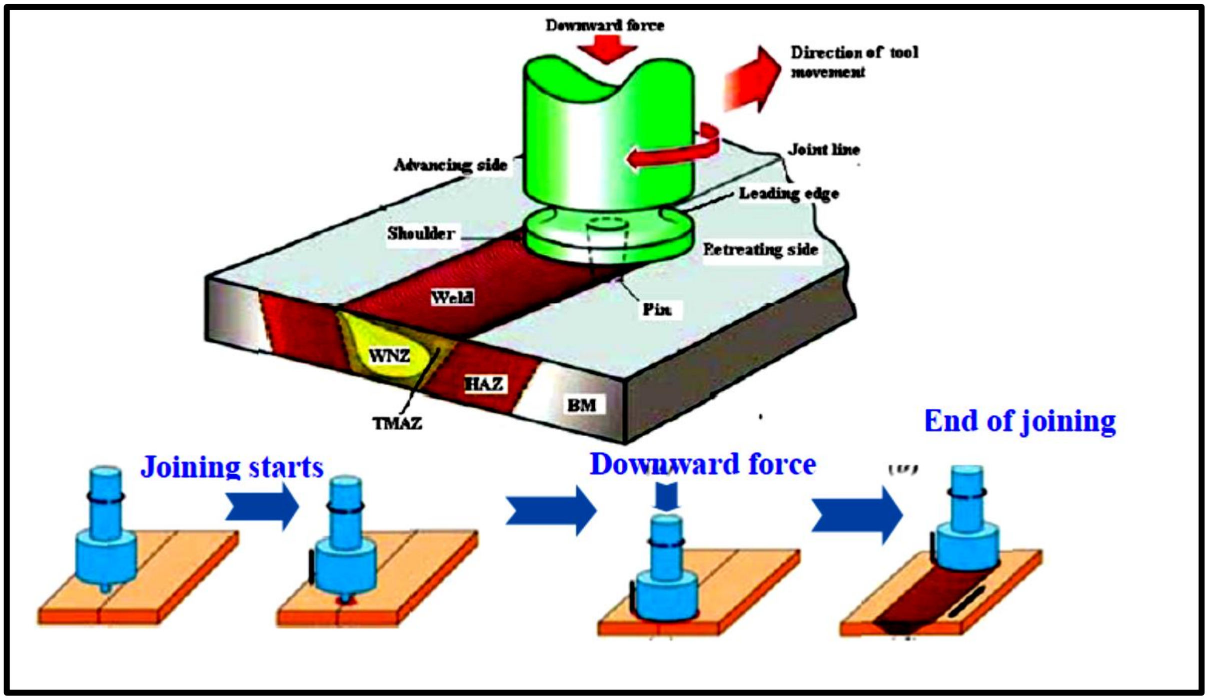


Figure (2): Basic terminologies and steps in FSW.

Limitations of FSW:

- Rigid and robust fixtures are required.
- Visible end hole is created.
- Inability to make filler welds.

FSW Typical Applications :

The industrial application of friction stir welding includes following :

- Aerospace: Wings, fuselage, cryogenic fuel tanks, aviation fuel tanks, aircraft structure, and external aircraft throw away tanks.
- Marine: Deck panes, bulkheads, floors, hull and superstructures, refrigeration plants, internal frameworks, marine and transport structures.
- Railway: High speed trains, container bodies, railway tankers, good wagon and underground rolling stocks.
- Automotive: Engine and chassis cradles, wheel rims, tailored blanks, armour plate vehicles, motorcycle and bicycle frames, buses and airfield vehicles, fuel tankers, suspension parts, crash boxes.
- Construction: Bridges, reactors for power and chemical industries, pipelines, heat exchangers, air conditioners, offshore drilling rigs etc.
- Other applications include: Electric motor housing, connectors, busbars, encapsulation of electronics and joining of aluminum to copper, food tins etc.

2-2 Cold welding

This process is useful for joining two dissimilar metals. A common example is seen in rolled sheets that are used to make coins in some countries; another example is construction of bi-metal strips.

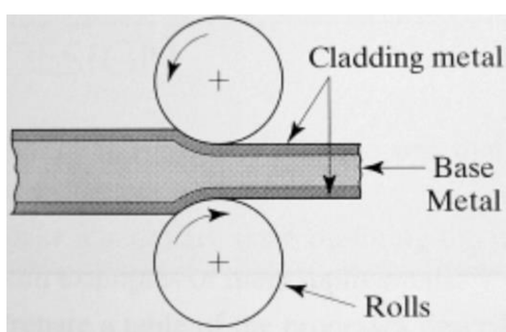


Figure (3): Roll bonding [source: Kalpakjian and Schmid]

2-2 Ultrasonic welding (USW)

Ultrasonic welding (USW) is a solid state process in which coalescence is produced by the localized application of high frequency (10,000-20,000 Hz), low amplitude orthogonal (i.e. shearing) vibration is applied to surfaces that are held together under a rather light static normal force. Although there is some increase in temperature at the faying surfaces. The interface temperature in this process reaches maximum of 0.3~0.5T_m – in other words, there is no melting/fusion.

Instead, it appears that the rapid reversals of stress along the contact interface facilitates the coalescence by breaking up and dispersing the oxide films and surface contaminants, allowing clean material to form a high strength bond. The vibration causes the surfaces to rub against each other, breaking up all contaminants and oxide layers, and the resulting clean surfaces weld together.

Figure (4) illustrates the basic components of the ultrasonic welding process. The ultrasonic transducer is essentially the same as that employed in ultrasonic machining, depicted schematically in the Fig. (4). It is coupled to a force-sensitive system that contains a welding tip on one end. The pieces to be welded are placed between this tip and a reflecting anvil, thereby concentrating the vibratory energy. Either stationery tips (for spot welds) or rotating discs (for seam welds) can be employed.

There are four variations of the process based on the type of weld produced. These are spot, ring, line and continuous seam welding.

Ultrasonic Spot Welding:

The individual welds are produced by momentary introduction of vibratory energy into the workpieces as they are held together under pressure between the sonotrode tip and the anvil face. The tip vibrates in a plane essentially parallel to the plane of the weld interface, perpendicular to the axis of the static force application. Spot welds between sheets are roughly elliptical in shape at the interface. They can be overlapped to produce an essentially continuous weld joint.

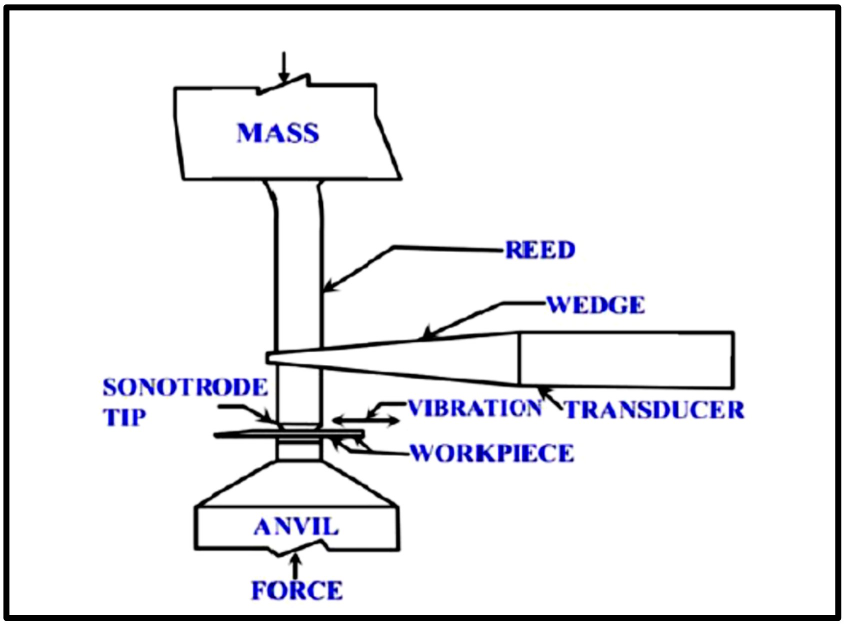


Figure (4) **Wedge-Reed Ultrasonic spot Welding system**

Ring Welding:

It produces a closed loop weld which is usually circular in form but may also be square, rectangular or oval. Here the sonotrode tip is hollow and the tip face is contoured to the shape of the desired weld. The tip is vibrated in a torsion plane parallel to the weld interface. The weld is completed in a single weld cycle.

Line Welding:

It is a variation of spot welding in which the workpieces are clamped between an anvil and a linear sonotrode tip. The tip is oscillated parallel to the plane of the weld interface and perpendicular to both the weld line and the directions of applied static force. The result is a narrow linear weld, which can be upto 150 mm in length, produced in a single weld cycle.

Continuous Seam Welding:

In a continuous seam welding, joints are produced between workpieces that are passed between a rotating, disk shaped sonotrode tip and a roller type or flat anvil. The tip may traverse the work while it is supported on a fixed anvil, or the work may be moved between the tip and a counter rotating or transverse anvil.

Advantages of USW:

- Ultrasonic welding has advantages over resistance spot welding such that it requires a little heat application during joining without melting of the material.
- Consequently, no cast nuggets or brittle inter-metallics are formed in ultrasonic welded parts.
- There can be no arc and hence no tendency to expel molten metal from the joints.
- The process permits welding thin to thick sections and a wide variety of dissimilar materials.
- Ultrasonic welding of aluminum, copper and other high thermal conductivity metals require substantially less energy than resistance welding.
- The pressures used in ultrasonic welding are much lower, welding time is shorter and deformation thickness is significantly lower than cold welding.
- Since the temperatures are low and no arching or current flow is involved, the process can be applied to heat-sensitive electronic components.
- Intermediate compounds seldom form, there is no contamination of weld or surrounding areas.
- The equipment is simple and reliable and only moderate operator skills are required. The required penetration is less than most competing processes (resistance welding) and lesser energy is needed to produce the welds.

Disadvantages of USW:

- Ultrasonic welding is restricted to the lap joint welding of thin materials-sheet, foil and wires and the attaching of thin sheets to heavier structural members.
- The maximum thickness of welds is about 2.5 mm for ‘Al’ and 1 mm for harder materials. It is possible to bond metals to non-metals, such as aluminium to ceramic or glass.

- **Applications:**

Weldability of different material through USW is presented in table (1). Typical applications include:

- Joining dissimilar metals in bimetallic plates,
- Microcircuit electrical contacts,
- Welding refractory or reactive metals,
- Bonding ultra-thin metals etc.

Table (1): Weldability in Ultrasonic Welding

METAL	Al	Cu	Ge	Au	Mo	Ni	Pt	Si	Steel	Zr
Al	•	•	•	•	•	•	•	•	•	•
Cu		•		•		•	•		•	•
Ge			•	•		•	•	•		
Au						•	•	•		
Mo					•	•			•	•
Ni						•	•		•	•
Pt							•		•	
Si										
Steel									•	•
Zr										•

2-3 Explosive Welding (EXW)

It is a solid state welding process wherein welds are produced by the high velocity impact of the workpiece as a result of the controlled detonation. The explosion accelerates the metal to a speed at which the metallic bond gets formed between them, when they collide against each other. The weld is produced within a fraction of a second, without the addition of a filler metal.

Explosive welding is used primarily for bonding sheets of corrosion- resistant metal to heavier plates of base metal (a cladding operation), particularly when large area are involved. The principles of explosive welding have been schematically illustrated in Fig. (3). The bottom sheet or plate is positioned on a rigid base or anvil and the top sheet is inclined to it with a small open angle between the surfaces to be joined. An explosive material, usually in the form of a

sheet, is placed on top of the two layers of metals and detonated in a progressive fashion, beginning from the mating surfaces. Compressive stress waves, of the order of thousands of Mega Pascal's, sweep across the surface of the plates. Surface films are liquefied or scared off the metals and are jetted out of the interface. The clean metal surfaces are then thrust together under high contact pressure. The result is a low temperature weld with an interface configuration consisting of a series of interlocking ripples. The bond strength is quite high and explosive clad plates can be subjected to a wide variety of subsequent processing, including further reduction in thickness by rolling. In this solid state welding process, numerous combinations of dissimilar metals can be joined.

Principles:

There are typically three components in explosion welding: Base Metal, Prime or cladding metal and explosives. The material at base is kept stationary as the prime component is welded to it.

The base component may be supported by a backer or an anvil, particularly when it is relatively thin. The base unit involving backer should be sufficiently rigid in order to minimize the distortions during the welding operation.

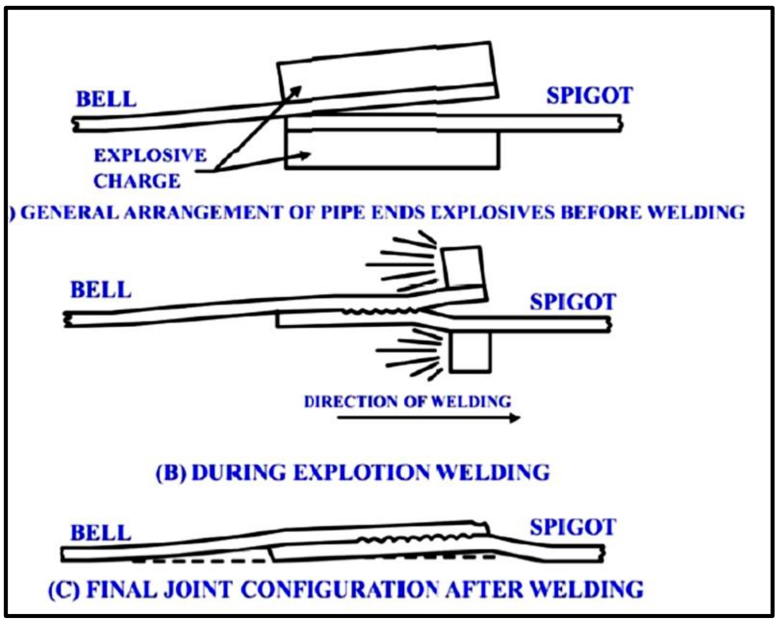
The prime component is usually positioned parallel to the base component or at an angle, in special applications. A stand-off distance is kept in case of parallel arrangements. The explosion locally bends and accelerates the prime component across the stand-off distance at a high velocity so that it collides at an angle and welds to the base component. This angular collision and welding front progresses across the joint as the explosion takes place.

The explosive, almost always in granular form, is distributed uniformly over the top surface of the prime component. The force which the explosion exerts on the prime component depends upon the detonation characteristic of the explosive used.

Applications of Explosive Welding:

In general, any metal can be explosion welded if it possesses sufficient strength and ductility to withstand the deformation required at the high velocities associated with the process. Metals that will crack when exposed to the shock associated with detonation of explosives and collision cannot be explosion welded. Metal with elongations of at least five to six percent and Charpy V notch impact strengths of 13.6 or better can be welded by this process.

Explosion welding does not produce change in bulk properties; it can produce some noticeable change in mechanical properties and hardness of metals, particularly in the intermediate area of the weld interface.



Schematic of the explosive welding of girth joint in pipe

Commercially significant metals and alloys that can be joined by explosion welding are as shown in the table (2)

Table (2): Commercially significant applications in explosive welding.

	Zirconium	Magnesium	Co Alloys	Platinum	Gold	Silver	Columbium	Tantalum	Titanium	Ni Alloys	Cu Alloys	Al Alooys	Stainless Steel	Alloy Steel	Carbon Steel
Carbon steels	•	•			•	•	•	•	•	•	•	•	•	•	•
Alloy steels	•	•	•					•	•	•	•	•	•	•	
Stainless Steels			•		•	•	•	•	•	•	•	•	•		
Aluminum alloys		•				•	•	•	•	•	•	•			
Copper alloys					•	•	•	•	•	•	•				
Nickel alloys		•		•	•			•	•	•					
Titanium	•	•				•	•	•	•						
Tantalum					•		•	•							
Columbium				•			•								
Silver						•									
Gold															
Platinum				•											
Cobalt alloys															
Magnesium		•													
Zirconium	•														