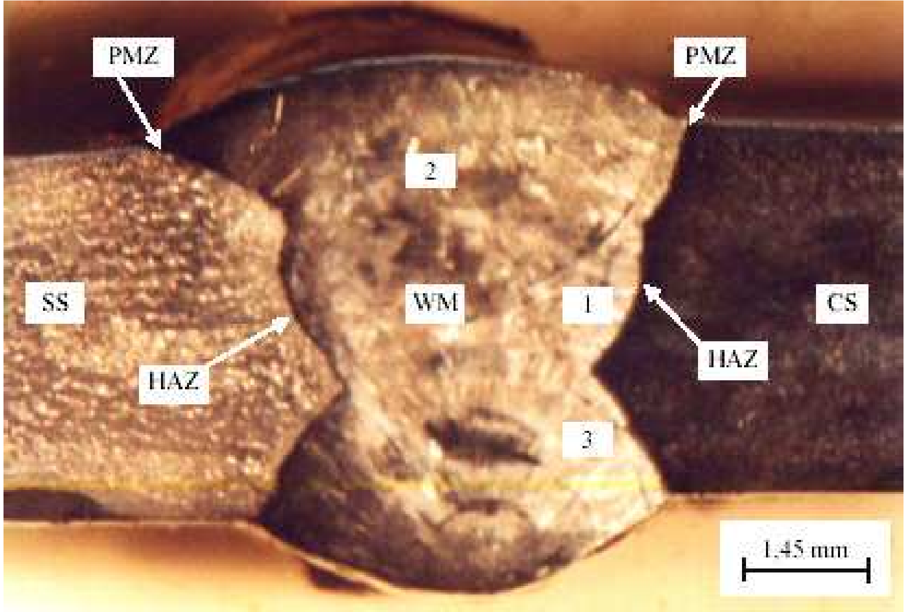
Handout

Dissimilar Metal Joining



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Like a human wedding, dissimilar metal welding is awesome.
But like a human wedding, welding dissimilar metals can be difficult, considering all the variables involved.
Ideally, like a human wedding, dissimilar metal welding should only be done with careful planning.

Objectives:

After studying this course, student will be able to:

- Give examples of possible material combinations and their application.
- Describe the types of joining process and filler materials which are suitable for a given material combination.
- Identify and select the proper method of joint preparation.
- Evaluate and determine characteristics of the dissimilar metal joint.
- Prepare research proposals and reports on dissimilar metal joints

Contents:

Chapter 1 Fundamentals of Dissimilar Metal Joint

1. Why Dissimilar Metal Joint is needed
2. Advantages and existing problems
3. Primary characteristics and weldability

Chapter 2 Review of Welding Processes

1. Gas Welding
2. Arc Welding
3. Resistance Welding
4. Solid Phase Welding
5. High Energy Density Welding

Chapter 3 Weld Quality and Inspection of Dissimilar Metals Weld

1. Defects
2. Faulty Weld Size and Profile
3. Corrosion
4. Mechanical Testing
5. Metallography of welds
6. Non Destructive Test of Welds

Chapter 4 Special Welding and Joining Topics

1. **Preliminary Research: Steel-Austenitic Stainless Steel Joint**
2. **Preliminary Research: Steel-Aluminum Joint**
3. **Preliminary Research: Steel-Ferritic Stainless Steel Joint**
4. **Preliminary Research: Composite-to-Metal Joining**
5. **Preliminary Research: Welding of Plastics**

Chapter 1

FUNDAMENTALS OF DISSIMILAR METAL JOINT

1.1. WHY DISSIMILAR METAL JOINT IS NEEDED

Dissimilar metal joint refers to the joining of two or more different materials or alloy systems. Since ancient times, people have been joining dissimilar metals. Ornaments and trinkets were made with metals of differing colors and workability, even though the joining methods used in ancient times were very different from those in present.

Nowadays, joining dissimilar metal is indispensable in manufacturing and constructing advanced equipment and machinery. Different kinds of metals feature different chemical, physical, and metallurgical properties: some are more resistible to corrosion, some are lighter, and some are stronger. Joining dissimilar metals is, therefore, to compose different properties of metals in order to minimize material costs and at the same time maximize the performance of the equipment and machinery. Presently, the methods of joining dissimilar metals include fusion welding, pressure welding, explosion welding, friction welding, diffusion welding, brazing, soldering, and adhesive bonding. This course, however, is more focused discussion on welding only, because it is used in a wide range of industries. The discussions of dissimilar metal joints using brazing, soldering and adhesive are only as additional.

Welding dissimilar materials is often required to fabricate weldments of different materials. It is also required to overlay the base material to prevent corrosion, oxidation from heat, and wear. Finally, welding dissimilar materials may be required for maintenance or repair of worn parts.

1.2. PROCEDURE FOR MANUAL WELDING DISSIMILAR METALS

1.2.1. Material Combinations/Applications

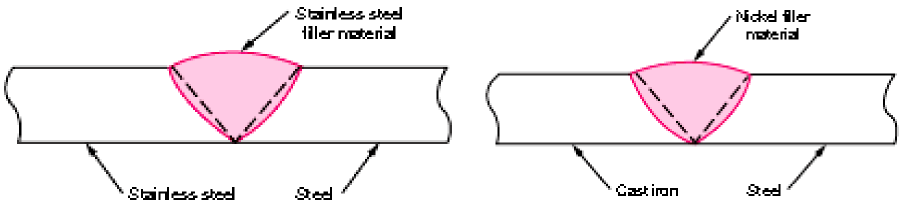
Many material combinations are possible using the arc welding process to make the weld. These may include:

- Steel alloys to steel.
- Steel to cast iron.
- Steel to stainless steel.
- Steel to nickel.
- Stainless steel to nickel.
- Stainless steel to inconel.
- Copper to steel.
- Copper nickel to steel.
- Copper aluminum to steel.
- Silicon bronze to steel.
- Surfacing alloys to iron base metals.
- Alloy metal to a nonalloy metal.

The applications of the weld to join the various materials include the following:

Butted materials, as shown in Figure 1.1(a), are depending on the alloy mix in the weld desired, one of the parent materials is used for filler material. Figure 1.1(b) shows a dissimilar metal being used as a filler material. The filler material is compatible with both parent materials.

Buttered materials, as shown in Figure 1.2, are used to join materials that are very different. However, each material must be "buttered" with a material that is compatible with the filler material used to make the final joint.



(a) (b)

Fig. 1.1(a) Stainless steel filler material is used in many steel-to-stainless steel combinations where ductility is of prime importance, (b) Nickel filler material is compatible with both cast iron and steel.

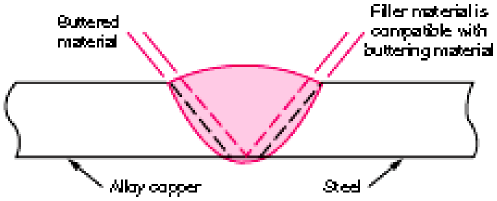


Fig. 1.2 The "buttering" material is applied to each material before the joint filler material is used

Cladded material, as shown in Figure 1.3, is used extensively in the manufacture of processing equipment. The "clad" is bonded to the base material at the rolling mill. The thickness of the "clad" will vary depending on the final use. The welding materials used must match the heavier base material and the cladding.

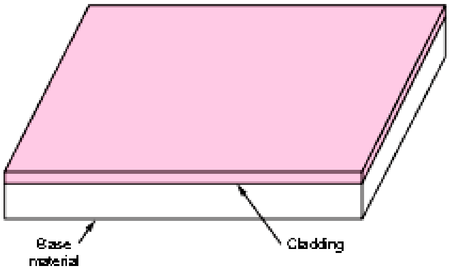


Fig. 1.3 Welds into the clad require matching filler materials. Welds into the heavier base material require filler materials for strength, ductility, and other mechanical properties.

Overlaid materials, as shown in Figure 1.4, are similar to a clad or buttered joint; however, overlays are generally thicker. As the overlay thickens, the amount of dilution decreases until the deposit contains the filler material chemistry. The special GTAW torch is oscillated during the operation to widen the weld bead. Figure 1.5(a) shows a GTAW bore cladding operation. Figure 1.5(b) shows a cross section of a bore cladded weld. The darkened zone is the heat-affected zone (HAZ) under the cladding.

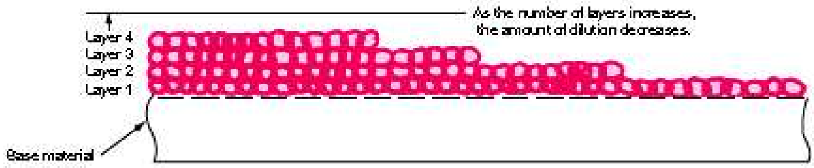
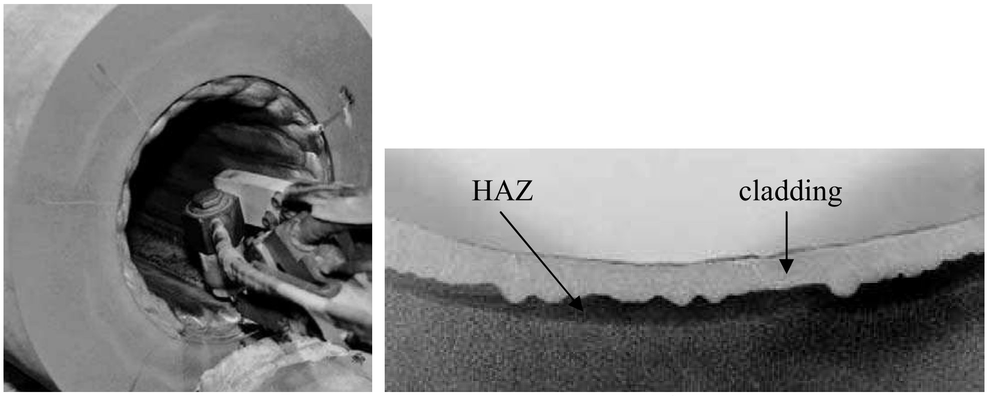


Figure 1.4 The number of weld layers required to achieve the desired chemistry is determined by testing the final joint design preparation by chemical analysis.



(a) (b)

Figure 1.5 (a). Several layers of cladding have been applied to the bore of the tube, (b). A cross section of the part is used to measure the height of the cladding and the penetration pattern.

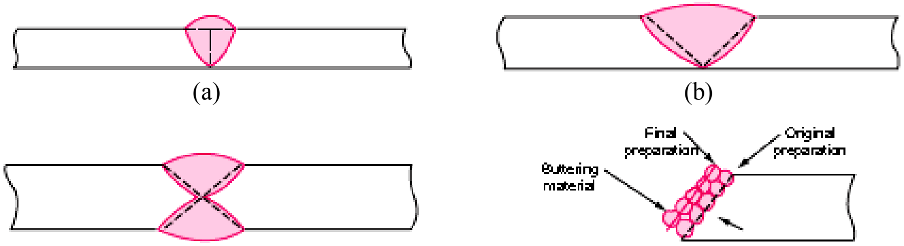
1.2.2. Butt Joints of Dissimilar Metals

Butt joints with square edges, as shown in Figure 1.6(a), are used only where the material thickness can be welded in a single pass. This type of joint has considerable dilution between the parent materials and the filler materials. These designs require a filler material compatible with each of the base materials due to the considerable amount of dilution.

Butt joints with V-grooves welded from one side, as shown in Figure 1.6 (b), are used to weld thicker material with multiple passes. Dilution is high at the edges of the joint and diminishes near the center of the joint. Stringer type beads reduce penetration and dilution when welding V-groove welds. Wash beads should be avoided, if possible, to reduce heat input and the amount of dilution from the base materials.

Butt joints with double V-grooves welded from both sides, Figure 1.6 (c), are used to weld thicker material with multiple passes on each side. Distortion and dilution of the parent metal is minimized as less metal is required to fill the joint. Use stringer beads to further reduce dilution.

Butt joints with single or double buttered edges are shown in Figure 1.6 (d). The buttered material is applied with sufficient height to achieve weld metal chemistry to match the filler material composition. Prior to welding the joint, the preparation desired for the final weld is prepared from the "buttered" material.



(a) (b)

(c) (d)

Figure 1.6(a) Square-groove weld joint, (b) V-groove welds, (c) Double V-groove welds have much less dilution of the base materials since less welding is involved (d) Butt joints with buttering or overlaid material.

1.2.3. Clad Material Joints

Clad material often requires two joint designs. One design is for the base metal and one design is for the cladding. The base material joint is made to standard practices. The cladding joint must be designed to allow cladding integrity. Figure 1.7 shows joint designs for preparing cladded materials and various weld applications.

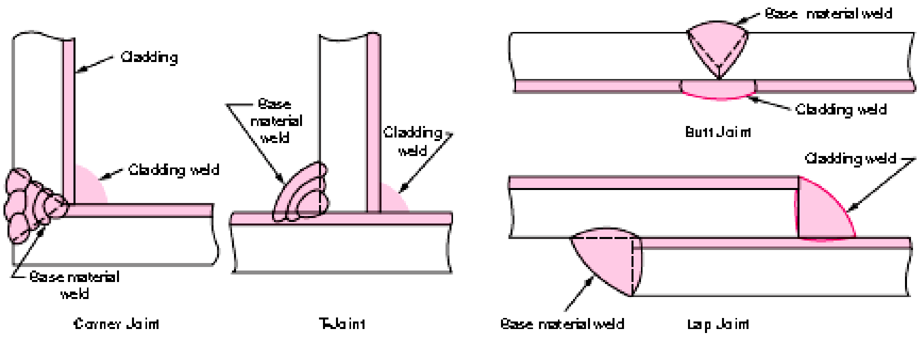
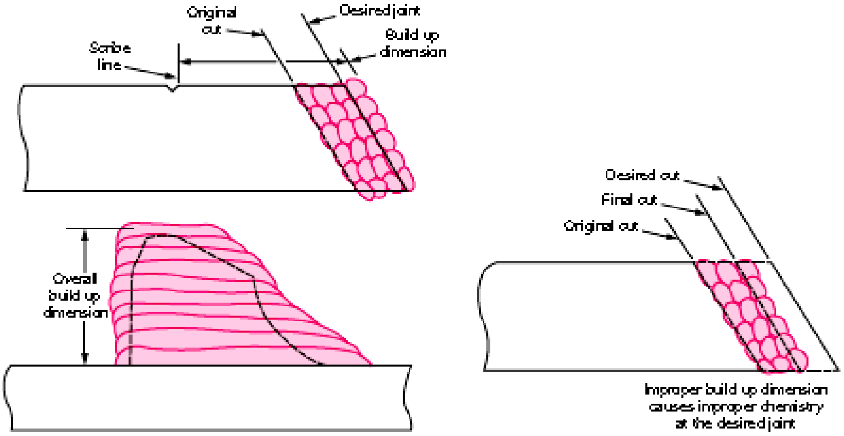


Figure 1.7 Common joint preparations used with cladded base materials.

1.2.4. Overlay Type Joints

Overlay type joints require a full weld metal chemistry at the edge of the weld. To achieve this condition, the number of layers of weld metal must be computed into the joint design, as shown in Figure 1.8 (a). Figure 1.8(b) illustrates a grooved overlay improperly prepared, which may result in improper chemistry in the final weld.



(a) (b)

Figure 1.8 (a). Reference lines or points are used to assure proper overlay build-up dimensions, **(b)** Insufficient build-up of the overlay may result in incorrect weld metal chemistry.

Table 1.1 Filler materials used for joining stainless steels and dissimilar metals

Base Alloy, Type	201, 202, 301, 302, 302B, 303[a], 304, 305, 308	304L	309, 309S	310, 310S, 314[a]	316	316L	317	317L	321, 347, 348	330[a]	402, 405, 410, 412, 414, 420[a]	430, 430F, 431, 440A, 440B, 440C[a]	446[d]	501, 502[c,d]	505[c,d]	Carbon Steels[c,d]	Cr-Mo Steels[c,d]
201, 202, 301, 302, 302B, 303[a], 304, 305, 308	E308	E308	E308	E308	E308	E308	E308	E308	E308	E309	E309	E309	E310	E309	E309	E309	E309
304L		E308L	E308	E308	E308	E308	E308	E308	E308	E309	E309	E309	E310	E309	E309	E309	E309
309, 309S			E309	E309	E309	E309	E309	E309	E309	E309	E309	E309	E310	E309	E309	E309	E309
310, 310S, 314[a]				E310	E316	E316	E317	E317	E308	E310	E309	E309	E310	E310	E310	E310	E309
316					E316[b]	E316	E316	E316	E308[b]	E309Mo	E309	E309	E310	E309	E309	E309	E309
316L						E316L	E316	E316L	E316L	E309Mo	E309	E309	E310	E309	E309	E309	E309
317							E317	E317	E308[b]	E309Mo	E309	E309	E310	E309	E309	E309	E309
317L								E317L	E308L	E309Mo	E309	E309	E310	E309	E309	E309	E309
321, 347, 348									E347	E309	E309	E309	E310	E309	E309	E309	E309
330[a]										E330	E309	E309	E310	E312	E312	E312	E312
403, 405, 410, 414, 416, 420											E410	E430[e]	E410[e]	E502[e]	E505[e]	E410[e]	E410[e]
430, 430F, 431, 440A, 440B, 440C												E430	E430	E502[e]	E505[e]	E430[e]	E430[e]
446													E446	E502[e]	E502[e]	E430[e]	E430[e]
501, 502														E502	E502[e]	E502[e]	E502[e]
505															E505	E505[e]	E505[e]

Notes: Grades shown are those most commonly selected for most applications; other combinations may be used. Wherever possible, recommendation is based upon the most available and lowest cost filler metal. Filler metal designations are those appearing in AWS Specification A5.9 for bare filler wire.

a These alloys are sensitive to weld cracks and fissures; for this reason, E312 filler metal is a frequently recommended alternative. It is preferred especially when thick sections or highly restrained joints are required. Buttering these metals with type 312 before joining is often desirable.

b E16-8-2 is preferred to lower embrittlement danger in elevated temperature service.

c When joining an austenitic steel, alternate choice is to butter carbon or chromium steel with E309 and join with E309 or with filler metal similar to austenitic base metal. E307 is also commonly used for welds between austenitic stainless steel and either carbon or low alloy steels.

d ENiCrFe3 is preferred for elevated temperature service, except when sulfur compounds are present.

e If austenitic weld metal is acceptable for service conditions, E309 or E310 is often employed.

1.2.5. Filler Materials

The choice of filler materials for the weld joint requires analyzing the composition of the base materials, dilution percentages, and the final use of the joint. In many cases, a sufficient number of welds have been made to establish which filler materials can be used successfully. See Table 1.1 through 1.5 and Figure 1.9. They include stainless steel filler metals for welding dissimilar steels, hardfacing and surfacing, filler metals for welding clad layers, alloys for joining clad steels, and filler wires for surfacing applications. Preheat temperatures for hardfacing are shown in Table 1.6.

Table 1.2 Base material and surfacing material combinations

Base Metal	Surfacing Material	Current Type Amps.	Rod Type	Deposit Rc Hardness
Mild and stainless steels	Haynes Stellite alloys	ACHF ACHF ACHF ACHF ACHF	Stellite #1 Stellite #6 Stellite #12 Stellite #93 Hascrome	54 39 47 62 23–43
Copper	Stellite #6 alloy	DCEN 180–230 for 3/16″ material	Stellite #6	42
Steel, copper, and silicon bronze	Aluminum bronze	DCEN	Aluminum-bronze rods	
Mild steel and cast iron	Bronze and copper	ACHF or DCEN 150 for 1/2″ material	A1-bronze and copper rods	
Stainless steel	Silver	ACHF 160 for 1/2″ material		
Mild steel	Stainless steel	ACHF or DCEN		
Carbon and alloy tool steels	Tungsten carbide	DCEN 300–375	Tube of 8/15 mesh tungsten particles	

Table 1.3 The cladding listed in the left hand column mavbe welded with anv of the other

Cladding Type	Filler Material
405, 410, 410S, 429, 430	309, 310 Inconel A, B, 182, or equivalent Inconel 82 or equivalent 430
304	309, 310 309L
304L	309L 308L 309Cb 309CbL
321, 347	309Cb, 310Cb 309CbL
316	347 309Mo, 310Mo 316L
316L	309MoL 316L
317	318 309MoL, 310Mo, 309Mo
317L Incoloy 825	317L 309MoL, 310Mo 317L Incoloy 65 or equivalent
	Incoloy 135 or equivalent Inconel 625 or equivalent Inconel 112 or equivalent
Inconel 600	Inconel A, B, 182, or equivalent Inconel 82 or equivalent
Monel 400	Monel
70Cu-30Ni 90Cu-10Ni	Monel 70Cu-30Ni
Nickel	Nickel
Copper	Copper, monel, nickel, inconel

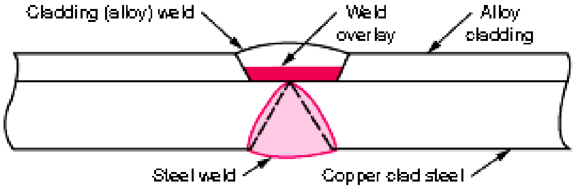


Figure 1.9. Sequence of welding clad steels

Table 1.4 Filler materials used in welding clad steels

Cladding Alloy	Alloy for Overlay on Steel	Alloy for Welding Cladding
Copper	RCu RCuAl-A2 RCuSi-A RNi-3	RCu
Copper-Zinc	RCuAl-A2	RCuAl-A2
Copper-Tin-Zinc	RCuSn-A	RCuSn-A
Copper-Aluminum	RCuAl-A2	RCuAl-A2
Copper-Silicon	RCuSi-A	RCuSi-A
Copper-Nickel	RCuNi	RCuNi

Table 1.5 Common filler materials used for surfacing

Wire Designation	Brinell Hardness	Yield Strength (thousands) psi	Tensile Strength (thousands) psi	Applications
RCu	50–60	8	28	Corrosion resistant
RCuSn	70–85		35	Corrosion resistant, bearings
RCuSi-A	80–100	25	50–55	Erosion, corrosion
RCuNi	60–80	10–20	50	Bearings
RCuAl-A1	100–150	25–30	55–65	Bearing overlay
RCuAl-A2	130–190	30–35	60–75	Cavitation resistant
RCuAl-B	140–220	40–45	90–110	Bearing overlay
RCuAl-C	180–280	40–45	90–100	Cavitation resistant
RCuAl-D	250–350	50–55	75–85	Wear resistant
RCuAl-E	290–390	55–70	70–80	Bearings, dies
NiAl bronze	180–200	55–60	100	Erosion, corrosion resistant

Table 1.6 Preheating of the base material reduces the amount of cracking in the surfacing alloy during the cooling period

		Cobalt Base Alloys						Nickel Base Alloys						Fe-Cr Alloys
Hard Surfacing → Base Metal ↓		1	6	7	12	T-400	T-800	44	45	46	10XN	A	T-700	Niobend
Carbon steel	°F	600	300	200	500	900	900	200	400	900	400	70	900	70
.30C maximum	°C	325	150	95	275	480	480	95	205	480	205	20	480	20
Carbon steel	°F	600	400	300	500	900	900	200	400	900	400	100	900	200
.30–.50C	°C	325	205	150	275	480	480	95	205	480	205	40	480	95
Low alloy steels up	°F	600	400	300	500	900	900	200	400	900	400	100	900	200
to 3% total alloys	°C	325	205	150	275	480	480	95	205	480	205	40	480	95
Medium alloy steels	°F	600	400	400	500	900	900	200	400	900	400	200	900	300
3–10% total alloys	°C	325	205	205	275	480	480	95	205	480	205	95	480	150
High alloy steels	°F	600	400	400	500	900	900	200	400	900	400	200	900	300
Martensitic e.g. Type 410	°C	325	205	205	275	480	480	95	205	480	205	95	480	150
High alloy steels	°F	600	300	200	500	900	900	200	400	900	400	100	900	100
Ferritic e.g. Type 430	°C	325	150	95	275	480	480	95	205	480	205	40	480	40
High alloy steels	°F	500	300	200	400	900	900	200	400	900	400	70	900	70
Austenitic e.g. Types 304, 316	°C	275	150	95	205	480	480	95	205	480	205	20	480	20
Nickel alloys	°F	500	300	200	400	900	900	200	400	900	400	70	900	70
e.g. Inconel* e.g. Monel*	°C	275	150	95	205	480	480	95	205	480	205	20	480	20

*Trade names of the International Nickel Co., Inc.

Chapter 2

REVIEW OF WELDING PROCESSES

In the following paragraphs distinguishing features, attributes, limitations and comparisons where applicable will be discussed for the commonly used welding processes. This introduction to the welding processes will help the modern welding engineers to consider alternative processes available for the situation. This aspect may otherwise be overlooked. A major problem, frequently arises when several processes can be used for a particular application. Selection could be based upon fitness for service and cost. These two factors, sometimes, may not be compatible. Process selection is also affected by such factors as:

(*a*) production quantity, (*b*) acceptability of installation costs, (*c*) joint location, (*d*) joint service requirements, (*e*) adaptability of the process to the location of the operation, (*f*) availability of skill/experience of operators.

In this review of conventional welding processes we shall be discussing Gas Welding, Arc Welding, Shielded Metal Arc, Submerged Arc, Tungsten Inert Gas, Metal Inert Gas, Metal Active Gas Welding, Resistance Welding, Electroslag Welding, Spot, Seam and Projection Welding, Flash Butt and Upset Butt Welding, and high Frequency Welding.

2.1. GAS WELDING

Gas welding includes all the processes in which fuel gases are used in combination with oxygen to obtain a gas flame. The commonly used gases are acetylene, natural gas, and hydrogen in combination with oxygen. Oxyhydrogen welding was the first commercially used gas process which gave a maximum temperature of 1980°C at the tip of the flame. The most commonly used gas combination is oxyacetylene process which produces a flame temperature of 3500°C. This process will be discussed in detail in the following paragraphs.

1. Oxyacetylene welding flame uses oxygen and acetylene. Oxygen is commercially made by liquefying air, and separating the oxygen from nitrogen. It is stored in cylinders as shown in Fig. 2.1 at a pressure of 14 MPa. Acetylene is obtained by dropping lumps of calcium carbide in water contained in an acetylene generator according to the following reaction.

$$CaC_2 + 2H_2O = Ca(OH)_2 + C_2H_2$$

Calcium carbide + Water = Slaked lime + Acetylene gas

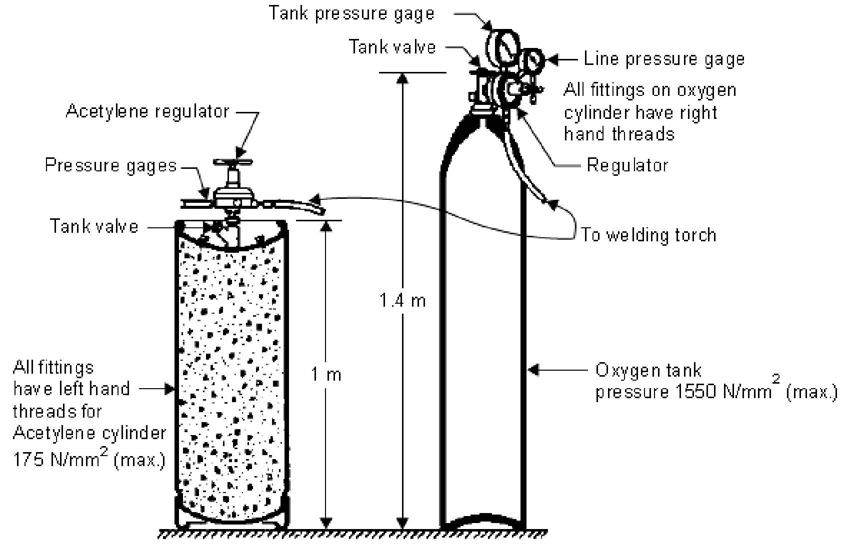
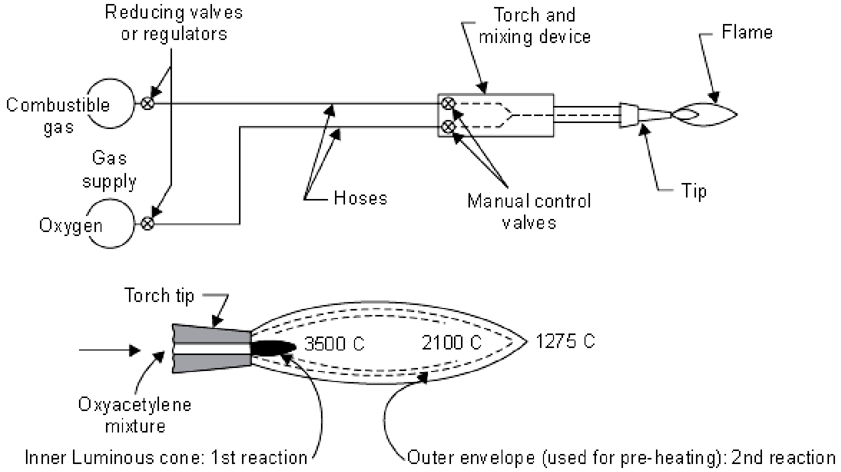


Fig. 2.1 Cylinders and regulators for oxyacetylene welding [1]

2. Concentrated heat liberated at the inner cone is 35.6% of total heat. Remaining heat develops at the outer envelope and is used for preheating thus reducing thermal gradient and cooling rate improving weld properties.
3. **1** Volume O_2 is used to burn **1** Volume of acetylene, in the first reaction. This oxygen is supplied through the torch, in pure form $1\frac{1}{2}$ Volume of additional oxygen required in the second reaction is supplied from the atmosphere.
4. When oxygen is **just enough** for the first reaction, the resulting flame is **neutral**. If less than enough, → the flame is said to be reducing flame. If more than enough oxygen is supplied in the first reaction, the flame is called an oxidizing flame.
5. Neutral flame has the widest application.

- Reducing flame is used for the welding of **monel metal**, nickel and certain alloy steels and many of the non-ferrous, hardsurfacing materials.
- Oxidising flame is used for the welding of brass and bronze.



$C_2H_2 + O_2 \longrightarrow 2\,CO + H_2$

$2CO + O_2 = 2CO_2 + 570$ kJ/mol of acetylene

Total heat liberated by 1st reaction

$H_2 + \frac{1}{2}O_2 = H_2O + 242$ kJ/mol

(227 + 221) = 448 kJ/mol C_2H_2

Total heat by second reaction = (570 + 242) = 812 kJ/mol of C_2H_2

Total heat supplied by the combustion = (448 + 812) = 1260 kJ/mol of C_2H_2

Fig. 2.2 Schematic sketch of oxyacetylene welding torch and gas supply [1].

Advantages:

1. Equipment is cheap and requires little maintenance.
2. Equipment is portable and can be used in field/or in factory.
3. Equipment can be used for cutting as well as welding.

Acetylene is used as a fuel which on reaction with oxygen liberates concentrated heat sufficient to melt steel to produce a fusion weld. Acetylene gas, if kept enclosed, decomposes into carbon and hydrogen. This reaction results into increase in pressure. **At 0.2 N/mm^2 pressure,** the mixture of carbon and hydrogen may cause **violent explosion** even in the absence of oxygen, when exposed to spark or shock. To counter this problem, acetylene is dissolved in acetone. **At 0.1 N/mm^2** one volume of acetone dissolves **twenty volumes of acetylene.** This solubility **linearly increases to 300** volumes of acetylene per one volume of acetone, **at 1.2 N/mm^2**.

An excess of oxygen or acetylene is used depending on whether oxidising or reducing (carburizing) flame is needed.

Oxidizing (decarburizing) flame is used for the welding of brass, bronze and copper-zinc and tin alloys, while reducing (carburising) flame is used for the welding of low carbon and alloy steels monel metal and for hard surfacing. Neutral flame is obtained when the ratio of oxygen to acetylene is about 1 : 1 to 1.15 : 1. Most welding is done with neutral flame. The process has the advantage of control over workpiece temperature, good welds can therefore be obtained. Weld and HAZ, being wider in gas welding resulting in considerable distortion. Ineffective shielding of weld-metal may result in contamination. Stabilised methyl acetylene propadiene (MAPP) is replacing acetylene where portability is important. It also gives higher energy in a given volume.

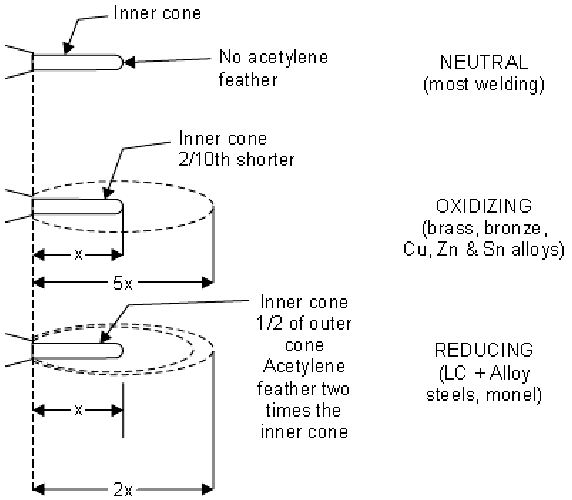


Fig. 2.3 Neutral, oxidizing and reducing flames

2.2. ARC WELDING

An arc is a sustained electric discharge in a conducting medium. Arc temperature depends upon the energy density of the arc column. Arc could be used as a source of heat for welding.

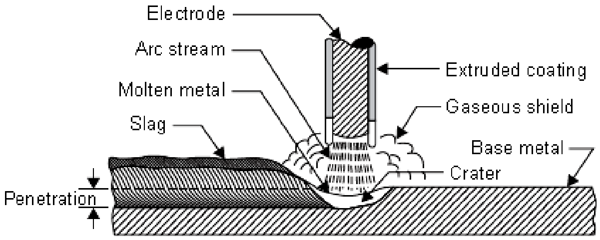


Fig. 2.4 Diagrammatic sketch of arc flame

Arc welding is a group of welding processes that use an electric arc as a source of heat to melt and join metals, pressure or filler metal may or may not be required. These processes include

- Shielded metal arc welding (SMAW)
- Submerged arc Welding (SAW)
- Gas metal arc (GMA, MIG, MAG)
- Gas tungsten arc (GTA, TIG)
- Plasma arc welding (PAW)
- Electroslag/Electrogas Welding

Arc is struck between the workpiece and the electrode and moves relative to the workpiece, manually or mechanically along the joint.

Electrode, may be **consumable** wire or rod, carries current and sustains the arc between its tip and the work. Non consumable electrodes could be of carbon or tungsten rod. Filler metal is separately supplied, if needed.

The electrode is moved along the joint line manually or mechanically with respect to the workpiece. When a non-consumable elecrode is used, the filler metal, if needed, is supplied by a separate rod or wire of suitable composition to suit the properties desired in the joint. A consumable electrode, however, is designed to conduct the current, sustain the arc discharge, melt by itself to supply the filler metal and melt and burn a flux coating on it (if it is flux coated). It also produces a shielding atmosphere, to protect the arc and weld pool from the atmospheric gases and provides a slag covering to protect the hot weld metal from oxidation.

2.2.1. Shielded Metal Arc Welding (SMAW)

It is the most commonly used welding process. The principle of the process is shown in Fig. 2.4. It uses a consumable covered electrode consisting of a core wire around which a flux coating containing fluorides, carbonates, oxides, metal alloys and cellulose mixed with silicate binders is extruded.

- This covering provides arc stabilizers, gases to displace air, metal and slag to support, protect and insulate the hot weld metal.
- Electrodes and types of coating used are discussed in more detail in chapter **4**. The electrodes are available in diameters ranging from 2 mm (for thin sheets) to 8 mm (for use at higher currents to provide high deposition rates). Alloy filler metal compositions could be formulated easily by using metal powders in the flux coating.
- This process has some advantages. With a limited variety of electrodes many welding jobs could be handled. Equipment is simple and low in cost. Power source can be connected to about 10 kW or less primary supply line.
- If portability of the power source is needed a gasoline set could be used. Solid-state, light weight power sources are available which can be manually carried to desired location with ease. It, therefore, finds a wide range of applications in construction, pipe line and maintenance industries.
- The process is best suited for welding plate thicknesses ranging from 3 mm to 19 mm. Greater skill is needed to weld sections less than 3 mm thickness.
- Hard surfacing is another good application of this process.

SMAW is used in current ranges between 50-300 A, allowing weld metal deposition rates between 1-8 kg/h in flat position.

- Normally a welder is able to deposit only 4.5 kg of weld metal per day. This is because usually in all position welding small diameter electrodes are used and a considerable electrode manipulation and cleaning of slag covering after each pass is necessary. This makes the labour cost quite high. Material cost is also more because only 60% of the electrode material is deposited and the rest goes mainly as stub end loss.
- Inspite of these deficiencies, the process is dominant because of its simplicity and versatility. In many situations, however, other more productive welding processes such as submerged arc and $C0_2$ processes are replacing SMAW technique.

Brief details regarding electrode flux covering, its purpose and constituents are given below:

SMA Welding uses a covered electrode core wire around which a mixture of silicate binders and powdered materials (*e.g.* carbonates, fluorides, oxides, cellulose and metal alloys) is extruded and baked producing a dry, hard concentric covering.

Purpose of covering: 1. stabilizes arc 2. produces gases to shield weld from air, 3. adds alloying elements to the weld and 4. produces slag to protect and support the weld 5. Facilitate overhead/position welding 6. Metallurgical refining of weld deposit, 7. Reduce spatter, 8. Increase deposition efficiency, 9. Influence weld shape and penetration, 10. Reduce cooling rate, 11. Increase weld deposition by adding powdered metal in coating.

Coating constituents:

1. Slag formers: SiO_2, MnO_2, and $FeO.Al_2O_3$ (sometimes).
2. Improving Arc characteristics: Na_2O, CaO, MgO and TiO_2.
3. Deoxidizers: Graphite, Al and woodflour.
4. Binders: Sodium silicate, K-silicate and asbestus.
5. Alloying elements: to enhance strength: V, Ce, Co, Mo, Al, Zr, Cr, Ni, Mn, W.

Contact electrodes have thick coating with high metal powder content, permit DRAG or CONTACT welding and high deposition rates.

2.2.2. Submerged Arc Welding (SAW)

Submerged arc welding (SAW) is next to SMAW in importance and in use. The working of the process is shown in Fig. 2.5. In this process the arc and the weld pool are shielded from atmospheric contamination by an envelope of molten flux to protect liquid metal and a layer of unfused granular flux which shields the arc. The flux containing CaO, CaF_2 and SiO_2 is sintered to form a coarse powder. This flux is then spread over the joint to be made.

- Arc is covered. Radiation heat loss is eliminated and welding fumes are little.
- Process is mechanized or semi-automatic. High currents (200 2000 A) and high deposition rates (27-45 kg/h) result in high savings in cost.

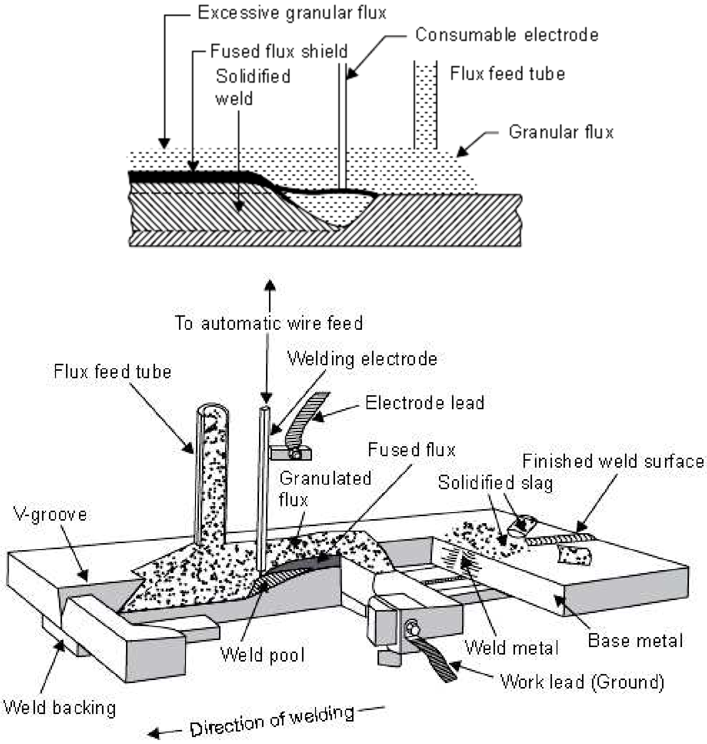


Fig. 2.5 Submerged arc welding process

- Power sources of 600-2000 A output, automatic wire feed and tracking systems on mechanized equipment permit high quality welds with minimum of manual skill. Welding speeds up to 80 mm/s on thin gauges and deposition rates up to 45 kg/h on thick sections are major advantages of this process.
- Plate thicknesses up to 25 mm could be welded in a single pass without edge preparation using dcep.
- Process is commonly used for welding all grades of carbon, low alloy and alloy steels.
- Various filler metal-flux combinations may be employed to obtain desired weld deposit characteristics to suit the intended service requirements. Nearly one kg of flux is consumed per kg of filler wire used.
- The process is ideal for flat position welding of thick plates requiring consistent weld quality and high deposition rates.
- Constant voltage dc power supply is self regulating and could be used on constant-speed wire feeder easily. It is, therefore, commonly used power source and is the best choice for high speed welding of thin gauge steels.

2.2.3. Tungsten Inert Gas (TIG)

- In TIG welding an arc is maintained between a non-consumable tungsten electrode and the work-piece, in inert gas medium, and is used as a heat source. Filler metal is fed from outside. The principle of operation of the process is shown in Fig. 2.6.
- Direct current is normally used with electrode negative polarity for welding most metals except aluminium, magnesium and their alloys, because of the refractory oxide film on the surface which persists even when the metal beneath melts. With electrode positive, cathode spots form on aluminium surface and remove oxide film due to ionic bombardment, but excessive heat generates at the electrode.
- Welding aluminium is best achieved by using alternating current. Large heat input to the workpiece is supplied during the electrode negative half of the cycle. During electrode positive half cycle the oxide film is removed. Since a high reignition voltage is required when the work is negative various means are used to compensate for this effect. Oxide fails to disperse if such means are not used.
- Electrode material could be pure tungsten for d. c. s. p. Thoriated tungsten or zirconated tungsten can work with a.c. as well as with d.c. welding. In a. c. welding, heat input to the electrode is higher, the tip invariably melts. Electrodes containing thoria or zirconia give steadier arc due to their higher thermionic emissivity compared to the pure tungsten electrode.
- Shielding gases used are: argon, helium, and argon helium mixtrure. For very reactive metals welding should be done in an argon filled chamber to obtain ductile welds. In open-air welding with normal equipment some contamination with argon always occurs. Deoxidants are added to the filler metal as a consequence when welding rimming or semi-skilled carbon steel, monel metal, copper, cupro-nickel and nickel.
- Copper can be welded with nitrogen as a shielding gas. Nitrogen reacts with liquid tungsten and not with copper. Thoriated tungsten electrode with straight polarity should be employed. With nitrogen atmosphere anode heat input per ampere is higher compared to argon atmosphere. It is good for high conductivity metal as copper.
- The process is costly and is used only where there is a definite technical advantage *e.g.* welding copper, aluminium, magnesium and their alloys up to 6 mm thick; alloy steels, nickel and its alloys up to 2.5 mm thick, and for the reactive metals.
- Argon spot welds could be made with a torch having the nozzle projecting beyond the electrode tip; it is held against the work, arc is struck and maintained for a preset time and argon is cut-off after a delay. A molten pool forms on the top sheet and fuses into the sheet underneath, producing a plug/spot weld. This welding is ideal for situations having access to one side of the joint only. The equipment required is light

and portable. Process is slow and not adaptable to fully mechanised control as spot welding.

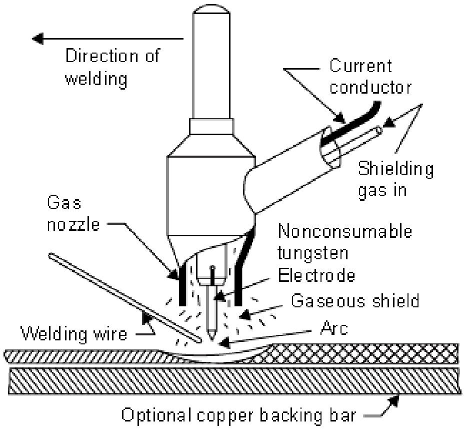


Fig. 2.6 Tungsten Inert Gas (TIG) Welding

2.2.4. Metal Inert Gas (MIG)

In MIG welding the arc is maintained between a consumable electrode and the workpiece in inert gas medium. It is used as a heat source which melts the electrode and thus supplies the filler metal to the joint. The principle of operation is shown in Fig. 2.7. The apparatus consists of a coil of consumable electrode wire, a pair of feed rolls, a welding torch having a control switch and an inert gas supply. Consumable wire picks up current while it passes through a copper guide tube.

- Electrode wire diameter is between 1 .5 mm to 3.0 mm and current used is between 100 to 300 A for welding aluminium, copper, nickel and alloy steels (current density is of the order of 100A per mm square: thus projected transfer occurs). The arc projects in line with the wire axis and metal also transfers in the same line.

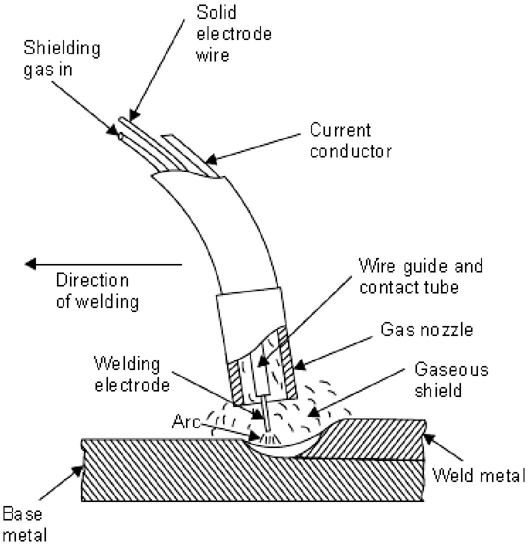


Fig. 2.7 Metal Inert Gas (MIG) Welding

- Projected transfer occurs within a range of current. Below the lower limit the transfer is gravitational and above the upper limit, for aluminium, the metal flow is unstable resulting in the formation of dross, porosity and irregular weld profile.
- Welding may be done below the threshold current and conditions could be adjusted to get short-circuit transfer. Wires of 0.75 mm diameter or less with wire reel directly mounted on the gun itself could be used with short circuit or dip transfer. Such a welding is called fine-wire welding and is suitable for joining sheet metals.
- Dcrp is commonly used and a power source with flat characteristics is preferred for both projected and short circuiting transfer, as it gives more consistent arc-length. Welding of aluminium is only possible with dcsp. Drooping characteristic power sources may also be used with a choke incorporated in the circuit to limit the short circuit current and prevent spatter.
- Shielding gas is normally argon, but argon-oxygen mixtures (oxygen: 20%) are sometimes used for welding austenitic stainless steels in order to impove weld profile. Similarly 80% Ar + 20% CO_2 improves weld profile of carbon steel and sheet metal and is cheaper and better than pure argon. CO_2 shielding can also be used.
- The process is suitable for welding high alloy steels, aluminium, copper, nickel and their alloys. it is complementary to TIG, being particularly suited to thicker sections and fillet welds.
- MIG spot welding gives deeper penetration and is specially suitable for thick materials and for the welding of carbon, low alloy and high alloy steels.

2.2.5. Metal Active Gas (MAG)

This process differs from MIG in that it uses CO_2 instead of inert gases (argon or helium) both the normal and fine-wire machines could be used. The differences are: metal transfer mode, power source, cost and field of application. The process is schematically shown in Fig. 2.8.

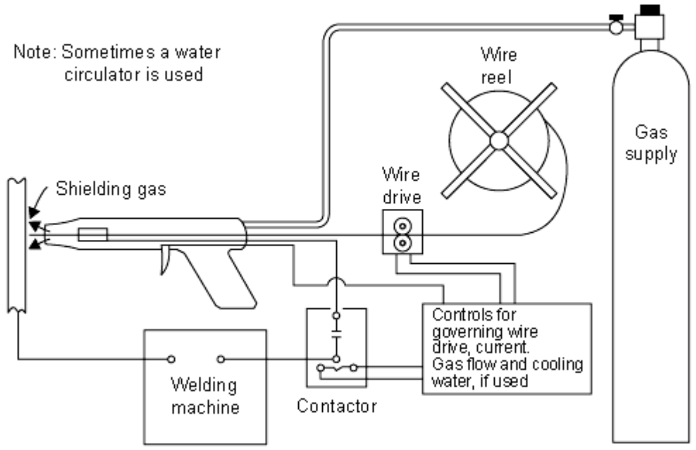


Fig. 2.8 Schematic diagram of MIG/MAG (CO_2) welding

- In CO_2 welding there is no threshold current to change transfer mode from gravitational to projected type. At low currents the free flight transfer is of repelled type and there is excessive scatter loss. This situation is quite common in fine wire welding but can be overcome by adjusting welding parameters to obtain short-circuiting mode of transfer (the drop comes in contact with the weld pool and is detached from the wire by surface tension and electromagnetic forces before it can be projected laterally). If the current is excessive during short-circuiting, detachement will be violent and will cause spatter.
- To get rid of this problem the power source is modified either by adjusting the slope of a drooping characteristic machine or by inserting a reactance in the circuit of a flat

characteristic machine. Thus the short circuit current is limited to a suitable level. At currents in excess of 200 A using 1.5 mm or thicker wires the process is sufficiently regular permitting free flight transfer but welding is to be done in flat position only.

- At arc temperature carbon di-oxide dissociates to carbon monoxide and oxygen. To save metal from oxidation, deoxidized wire for welding carbon steel is essential, otherwise 40% of the silicon and manganese content may be lost.
- This process finds its main application in the welding of carbon and low alloy steels.

2.2.6. Atomic Hydrogen Welding

In atomic hydrogen welding a single phase AC arc is maintained between two tungsten electrodes and hydrogen gas is introduced into the arc. Hydrogen molecules absorb heat from the arc and change into atomic hydrogen. This atomic hydrogen when comes in contact with the plates to be welded recombines into molecular hydrogen, liberating a large amount of intense heat giving rise to a temperature of 6100°C. Weld filler, metal may be added using welding rod as in oxy-acetylene welding. It differs from SMAW in that the arc is indendent of base metal (work) making electrode holder a mobile without arc getting extinguished. Thus heat input to the weld could be controlled by manually to control weld metal properties. The process has the following special features:

1. High heat concentration.
2. Hydrogen acts as a shield against oxidation.
3. Filler metal of base composition could be used.
4. Most of its applications can be met by MIG process, it is, therefore, not commonly used.

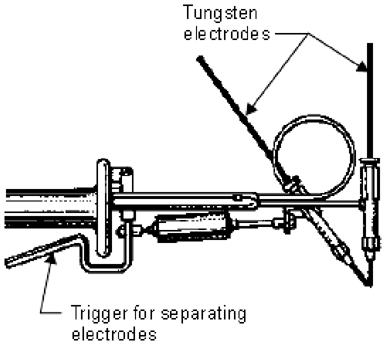


Fig. 2.8 Atomic hydrogen welding torch

2.3. RESISTANCE WELDING

2.3.1. Electroslag Welding

The electroslag welding is used for welding thick plates. The plates have square edge preparation and are set vertically up with about 25 mm gap in between as shown in Fig. 2.9. A starting piece is provided at the bottom. Some flux and welding wire electrodes are fed into the gap between the edges. Arc starts and the slag melts. Molten slag is conductive, the arc is short circuited and heat is generated due to the passage of heavy currents through the slag. The slag agitates vigorously and the parent metal and the filler metal melt, forming a liquid metal pool covered by a layer of liquid slag. This pool is retained by water cooled copper dams. A little flux is added from time to time to maintain a slag pool of constant depth. A number of electrodes could be used depending upon the plate thikness.

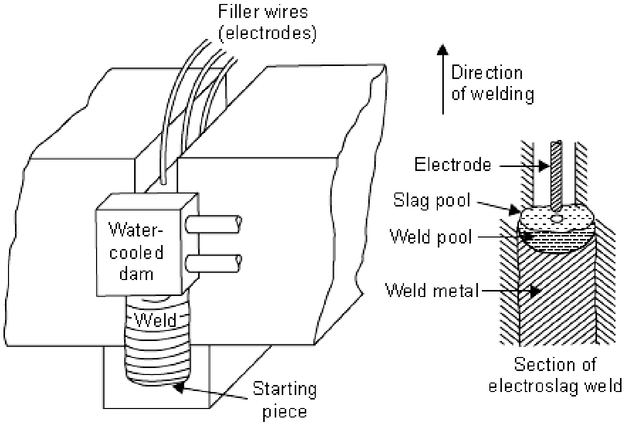


Fig. 2.9 Electroslag welding set-up

Power source could be a. c. but d. c. is preferred for alloy steel welding. Welding speed is low and weld pool is large, the cooling rates are, therefore, slow. The microstructure of weld metal and HAZ shows coarse grains. To obtain good impact resistance, carbon and low alloy steels need normalizing treatment.

Slow cooling combined with low hydrogen content of weld metal greatly minimizes the risk of cracking of welds on low alloy steels. As the weld pool is properly protected from atmospheric contamination, the use of deoxidized wire is not essential.

Electroslag welding is used for the vertical welding of plate and sections over 12 mm thick in carbon and low alloy steels and has been used for the welding of high alloy steels and titanium.

2.3.2. Spot Welding

- In this process, the parts to be joined are normally overlapped and the metal at the interface fuses due to resistance heating. The principle of operation of the process is shown in Fig. 2.10. The workpieces are clamped between two water cooled copper electrodes. On the passage of a high transient current the interface melts over a spot and forms a weld. The cooling of the electrode limits the size of the spot. A very high current (10,000 amp or more) is used for a short duration (fraction of a second) to complete the weld. The interfaces to be joined are initially cleaned by various methods: grinding, scratch brushing or vapour degreasing. A spot weld normally contains small porosity (due to shinkage) in the weld center which is usually harmless.

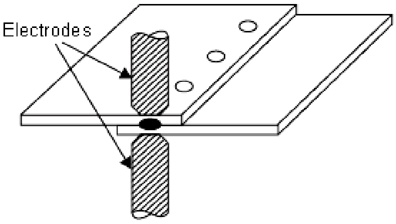


Fig. 2.10 Principle of resistance spot welding

- If a series of spots are to be welded, a higher current is necessary in view of short circuiting provided by the previous weld.
- Cooling of the weld is rapid and steels having more than 0.15% carbon and low alloy steels may require softening of hard structure by passing a second, less intense currect pulse after the welding pulse.

- Electrodes should have high electrical an thermal conductivity and should have resistance to wear. Copper alloys (*e.g.* Cu 0.5% Cr, sintered tungsten copper compacts) have been developed which retain hardness even when exposed to welding heat.
- Power source for resistance welding should give a low voltage high current output for steel and nickel alloys to be spot welded. Silver, aluminium, copper and their alloys pose problem in welding due to high electrical and thermal conductivity necessitating high current pulses for short duration.
- Cracking and expulsion of molten metal occurs from excessive welding current and may be avoided by correct adjustment of welding variables.

2.3.3. Projection Welding

Projection welding is a variation of spot welding. Projections are formed on one of the pieces to be joined, usually by pressing the parts between flat copper electrodes. A current pulse makes the weld at the tip of the projection leaving clean surfaces without indentations. Schematic of the set-up is shown in Fig. 2.11.

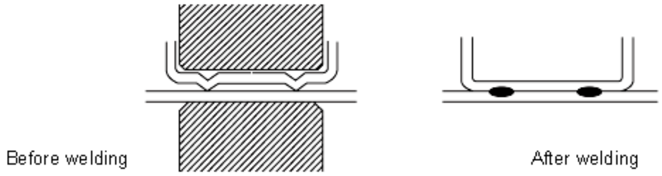


Fig. 2.11 Projection welding

2.3.4. Seam Welding

Seam welding is a continuous spot welding process where overlapped parts to be welded are fed between a pair of copper alloy (roller disc shaped) electrodes (Fig. 2.12).

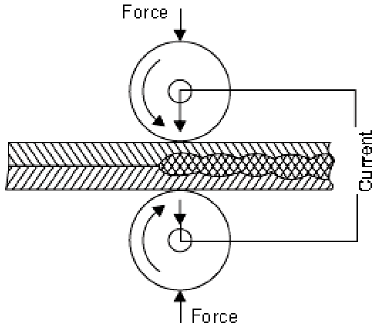


Fig. 2.12 Sketch of seam welding

2.3.5. Flash Welding

It is classified as a resistance welding process as the heat is generated at the faying surfaces of the joint by resistance to the flow of electric current, and by arcs across the interface. A thin layer of liquid metal forms at the faying surfaces. When the parts are forced together to form a joint, the layer of liquid metal on the faces alongwith the impurities is expelled, the hot metal upsets and forms a flash. No external filler metal is added during welding. Welds can be made in sheet and bar thicknesses ranging from 0.2 to 25 mm (sheets) and 1 to 76 mm (bars). Machines are available in capacities ranging from 10 kVA to 1500 kVA. The distance by which the pieces get shortened due to upsetting is called flashing allowance. The process is used for joining rails, steel strips, window frames, etc.

2.3.6. Butt (upset) Welding

The principle of the process is shown in Fig. 2.13. Here the workpiece temperature at the joint is raised by resistance to the passage of an electric current across the interface of the joint. The parts to be joined (wires or rods usually) are held in clamps, one stationary and the other movable which act as conductors for the low voltage electric supply and also apply force to form the joint. Force is applied only after the abutting surfaces reach near to the melting temperature. This causes up-setting. Uniform and accurately mating surfaces are desirable to exclude air and give uniform heating.

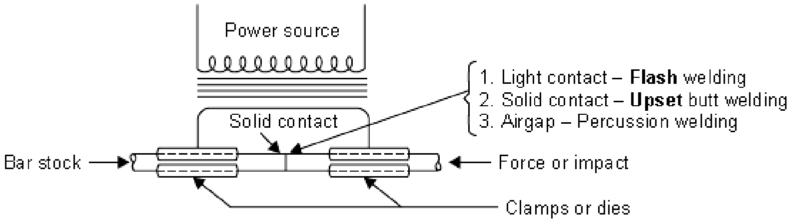


Fig. 2.13 Sketch of resistance butt welding

2.3.7. Percussion Welding

This process makes butt welds at **incredible** speed, in almost any combination of dissimilar materials and without the flash formation (Fig. 2.14). It relies on arc effect for heating.

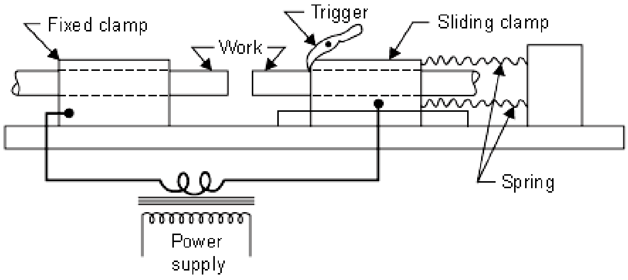


Fig. 2.14 Principle of percussion welding

The pieces to be joined are kept apart, one in a stationery holder and the other in a moveable clamp held against a heavy spring pressure. When the movable clamp is released the part to be welded moves towards the other part. Arcing occurs when the gap between the pieces to be welded is 1.6 mm. The ends to be welded are prepared for accurate mating. An extremely heavy current impulse flows for a short duration (0.001 to 0.1 second) across the gap between the pieces **forming an arc.** The intense heat developed for a very short duration causes superficial melting over the entire end surfaces of the bars. Immediately after this current pulse, the pieces are brought together with an impact blow (hence the name percussion) to complete the weld.

The electric energy for the discharge is built-up in one of two ways. In the electrostatic method, energy is stored in a capacitor, and the parts to be welded are heated by the sudden discharge of a heavy current from the capacitor. The electromagnetic welder uses the energy discharge caused by the collapsing of the magnetic field linking the primary and secondary windings of a transformer or other inductive device. In either case intense arcing is created which is followed by a quick blow to make the weld.

Special Applications:

- Heat treated parts can be joined without affecting the heat treatment.
- Parts having different thermal conductivities and mass can be joined successfully. For example stellite tips to tool shanks, copper to alluminium or stainless steel. Silver

contact tips to copper, cast iron to steet, zinc to steel. These welds are produced without flash or upset at the joint.

Limitation:

The limitation of the process is that only small areas upto 650 mm^2 of nearly regular sections can be welded.

2.3.8. High Frequency Resistance Welding

In high frequency resistance welding shown in Fig. 2.15, welding current of 200 450,000 Hz frequency passes between the electrodes in contact with the edges of a strip forming a tube when it passes through forming rolls. The rolls also apply welding pressure. The amount of upset is regulated by the relative position of the welding electrodes and the rolls applying the upset force. The required welding heat is governed by the current passing through the work and the speed of tube movement.

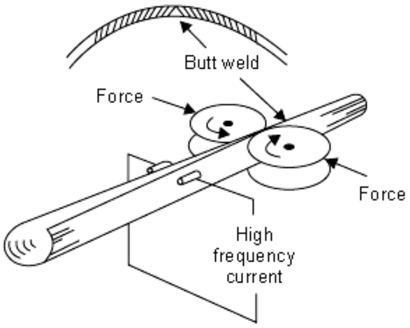


Fig. 2.15 Sketch of high frequency resistance welding

2.4. SOLID PHASE WELDING

This group of welding processes uses pressure and heat (below the melting temperature) to produce coalescence between the pieces to be joined without the use of filler metal. The processes under this category include: Diffusion Bonding, Cold Welding, Explosive Welding, Friction Welding, High Frequency Pressure Welding, Forge Welding, Hammer Welding, Ultrasonic Welding, etc. The important ones will now be discussed.

2.4.1. Friction Welding

Friction heat between two sliding/rotating surfaces is employed in this process to form a joint. The principle of working of the process is shown in Fig. 2.16. The pieces to be joined are clamped in chucks. One chuck rotates against a stationary one. Pressure is used to generate enough heat to reach a bonding temperature within a few seconds. At this stage the rotation is stopped and pressure is retained or increased to complete the weld. To accomodate awkward or very long parts, an intermediate slug or disc is rotated in between the sections to be joined.

2.4.2. High Frequency Pressure Welding

This process differs from H.F. resistance welding in that the current is induced in the surface layer by a coil wound around the workpiece. This causes surface layer to be heated. Weld is formed by a forging action of the joint (Fig. 2.17). It is used in the manufacture of tubes. The process is also termed as H.F. Induction Welding.

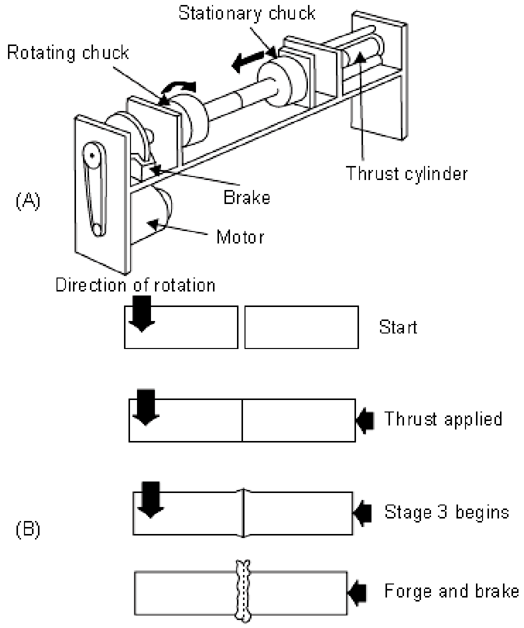


Fig. 2.16 Friction welding (A) Equipment (B) Stages

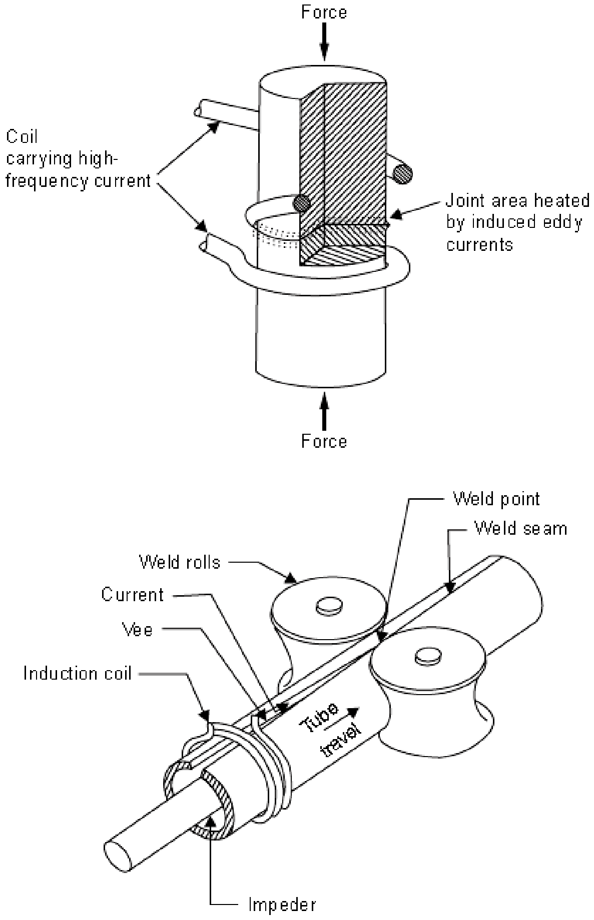


Fig. 2.17(Sketch of high-frequency pressure welding

2.4.3. Ultrasonic Welding

- Ultrasonic process of welding is shown in Fig. 2.18. The core of magnetostrictive ultrasonic vibrations generator (15-60 kHz) is connected to the work through a horn having a suitable shaped welding tip to which pressure is applied. The combination of ultrasonic vibrations with moderate pressure causes the formation of a spot weld or seam weld (with modified apparatus). The deformation caused is less than 5 percent.

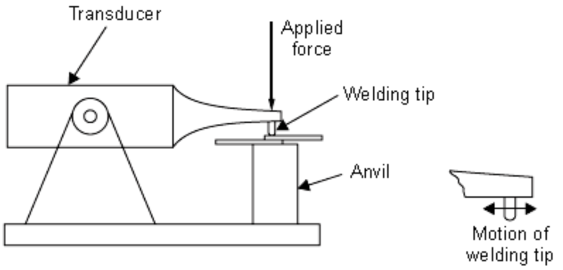


Fig. 2.18(a) Ultrasonic welding

- Friction between the interface surfaces, along the axis of the welding tip, causes the removal of surface contaminants and oxide film exposing the clean metallic surface in contact with each other which weld together due to applied pressure. Weld produced is as strong as parent metal.
- Some local heating may occur and some grains may cross the interface but not melting or bulk heating occurs.

The process is briefly discussed in the following paragraphs:

1. It is solid state joining process for similar or dissimilar metals in the form of thin strips or foils to produce, generally lap joints.
2. H.F. (15000 75000 Hz) vibratory energy gets into the weld area in a plane parallel to the weldment surface producing oscillating shear stresses at the weld interface, breaking and expelling surface oxides and contaminants.
3. This interfacial movement results into metal-to-metal contact permitting coalescence and the formation of a sound welded joint.

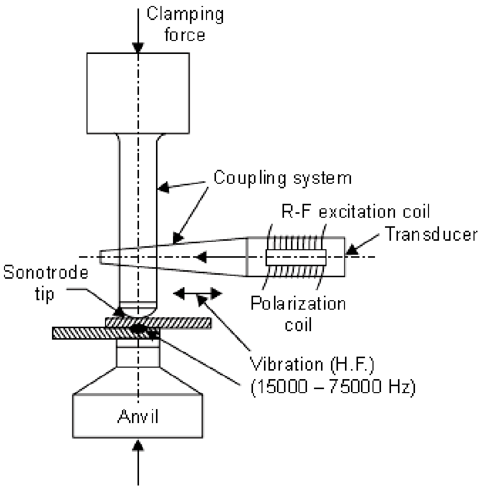


Fig. 2.18(b) Ultrasonic welding (detailed sketch)

4. Before welding the machine is set for clamping force, time and power and overlapping plates are put on the anvil sonotrode is then lowered and clamping force is built to the desired amount (a few Newton to several hundred Newton) and ultrasonic power of sufficient intensity is then introduced. Power varies from a few watts for foils to several thousand watts for heavy and hard materials and is applied through the sonotrode for a pre-set time. Power is then automatically, cutoff and weldment released, time taken is less than 1 sec.
5. Continuous seams can also be produced using disc type rotary sonotrode and disc type or plain anvil.
6. Machine parameters are adjusted for each material and thickness combination.
7. Materials from very thin foils and plates upto 3 mm thickness can be welded.
8. Advantages and applications include.
   (*a*) The process is excellent for joining **thin sheets** to **thicker** sheets.
   (*b*) Local plastic deformation and mechanical mixing result into sound welds.
   (*c*) Ring-type continuous welds can be used for hermetic sealing.
   (*d*) Many applications in electrical/electronic industries, sealing and packaging, air craft, missiles, and in fabrication of nuclear reactor components.
   (*e*) Typical applications of the process include: welding of ferrous metals, aluminium, copper, nickel, titanium, zirconium and their alloys, and a variety of dissimilar metal combinations. It is applicable to foils and thin sheets only.
   (*f*) Other applications include: almost all commonly used armatures, slotted commuters, starter motor armatures, joining of braded brush wires, to brush plates, and a wide variety of wire terminals.
   (*g*) With newly developed solid-state frequency converters, more than 90% of the line power is delivered electrically as high frequency power to the transducer.
   (*h*) In the case of ceramic transducers as much as 65 70% of the input electrical line power may be delivered to the weldmetal as acoustical power.

Energy required to weld

Energy required to weld a given meterial increases with material hardness and thickness. This relationship for spot welding is given by

$$E_a = 63\, H^{3/2}\, t^{1.5}$$

where E_a = acoustical energy in joules

H = Vicker's microhardness number

t = material thickness adjascent to active in inches.

This equation is valid for Aluminium, Steel, Nickel and Copper for thicknesses upto 0.81 mm.

2.4.4. Explosive Welding

Explosive welding is a welding process that uses a controlled application of enormous pressure generated by the detonation of an explosive. This is utilized to accelerate one of the components called the flyer to a high velocity before it collides with the stationary component. At the moment of impact the kinetic energy of the flyer plate is released as a compressive stress wave on the interface of the two plates. The pressure generated is on the order of thousands of megapascals. The surfaces to be joined must be clean. The surface films, if any, are liquefied, scarfed off the colliding surfaces leaving clean oxide free surfaces. This impact permits the normal inter-atomic and intermolecular forces to affect a bond. The result of this process is a cold weld **without** a HAZ. Combination of dissimilar metals, copper to stainless steel, aluminium to steel or titanium to steel can be easily obtained by this process. EW is well suited to cladding application. The principle of operation is shown in Fig. 2.19.

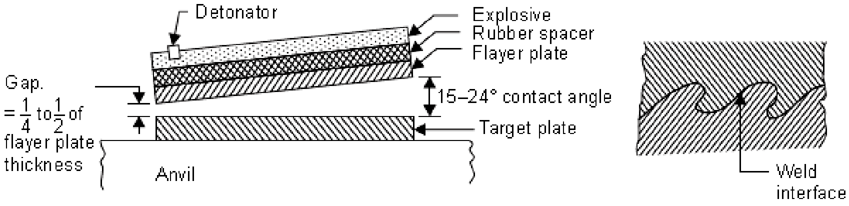


Fig. 2.19 Principle of operation of explosive welding

The main features of the process are listed below :

1. It joins plates face-to-face.
2. One of the plates called the target plate is kept fixed on anvil. The other plate called the flayer plate is kept at an angle of 15–24° to the target plate. The minimum gap is $\frac{1}{4}$ to $\frac{1}{2}$ the flayer plate thickness.
3. A layer of explosive charge is kept on the flayer plate with intervening layer of rubber spacers.
4. When explosive charge is detonated the flayer plate comes down and hits the target plate with a high velocity (2400–3600 m/s) and the plates get welded face-to-face.
5. The process can be used to join dissimilar materials and the weld interface is seen to be wavy as shown in figure.
6. The various oxides/films present on metal surfaces are broken up or dispersed by the high pressure.
7. Areas from 0.7 to 2 m^2 have been bonded by this process.
8. Process is simple, rapid and gives close thickness tolerance.
9. Low melting point and low impact resistance materials cannot be welded by this process effectively.
10. Explosive detonation velocity should be approx 2400–3600 m/s. The velocity depends on the thickness of explosive layer and its packing density.
11. Low melting point and low impact resistance materials cannot be welded effectively by this process.

2.5. HIGH ENERGY DENSITY WELDING

2.5.1. Electron Beam Welding

- Electron beam welding uses the kinetic energy of a dense focussed beam of high velocity electrons as a heat source for fusion. In the equipment for this process, electrons are emitted by a cathode, accelerated by a ring-shaped anode, focussed by means of an electromagnetic field and finally impinge on the workpiece as shown schematically in Fig. 2.20. The operation takes place in a vacuum of about 10^{-3} mm of mercury. Accelerating voltages are in the range of 20-200 kV and welding currents are a few milliamperes, the total power is of the same order of magnitude as in SMAW, except that in this process power concentrations of 1–100 kW/mm^2 are routinely achieved and upto 10 MW/mm^2 can be obtained.
- As the accelerating voltage is increased, the intensity of the X-rays emitted from anode increases. In high voltage equipment means are used to limit X-ray emission within permissible limits.
- Focussing coils can concentrate the beam on a spot of a few micron in diameter. With such a concentrated spot there is a threshold voltage above which the beam penetrates the metal and when the work is traversed relative to the beam a weld bead of exceedingly narrow width relative to the plate thickness is formed.

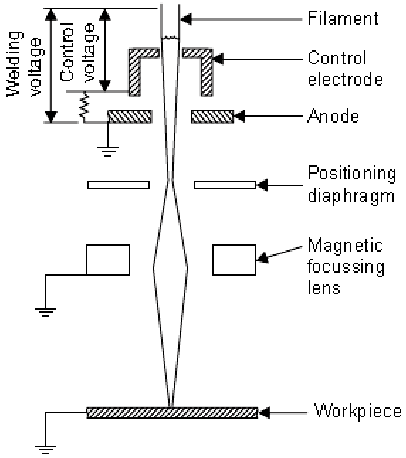


Fig. 2.20 Principle of electron beam welding

- This type of weld could be used for welding dissimilar materials and it is used when the effect of welding heat is to be minimized (distortion is minimum).
- The beam may be defocussed and could be used for pre-heating or post-welding heat treatment. Periodic defocussing could be useful for metals having high vapour pressure at the melting point. The process is applicable to metals that do not excessively vaporize or emit gas when melted. Can weld metals sensitive to interstitial embrittlement.
- The process is specially suitable for welding dissimiiar metals and reactive metals (super alloys (previously impossible to weld)) and for joints requiring accurate control of weld profile and penetration and for joining turbine and aircraft engine parts where distortion is unacceptable. Its major limitation is the need for a vacuum chamber. It can join plate thicknesses from thin foils to 50 mm thick plates. The gun is placed in a vacuum chamber, it may be raised lowered or moved horizontally. It can be positioned while the chamber is evacuated prior to welding. The circuit is energised and directed to the desired spot. Usually the beam is stationary and the job moves at a desired speed.
- Temperatures attained can vaporise any known metal (even tungsten). There are three commercial versions of the EBW process, depending upon the degree of vacuum used as given in the following table:

Table 2.1 Commercial versions of EBW process

S. No.	*EBM Type*	*Vacuum pressure*	*Working distance limit*	*Thickness range for single pass weld*	*Systems power level*	*Special Applications*
1.	Hard vacuum process	10^{-4} torr (0.013 Pa)	Upto 750 mm.	A few thousand Angstrom to 225 mm	1 – 25 kW	Gives best properties when welding interstitially sensitive materials
2.	Soft vacuum process	10^{-1} torr (13 Pa)	Upto 300 mm	Upto 50 mm	15 kW	–do–
3.	Non-vacuum	100 kPa (1 atm.)	25 mm	13 mm	—	Cannot successfully weld interstitially sensitive materials

- Deep penetration, with depth-to-width ratio of 20 : 1, is a unique characteristic of this process. It is mainly due to high power densities achievable with electron beams, which cause instantaneous volatilization of metal. A needle like metal vapour filled cavity or keyhole is produced through the metal plate thickness. As the welding proceeds this key-hole moves forward alongwith the beam and gravity and surface tension act to cause molten metal to flow into the cavities just behind. The limited ability of the beam to traverse the metal thickness is a unique property that ensures full penetration through the metal thickness.
- The process can be adapted to numerical control and can be performed in air or under a blanket of CO_2 but the welds suffer from contamination.

2.5.2. Laser Beam Welding

Laser is the abbreviation of light amplification by stimulated emission of radiation. It is very strong coherent monochromatic beam of light, highly concentrated with a very small beam divergence. The beam exiting from the laser source may be 1 10 mm in diameter, when focussed on a spot has energy density of more than 10 KW/mm^2. Laser beam welding is a thermoelectric process accomplished by material evaporation and melting. Focussing is achieved by various lens arrangements while focusing of electron beam is achieved by electrostatic and magnetic means. Because of this focusing, high power densities are achieved by both the 'electron' and the 'Laser' beams.

- The process does not require a vacuum chamber, size of HAZ is smaller and the thermal damage to the adjascent part is negligible. Laser can be used to join dissimilar metals, difficult-to-weld metals *e.g.* copper, nickel, chromium, stainless steel, titanium and columbium. Currently the process is largely in use in aerospace and electronic industries.
- The principle of working of a Laser Welder is shown in Fig. 2.21(*a*). An intense green light is thrown on a speciai man-made ruby, 10 mm in diameter, containing about 0.05% by weight of chromium oxide. The green light pumps the chromium atoms to a higher state of energy. Each of these excited atoms emits red light that is in phase with the colliding red light wave.

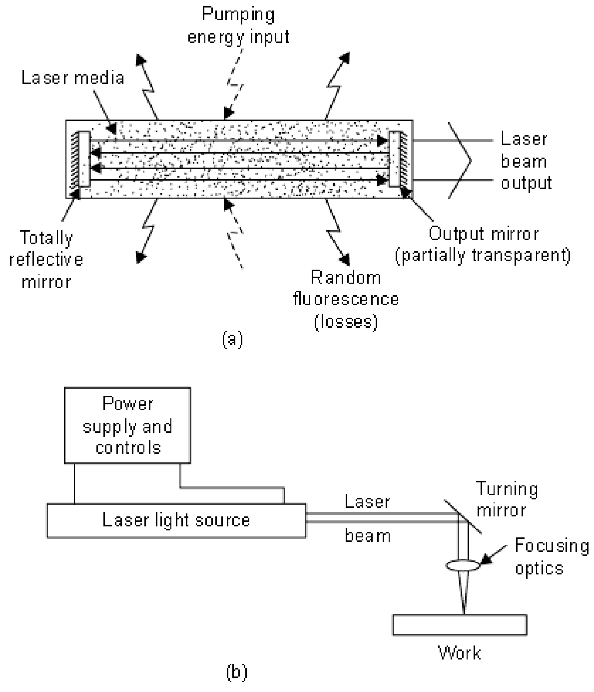


Fig. 2.21(b) Schematic diagram of laser welding

- Thus, the red light gets continuously amplified. To further enhance this effect the parallel ends of the rod are mirrored to bounce the red light back and forth within the rod. When a certain critical intensity of pumping is reached, the chain reaction of collisions becomes strong enough to cause a burst of red light. The mirror in the front of the rod is only a partial reflector, allowing the burst of light to escape through it.
- Lasers used for welding could be of two types:
  1. Solid-state lasers
  2. Gas Lasers (The chief gas Laser is CO_2 laser)

Solid-state lasers are ruby, Nd : Glass and Nd : YAG. The last two are the Lasers in which (Nd : Glass) or single crystals of Yttrium-Aluminium-Garnet (Nd : YAG) are doped with Nd (neodymium) ions as the active medium. The chief gas laser is CO_2 laser.

- Ruby and Nd: Glass are capable of high **energy pulses** but are limited in maximum repetition rate, Nd YAG and CO_2 Lasers can be continuous wave or pulsed at very high repetition rate.
- Incident laser radiations do reflect back from metallic surfaces in appreciable amounts, sufficient energy is still absorbed to maintain a continuous molten puddle. Ruby and Nd: Glass lasers, because of their high energy outputs per pulses, overcome this reflectivity problem.
- Due to inherently low pulse rates 1 50 pulses per second, welding speeds for thin sheets are extremely slow. In contrast Nd : YAG and inparticular CO_2 lasers are capable of very high continous wave outputs or they can be pulsed at several thousand pulses per second, giving rise to high speed continuous welding.

Pulsed Laser Beam Welding

A pulse of focussed laser energy beam when incident on a metallic surface is absorbed within a very small area and may be treated as a surface heating phenomenon. Thermal response beneath the focussed spot depends upon heat conduction. The depth 'x' to which the energy is felt in time 't' depends upon thermal diffusivity, k, and is given by $\sqrt{4kt}$. This leads to the concept of thermal time constant for a metal plate of thickness 'x'.

$$x = \sqrt{4kt}$$

$$x^2 = 4kt$$

$$t = \frac{x^2}{4k}$$

This represents the pulse duration required for full panetration. (through melting). For 0.13 to 0.25 mm metal sheets, thermal time constants are comparable to pulse duration. If the laser pulse is very short as compared to thermal diffision time, the pulse energy remains at the surface and rapid localized heating occurs with very little depth of penentration. This accumulation of heat at the surface causes metal to vaporize from the surface.

In laser beam welding the bottom lower surface of the sheet must reach the melting temperature before the upper surface reaches the vaporization point. Thus, thermal diffusivity and pulse duration control the depth to which successful porosity free welds could be made. Typically a solid-state laser can be pulsed for an 'on' period of 10 milliseconds. This limits the depth of penetration to 1 mm.

Continuous Wave Laser Beam Welding

Lasers like Nd : YAG and CO_2 are capable of making high speed continuous metal welds. Laser's, more than 500 watts capacity are capable of welding steel sheets 0.25 mm thick at several mm/second. CO_2 lasers of 10 kW continuous wave output power can produce deep penetration welds in 13 mm thick steel plates at 25 mm/s.

When heating or melting a metal with a Laser beam, the concept of energy absorbed per unit volume of metal becomes a controlling parameter. The energy absorbed can be written in dimensions of J/mm^3. This parameter becomes a measure of power dersity/welding speed. For example

$$W/mm^2 \times S/mm = J/mm^3$$

The focused spot size '*d*' of a laser beam is given by

$$d = f\,\theta$$

where *f* is the focal length of the lens and θ is the full angle beam divergence. The power density, *PD*, at the focal plane of the lens is given by

$$PD = \frac{4P_1}{\pi d^2}$$

where P_1 is the input power, hence

$$PD = \frac{4P_1}{\pi (f\,\theta)^2}$$

Therefore power density depends upon the laser power and beam divergence. For a laser beam operating in the basic mode, the energy distribution across the beam is gaussian, the beam divergence is

$$\theta \propto \frac{\lambda}{a} \qquad \text{Thus } PD \propto \frac{4P_1\lambda^2}{\pi f^2 a^2}$$

where a is a characteristic dimension of the laser beam and λ is the wavelength of laser radiation. It can, therefore, be noted that the power density is inversely proportional to the square of the wavelength of the laser radiation.

This continuous power provided by continuous wave laser beam makes high power carbon dioxide laser with **deep** penetration capability. There is precise controt of energy delivery to highly localized regions. This is good for "narrow gap", geometries and permits welding without the need for filler metal. This results in savings in filler metal. Deep penetration welds made by this process are similar to the electron beam welds. The process offers the following advantages.

Advantages:

1. Vacuum environment is not required, reative metals can be protected from the atomosphere by inert gas shields.
2. X-rays are not generated by the beam.
3. Laser beam can be manipulated using the principles of optics. This permits easy automation.
4. Can successfully join a variety of metals and alloys.
5. Because of low energy inputs per unit weld length, the cooling rates are high. Cooling rates and associated problems could be modified by pre- or post heating.

Typical CO_2 Laser Beam Welding Performance

S. No.	*Laser Power Level*	*Plate material*	*Material thickness/penetration*	*Welding speed*
1.	5 kW	Carbon steel	2.5 mm	85 mm/s
		Stainless steel	5.0 mm	42 mm/s
2.	10 kW	Aluminium	5.0 mm	38 mm/s
		Titanium	5.00 mm	57 mm/s
3	15 kW	304 stainless steel	18 mm penetration	8 mm/s
			15 mm penetration	25 mm/s
4	6 kW	Steel	Thin gauge	1270 mm/s

6. Ruby lasers are used for spot welding of thin gauge metals, microelectronic components, tasks requiring precise control of energy input to work.
7. 100 kW pulses of one millisecond duration give a series of overlapping spot welds which could be used for special applications.
8. The electrical efficiency of the process is 10 20% only.
9. With slight modifications, the process could be used for gas assisted cutting and for surface heat treating and alloying applications.
10. Typically a solid state laser can be pulsed for an on period of 10 milliseconds. This limits the depth of penetration to 1.0 mm.

Table. Thermal time constants for laser beam welding, seconds

Material	*Time in seconds*		
	Thickness 0.18 mm	*Thickness 0.64 mm*	*Thickness 2.5 mm*
Copper	0.035	0.884	14.1
Aluminium	0.047	1.170	18.8
1% C-steel	0.333	8.330	133.3
Stainless steel	1.004	25.10	401.7
Titanium	0.593	14.8	237.3
Tungsten	0.060	1.509	34.1

2.5.3. Plasma Arc Welding

Plasma is the fourth state of matter (other three being: solid, liquid and gas). It is hot ionized arc vapour. In arc welding this arc plasma is blown away by moving gas streams, but in a plasma torch it is contained and used effectively giving rise to the following processes:

- Plasma arc welding
- Micro-plasma arc welding
- Plasma spraying

Plasma Welding

- Plasma welding is an extension of TIG welding. The main difference is the water cooled nozzle in between the electrode and the work. This causes constriction of the arc column, resulting in very high arc temperature between 16,600 3300°C. Fig. 2.22 shows two main types of torhes in common use: Transferred Arc and Non-transferred Arc. In the first type the tip of the tungsten electrode (d.c. negative) is located within the torch nozzle. The torch consists of an electrode, a watercooled nozzle, for arc constriction and a passage each for supply of water and gas. A power supply unit provides d.c. The welding area is blanketed by shielding, gas supplied through an outer gas cup. Transferred arc transfers heat directly from electrode in the torch to the workpiece.
- When the gas (argon) is fed through the arc it becomes heated to the plasma temperature range (16,600 33.000°C). The arrangement is such that the arc first strikes to the nozzle. The plasma so formed is swept out through the nozzle and the main current path is then formed between the electrode and the work piece. The transferred (constricted) arc may be used for cutting metals that are not so readily cut by oxy-acetylene torch (non-ferrous metals and stainless steel). For best cutting action argon/hydrogen or nitrogen hydrogen mixtures are used. This requires high output voltage welding machines.A non-transferred arc is established between the electrode and torch nozzle indpendent of the workpiece. The heat is carried by the hot gases (plasma) coming out from the torch. The transferred arc delivers heat more effectively to the workpiece as the heat is generated by the anode spot on the workpiece as well as the plasma jet heat. Thus it is most commonly used.

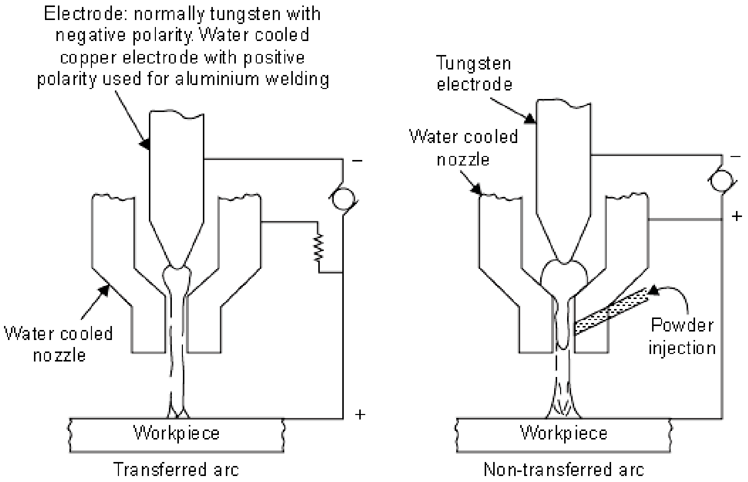


Fig. 2.22 Plasma arc welding

- Plasma welding makes use of the key-hole technique. When the plasma jet strikes metal it cuts or keyholes entirely through the workpiece making a small hole and molten metal in front of the arc flows around the arc column, and is drawn behind the hole by surface tension. Thus butt welds on 12.5 mm or larger thicknesses could be made in a single pass with full penetration. It is good for welding plates accessible from one side only.
- Plasma arc welding can weld carbon steels, stainless steels, copper, brass, aluminium, titanium, monel and inconel including hastalloys, molybdenum and tantalum etc.

Micro-Plasma Arc Welding is a modified process using currents between 0.1 10 A.

It is capable of welding extremely thin sheets and foils between 0.05 1.6 mm thickness. The precise control of heat is achieved through "Pulsed mode" operation.

Plasma Spraying: In non-transferred arc torch the arc is struck between electrode and nozzle. The rate of gas flow through this torch is moderately high and a jet of plasma issues from the nozzle. For spraying, powder or wire is injected inta the plasma stream which is hot enough to melt any solid that does not decompose or sublime. Thus ceramics may be sprayed on to a metal surface. When metal is sprayed, high density caating is obtained. Shielding gases could be either argon or nitrogen or 5-25% hydrogen mixed with nitrogen or argon. The non-transferred torch is also known as a plasma device. Plasma heat could also be used to melt metal for certain applications.

■ QUESTIONS

2.1 Why shielded metal arc welding process is most commonly used. Briefly describe the process. What are the advantages and limitations of this process?

2.2 With neat sketches, compare the processes of shielded metal arc and submerged arc welding.

2.3 Distingnish between:

(*a*) TIG Welding, MIG Welding and MAG. Welding

(*b*) Normal Resistance Welding and electroslag welding

(*c*) Flash butt Welding and Percussion Welding

(*d*) Friction Welding, High frequency Pressure Welding and Ultrasonic Welding.

2.4 Briefly describe with neat sketches bringing out the important features of the following welding processes:

(*a*) Laser Beam Welding

(*b*) Electron Beam Welding

(*c*) Plasma Arc Welding.

Chapter 3

WELD QUALITY AND INSPECTION OF DISSIMILAR METALS WELD

3.1. DEFECTS

As the welded joints are finding applications in critical components where the failure results into a catastrophy, the inspection methods and acceptance standards are increasing. Acceptance standards represent the minimum weld quality and are based upon test of welded specimens containing some discontinuities, usually a safety factor is added to yield the final acceptance standard. A good research effort is being directed to correlate the discontinuities with the performance.

In the present discussion we shall study the weld discontinuities commonly observed in the welds, their causes, remedies and their significance. Small imperfections, which cause some variation in the normal average properties of the weld-metal are called discontinuities. When the discontinuity is large enough to effect the function of the joint it is termed a defect.

Standard codes do permit limited level of defects based on fracture mechanics principles, taking consideration the service conditions of the fabrication. Inspite of all this, the fabricator must strive to prevent the occurrence of weld defects in the first instance and to rectify them if they do occur. There are many types of defects which have been classified in various documents (*e.g.,* BS499 part I, 1965). For our purpose we shall be discussing the most important ones shown in Fig. 3.1. These are undercuts, cracks, porosity, slag inclusions, lack of fusion and lack of penetration.

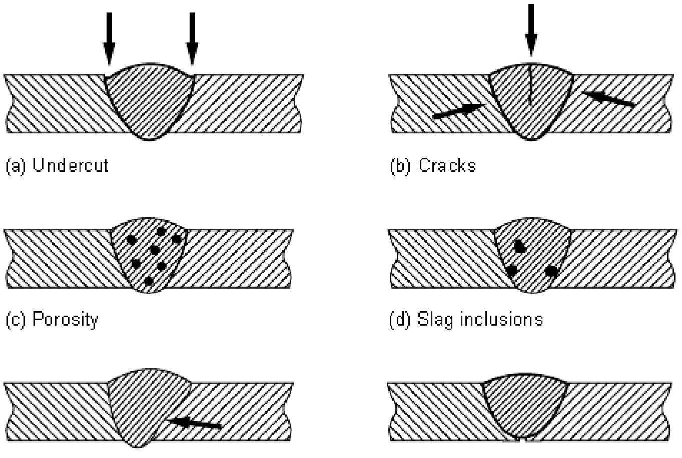


Fig. 3.1 Typical weld defects

3.1.1. Undercut

The term is used to describe a groove melted into the base metal adjacent to the toe of a weld and left unfilled by the weld metal. It also describes the melting away of the sidewall of a welding groove at the edge of a layer or bead. This melting away of the groove forms a sharp recess in the sidewall in the area in which the next layer or bead must fuse. (Slag may be "keyed" into this undercut which, if not removed prior to subsequent passes, may become trapped in the weld.) An undercut, therefore, is a groove that may vary in depth, with, and sharpness at its root.

3.1.2. Cracks

Cracks are linear ruptures of metal-under stress. Although sometimes wide, they are often very narrow separations in the weld or adjascent base metal. Usually little deformation is apparent. Three major classes of cracks are generally recognised: hot cracks, cold cracks, and macrofissures. All types can occur in the weld or base metal.

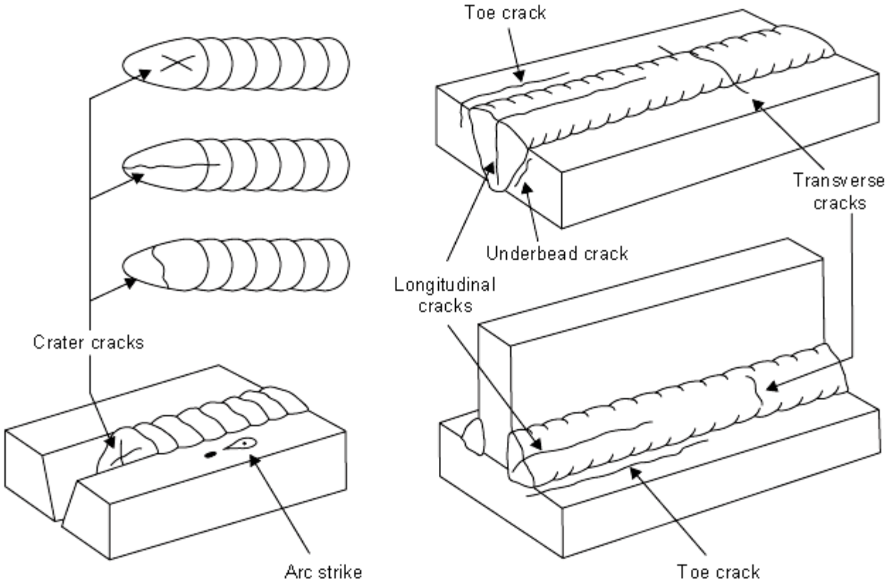


Fig. 3.2 Types of cracks in welded joints

Fig. 3.2 illustrates a variety of cracks including underbead cracks, toe cracks, crater cracks, longitudinal cracks, and transverse cracks. The underbead crack, limited mainly to steel, is base metal crack usually associated with hydrogen. Toe cracks in steel can be of similar origin. In other metals (including stainless steel), cracks at the toe are often termed edge of weld cracks, attributable to hot cracking in near the fusion line. Crater cracks are shrinkage cracks which result from stopping the arc suddenly.

3.1.3. Porosity

Porosity is the presence of a group of gas pores in a weld caused by the entrapment of gas during solidification (when solidification is too rapid). They are small spherical cavities, scattered or clustered locally. Sometimes, the entrapped gas may form a single large cavity which is termed as a blow hole.

Causes:

1. Lack of deoxidisers
2. Base metal sulphur content being high
3. Presence of oil, grease, moisture or mill scale on the joint surface
4. Excessive moisture in flux
5. Inadequate gas shielding
6. Low current or long arc
7. Rapid solidification of weld deposit

3.1.4. Slag Inclusion

This term is used to describe the oxides and other nonmetallic solid materials that are entrapped in weld metal or between weld metal and base metal. Slag inclusion may be caused by contamination of the weld metal by the atmosphere, however, they are generally derived from electrode-covering materials or fluxes employed in arc welding operations; or in multilayer welding operations, if there is failure to remove the slag between passes. It can be prevented by proper groove preparation before each bead is deposited and correcting the contours that will be difficult to penetrate fully with successive passes.

3.1.5. Lack of Fusion

It occurs due to the failure of the adjacent bead to bead and weld metal and base metal fusing together. This may happen due to the failure to raise the temperature of the base metal or failure to clean the surfaces before welding.

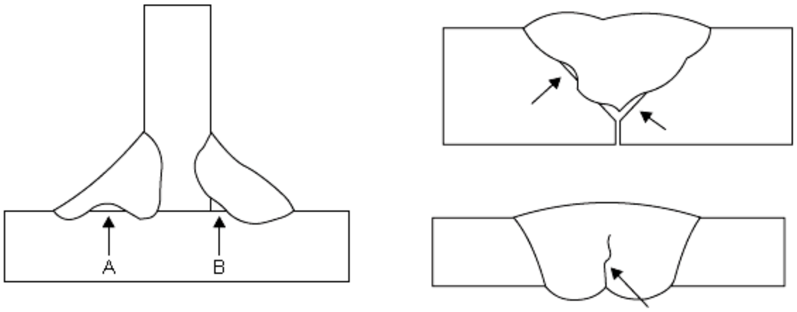


Fig. 3.3 Types of lack of fusion

3.1.6. Lack of Penetration

This defect, occurs when the weld metal fails to reach the root of the joint and fuse the root faces completely. It is caused by using incorrect electrode size with respect to the form of the joint, low welding current, inadequate joint design and fit-up. It occurs more often in vertical and overhead welding positions.

3.2. FAULTY WELD SIZE AND PROFILE

A weld, otherwise deposited correctly without a defect may not be acceptable due to the shape of its profile. Excessive or lack of reinforcement are both defective. Defective profiles on butt welds are shown in Fig. 3.4 while Fig. 3.5 describes desirable, acceptable and defective profiles on fillet welds. These faults arise from the use of an incorrect welding procedure and could be eliminated if the following factors are considered:

(*a*) correct joint preparation and fit-up
(*b*) proper electrode size and welding current
(*c*) number and locations of runs are correct
(*d*) correct welding speed is used.

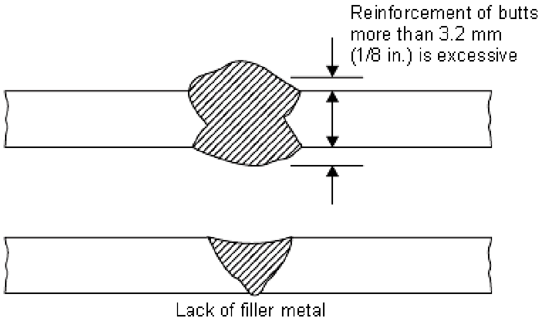


Fig. 3.4 Excessive reinforcement, Lack of filler metal

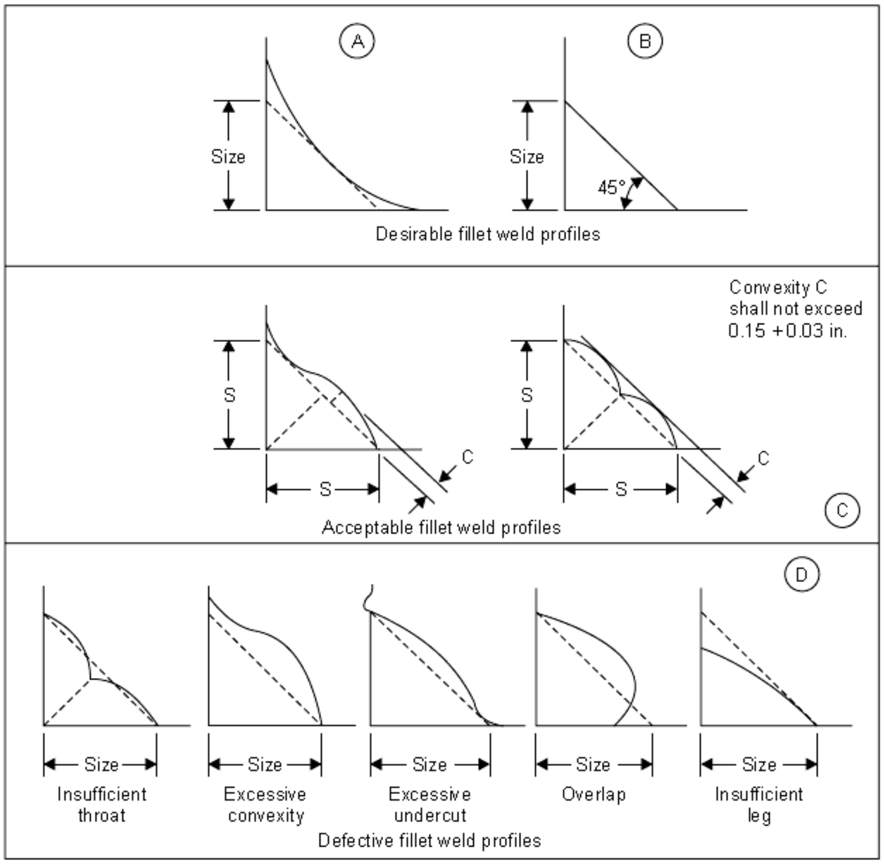


Fig. 3.5 Desirable, acceptable, and defective fillet weld profiles

3.3. CORROSION

Different types of corrosion common in metals and alloys are shown in Fig. 3.6. Some of these are related to welds. Their causes and remedies will be briefly discussed in the following paragraphs.

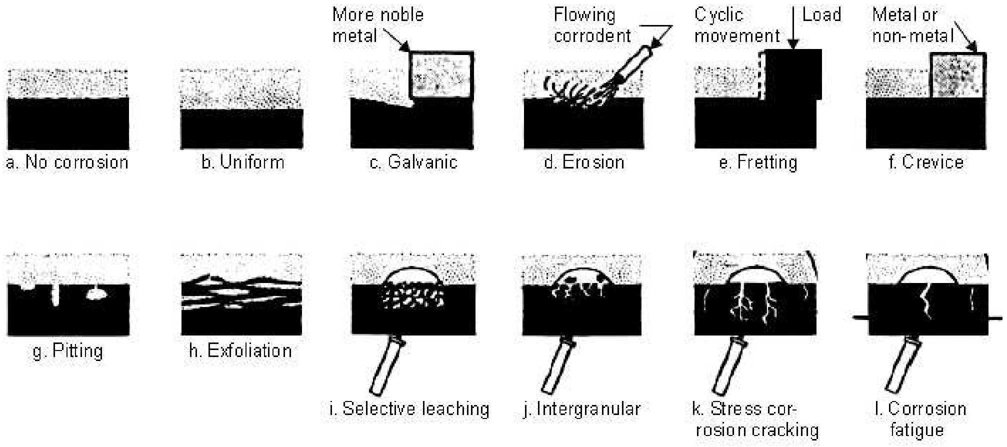


Fig. 3.6 Types of corrosion commonly found in metals and alloys

3.3.1. Galvanic Corrosion

This corrosion occurs when two metals in contact are exposed to a conductive medium. The electrical potential difference acts as a driving force to corrode one of the metals in the couple as electric current flows. **Active** metals corrode more than the **noble** metals.

Galvanic corrosion can occur in welds when the filler metal is of different composition than the base metal. It may occasionally occur because of cast weld metal and wrought base metal. Comparatively larger area of the noble compared to active metal will accelerate the attack. This situation is shown in Fig. 3.7.

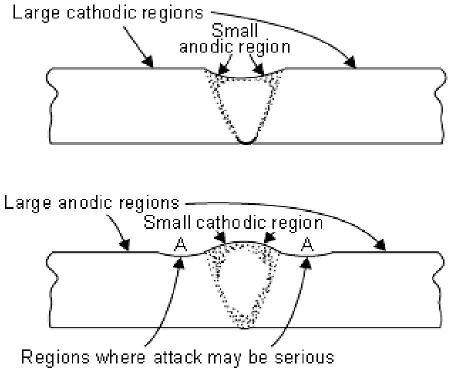


Fig. 3.7 Galvanic corrosion in welded joint, Top: weld metal less noble than base metal, Bottom: weld metal more noble than base metal

3.3.2. Crevice Corrosion

In a crevice the environmental conditions may become more aggressive with time as compared to the nearby open surface. Crevices in welded joints may occur in various ways: surface porosity, cracks, undercuts, inadequate penetration and design defects. Some materials are more susceptible to it than others. Materials that form oxide film for protection *e.g.*, aluminium and stainless steel are such examples. These materials may be alloyed to change their behaviour, together with designing to minimize crevices and maintenance to keep surfaces clean are some of the ways to combat the problem.

3.3.3. Intergranular Corrosion

The atomic mismatch at the grain boundaries makes it a favoured place for segregation and precipitation. Corrosion generally occurs because the corrodent prefers to attack regions that have lost an element that is necessary for adequate corrosion resistance. Susceptibility to intergranular attack is usually a by product of a heat treatment for example chromium carbides precipitate at the grain boundaries when the steel is heated to 650°C. This results in intergranular corrosion in a band array from weld where the temperature reached is 650°C. This problem can be avoided by post weld annealing.

3.3.4. Stress Corrosion

A combination of tensile stress and corrosive medium gives rise to cracking of a metal. Many alloys are susceptible to this attack, but fortunately the number of alloy-corrodent combinations that cause it are relatively few. Stresses that cause this arise from residuals stresses due to cold work, welding, thermal treatment and may be due to externally applied forces during assembly and service. Cracks may follow intergranular or transgranular path. There is a tendency of crack branching. The following list gives some characteristics of stress corrosion cracking:

(*a*) Stress corrosion requires a tensile stress. Below a threshold stress cracks do not occur.

(*b*) Cracking appears macroscopically brittle even though the material may be ductile in the absence of corrodent.

(*c*) Stress corrosion depends on metallurgical conditions of the alloy.

(*d*) In a given alloy a few specific corrodents cause cracking.

(*e*) Stress corrosion may occur in environments otherwise mild for uniform corrosion.

(*f*) Long time periods (often years) may pass before cracks become visible. The cracks then propagate fast and may cause unexpected failure.

(*g*) Stress corrosion is not yet understood in most cases, although there is now a large amount of data to help avoid this problem.

Methods of fighting stress corrosion problem include: stress relieving, removing critical environmental species or selecting a more resistant material.

3.3.5. Factors Affecting Corrosion Resistance of Welded Joints

1. Metallurgical structure composition of base-metal and weld-metal.
2. Thermal and mechanical treatment history before welding.
3. Welding process.
4. Welding procedure (manual, automatic, number of passes, welding speed, current and voltage.
5. Shielding gas composition and flow rate.
6. Size and geometry of weld deposit.

While reporting corrosion data for a welded joint, the items in the above list should also be reported.

The most common corrosion resistance evaluation method is to measure the weight lost during exposure to corrodent and convert it to an average corrosion rate using the formula

$$R = \frac{KW}{ADT}$$

where R = corrosion rate in depth of attack per unit time
K = constant (value depends on units used)
W = the weight lost by the specimen during the test
A = total surface area of the specimen
D = specimen material density
T = duration of the test.

The above formula suits well to the conditions shown in Figs. 3.8*a*, 3.8*b*, 3.8c. For Figs. 3.8*d* and 3.8*e*, the selective corrosion may be significantly large without resulting in a large amount of weight loss. This may cause error in finding average corrosion rate.

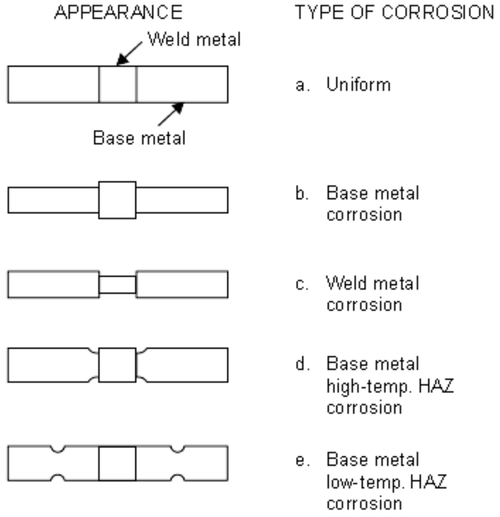


Fig. 3.8 Types of corrosion in a welded joint

3.4. MECHANICAL TESTING

A number of mechanical properties are used to characterize welds, including strength, ductility, hardness, and toughness. In general, the same samples and procedures are used in other areas of metallurgy. However, a prominent concern regarding the mechanical performance of welds is the direct comparison with base material. The goal is to ensure that the weld is not the weakest component of a structure, or if it is, to compensate for this in the design.

Strength. Yield and tensile strength are measured for all-weld-metal specimens using a standard tensile test (Ref 18), but with specimens removed from test plates welded according to AWS-specified procedures (Ref 19). These tests form the basis for the assignment of yield and ultimate strength values to welds made using a specific electrode and according to a set procedure. Additional tests are sometimes performed to compare the base metal and weld metal strengths. An example of this type of test is the transverse tensile test, in which the specimen is removed from the weld so that the loading axis is perpendicular to the weld bead and the weld reinforcement is left intact. The goal of this test is to verify that overload failure will occur in the base metal rather than in the weld metal or HAZ.

Ductility is another critical weld property. In addition to defects, many welding processes can produce hard, brittle microstructures. The standard measures of ductility--percent reduction in area and percent elongation--are obtained in a uniaxial tensile test. Another test often specified for welds is a bend test (face bends, roof bends, and side bends). In this test, a strip of material containing a weld is deformed around a specified radius and its surface is examined. The criteria for success or failure are the number and size of defects seen on the outer surface of the bend. An example of bend test criteria is the AWS *Structural Welding Code*, which calls for bending around a 19 mm (0.75 in.) radius for materials with yield strengths less than or equal to 345 MPa (50 ksi), a 25 mm (1 in.) radius for 345 to 620 MPa (50 to 90 ksi) materials, and a 32 mm (1.25 in.) radius for materials with yield strengths greater than or equal to 620 MPa (90 ksi).

Hardness. One common use of hardness values in weld specifications is as a check for the formation of microstructures that might have low ductility and toughness and thus are prone to cracking. For example, in pipeline steels, the formation of martensite in the HAZ is a cause for concern because of the potential for cracking. This is addressed by specifying maximum values for microhardness traverses across several sections of the weld. Hardness values are also used as an indicator of susceptibility to some forms of stress-corrosion cracking.

Toughness is the ability of a material to absorb energy during fracture. There are two approaches to toughness testing: impact toughness testing and fracture mechanics testing.

Impact Toughness Testing. To test impact toughness, a sample of specified geometry is subjected to an impact load, and the amount of energy absorbed during fracture is recorded. Usually the specimen is oriented so that the notch and expected plane of fracture run longitudinally through the weld metal. Charpy tests do not measure an inherent material property, but they result in a relative measure of impact toughness between materials. A very common use of the Charpy test is to determine a material's ductile-to-brittle transition temperature by performing tests at several different temperatures. AWS A5.1 (Ref 19) gives minimum Charpy impact values, at several temperatures, for welds made on carbon steel using a number of different electrodes.

Fracture Mechanics Testing. The second type of toughness testing is based on fracture mechanics, and it can use either linear elastic or elastic-plastic methodologies. Although elastic-plastic behavior (J_{Ic}) is becoming of interest in some cases, the bulk of fracture mechanics testing is based on linear elastic considerations. These tests, using specimens and procedures given in ASTM E 399 (Ref 20), are used to measure a material's fracture toughness (K_{Ic}), which is a material property. In the case of welding, fracture toughness is usually expressed using a value for crack tip opening displacement. Fracture toughness testing has only recently begun gaining acceptance as applicable to welds. The major shortcomings of this approach include the complexity and cost of testing and the wide variability in fracture toughness values for weld metal, due largely to the inhomogeneous nature of welds and residual stress effects.

3.4.1. Weld Tension Tests

The tension test for welds is not like that for the base metal because the weld test section is heterogeneous in nature containing base metal, heat affected zone and weld metal. To obtain correct assessment of the strength and ductility several different tests have to be carried out, using different specimens shown in Fig. 3.9 The following tests are commonly carried out.

All Weld-metal tension test. Specimen locations are shown in Fig. 3.9 The details of the specimen dimensions are shown in Fig. 3.10

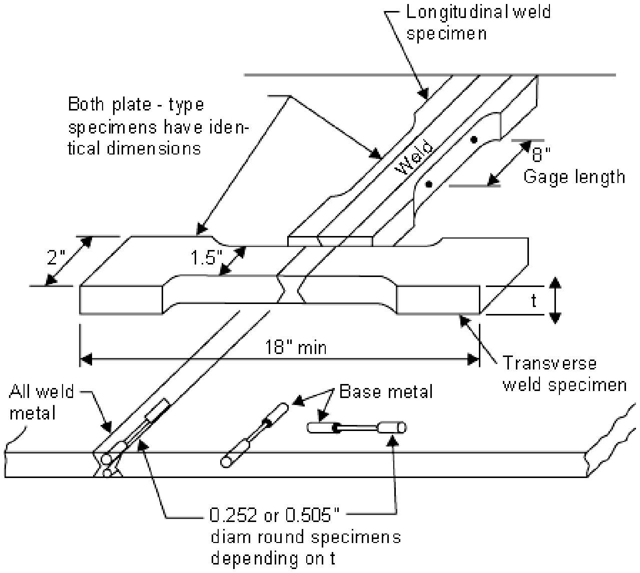
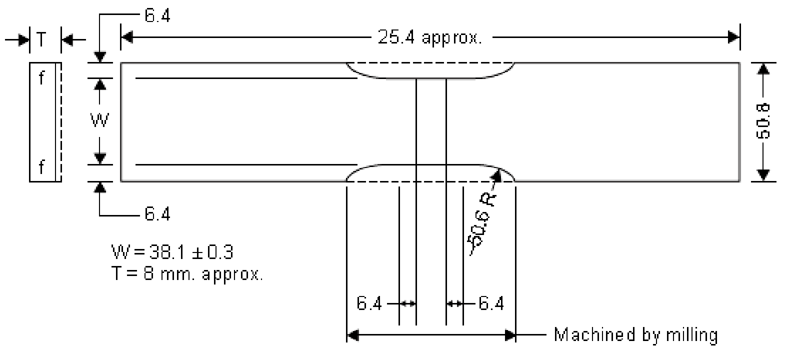


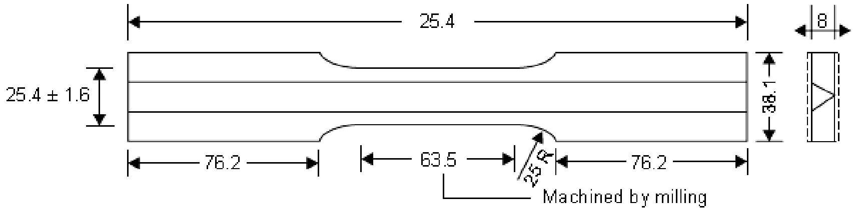
Fig. 3.9 Typical test specimens for evaluation of welded joint (inch)

Transverse butt-weld test. This test shows that the weld metal is stronger than base metal if the failure occurs in the base metal. It fails to give comparative idea about different types of electrodes. When the weld strength is lower than the base metal, the plastic strain occurs in the weld joint. Ultimate strength is thus obtained but no idea about the joint ductility is obtained from this test. Ideally there is no uniform straining within the specified gauge length and therefore, it is not possible to obtain a reliable measure of yield strength across a welded joint.

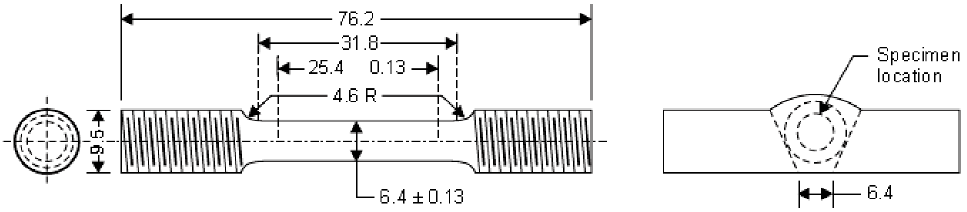
Longitudinal-butt-weld test. Here the loading is parallel to the weld axis. It differs from all-weld-metal test in that it contains weld, HAZ and base metal along the gauge length. All these zones must strain equally and simultaneously. Weld metal elongates with the base metal until failure occurs. This test thus provides more information about the composite joint than the transverse test specially when base metal and weld-metal strengths differ significantly.



(a) Transverse-weld tension specimen



(b) Longitudinal-weld tension specimen



(c) All weld metal tension specimen

Fig. 3.10 Tension test specimens (mm)

3.4.2. Tension Tests for Resistance Welding

Tension-Shear Test. The tension-shear test is the most widely used method for determining the strength of resistance spot welds. It is also used for evaluation of weld schedules for ferrous and nonferrous alloys. The test specimen in Fig. **3.11** is made by overlapping suitable size coupons and making a spot weld in the center of the overlapped area. A tensile test machine is used to make the test.

The test is used mainly to establish ultimate shear strength when the specimen is tested in tension. When this test is used in combination with the cross-tension test (Fig. **3.12**), the cross-tension strength/tension-shear strength ratio is referred to as a measure of ductility.

When gages less than about **1** mm (0.04 in.) are tested, a plug will usually be pulled from one sheet. This condition is typical of the fracture due to the eccentric loading caused by the overlapped sheets. As the thickness of the sheets or strength increases, the weld will fracture by shearing across the nugget (weld metal) at the interface.

When the thickness becomes large such as 4.8 mm (0.19 in.) and greater, the wedge grips of the test machine should be offset to reduce the eccentric loading which is accentuated by the thickness of the specimen. A more precise shear load will be imposed on the spot weld, thus minimizing a tension or peeling component.

The tension-shear test is commonly used in production assurance testing because it is an easy and inexpensive test to perform. Coupons welded at regular intervals are tested to a prior established standard of test results.

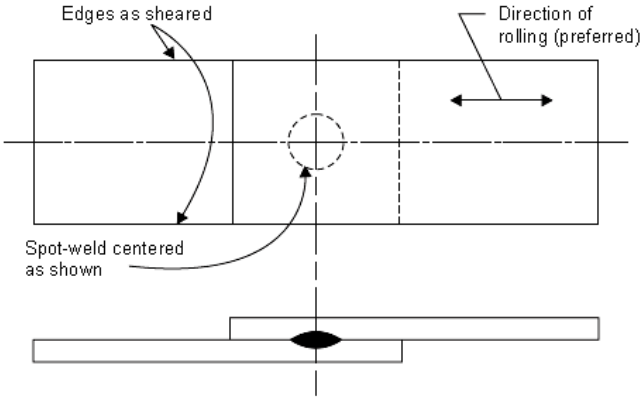
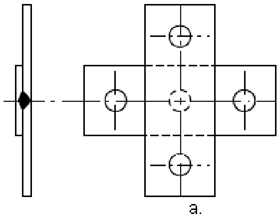
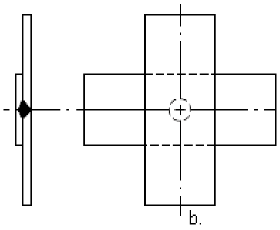


Fig. 3.11 Test specimens for tension shear of Resistance Welding



Thickness up to 4.8 mm (0.19 in.)



Thickness over 4.8 mm (0.19 in.)

Fig. 3.12 Cross-tension test of Resistance Welding

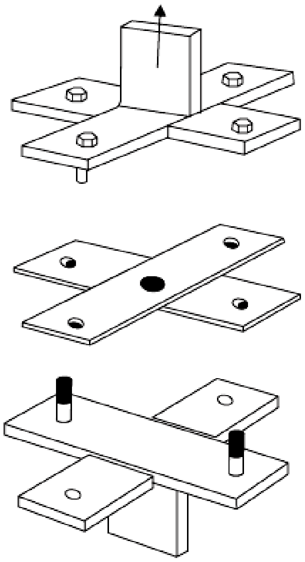


Fig. 3.13 Test jig for cross-tension specimens

The reader is directed to Recommended Practices for Resistance Welding. AWS C1.1, for more details with respect to test specimen dimensions and test fixtures as well as statistical methods for evaluating resistance weld test results. This publication is also applicable for the direct-tension test described in the next section.

Direct-Tension Test. The direct-tension spot weld test is used to measure the strength of welds for loads applied in a direction normal to the spot weld interface. This test used mostly for weld schedule development and as a research tool for the weldability of new materials. The direct-tension test can be applied to ferrous and nonferrous alloys of all thicknesses. The direct-tension test specimen is used to determine the relative notch sensitivity of spot welds.

There are two types of specimens used for the direct-tension test. The cross-tension specimens of Fig 10.5 can be used for all alloys and all thicknesses. When the metal gage is less than 1 mm (0.04 in.), it is necessary to reinforce the specimen to prevent excessive bending. Test jig for cross-tension specimens is shown in Fig. **3.13** for thicknesses up to 4.9 mm and Fig. **3.14** for greater thicknesses.

Peel Test. A variation of the direct-tension test is the peel test which is commonly used as a production control test. The test is shown in Fig **3.14(b)** The size of the plug or button is measured or correlated with weld sizes having known strengths that are produced by satisfactory production weld schedules. This weld test is fast and inexpensive to perform. Howerver, high strength or thicker specimens may fracture at the interface without producing a plug.

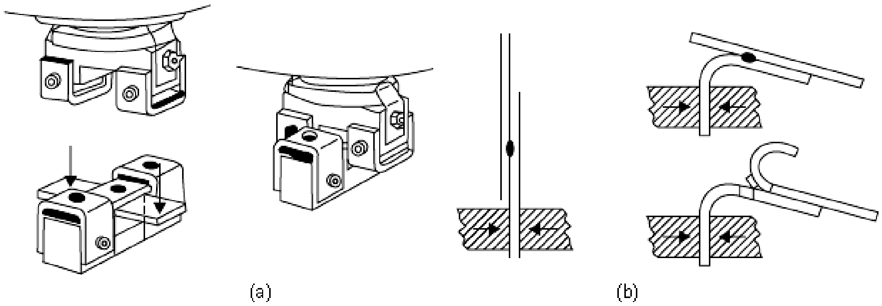


Fig. 3.14 Test jig for cross-tension specimens (t>4.8 mm)

3.4.2. Bend Tests

Bend tests on corner, but, lap and tee welds are shown in Fig. **3.15(a)**

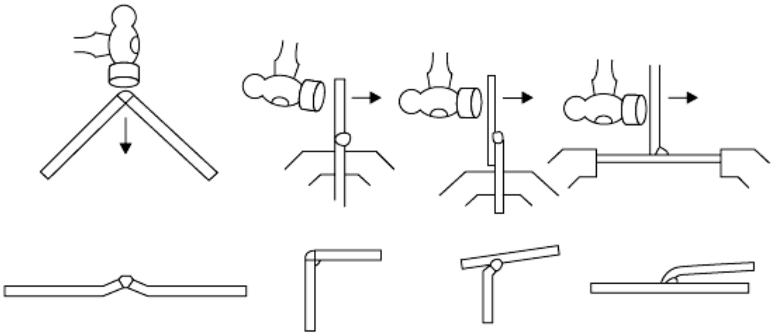
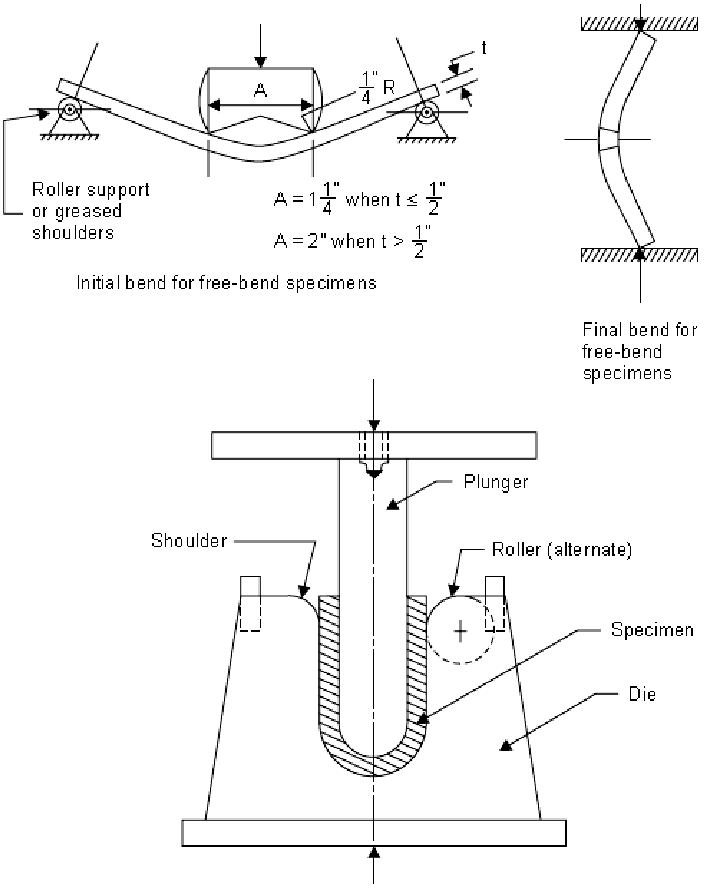


Fig. 3.15 (a) Bend tests



(b)

Fig. 3.15 (b) Typical fixtures for free bend testing (top) and guided bend (bottom)

3.5. METALLOGRAPHY OF WELDS

Generally, the weld is regarded as a junction between two or more pieces of metal in which their surfaces have to be raised to a plastic (e.g. friction welding) or liquid state by the application of heat with or without added metal and with or without the application of pressure. Each of these processes has their own unique characteristics e.g. penetration, speed of welding, slag generation, heat input, properties of weld, etc. and this in turn can have a considerable influence on the resultant microstructural detail. Fig 3.16 shows the various regions of weld and the possible defects. Consequently, any study on the effects of a particular welding process will require careful metallurgical examination of representative weld samples, irrespective of whether the objective is to examine the overall integrity of the weld or examine the microstructure/property relationship or to identify the nature and origin of defects. It follows then, that the accuracy of microstructural analysis and interpretation will depend on the production of prepared specimens, free from any artefacts which may have been introduced at any stage in the preparation process.

Two levels of metallographic inspection

The examination of metallographic sections through welded joints is commonly carried out at two levels of inspection:

Macro: Where magnifications up to 50x are employed with stereomicroscopes. Macro examination is commonly carried out on unmounted cross sections through welded joints and simply involves cutting and coarse/fine grinding techniques. The resultant finish is adequate for etching, followed by an examination of the macro features of the weld joint.

Micro: Where examination is at higher magnifications (up to 1000x) using optical microscopes. For micro examination techniques and hardness traverse, the provision of a polished, optically flat surface will be required. This involves cutting, mounting and grinding and polishing. One has to be aware from the outset, that artefacts can be introduced at any stage of the preparation process. This is particularly true of welded sections because not only do microstructural variations occur over relatively short distances but welds can also involve joints between dissimilar metals having widely different properties.

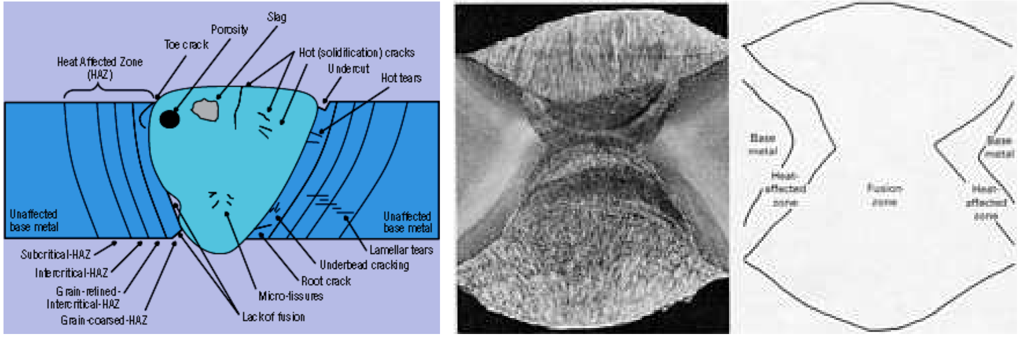
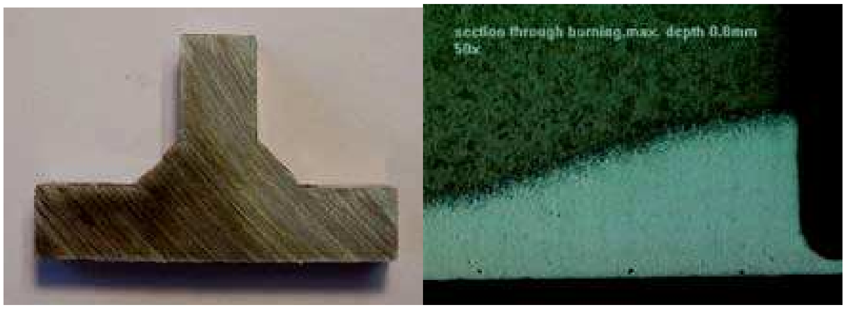


Fig 3.16 the various regions of weld and the possible defects.

3.5.1. Recommendations for the preparation of weld microsections.

Cutting

For most welder approval tests it is suggested that macro sections are cut in the transverse direction through weld stop/start positions. It is at these locations where any lack of skill on the part of the welder will result in the formation of weld defects. For weldability and other studies the section must be truly representative. Often, flame cutting is used as a primary cutting technique e.g. to remove a more manageable welded section from a larger fabrication. It is important in these cases that the macro/micro section is cut by an abrasive wet cutting process and is sectioned well away from the influence of any thermal damage from a primary thermal cutting operation. The introduction of any thermal damage during the cutting process (Fig. 3.17) must be avoided as it can alter the microstructure and properties in the welded joint. A thorough understanding of the preparation process is necessary to deal with the difficulties presented by the variations in the material properties in and across the welded joint, if flatness between microstructural features with different hardness values is to be achieved.



(a) (b)

Fig. 3.17 (a) Thermal damage on a steel weld. (b) Polished and etched transverse section shows depth to which thermal damage penetrates.

In order that deformation from cutting is minimized and the risk of thermal damage on the cut surface is avoided, it is important that:

- The correct type of abrasive cut-off wheel is selected.
- An appropriate feed speed is used.
- There is an adequate level of coolant supplied during cutting.

- The preparation method should be selected according to the material types of a weld and optimized to minimize the risk of relief between hard and soft phases in the weld, heat affected zone and parent material.

Mounting

Normally, macro sections for procedural testing are prepared unmounted because of time constraints, and because a finely ground finish is usually adequate for macro examination.

If semi-automatic preparation is an option, then there are a number of specimen holders which will accommodate unmounted cross sections from welded joints. If mounting is required then there is the option of hot compression mounting or cold mounting. It is not uncommon, however, in weld examination to have relatively large cross sections. In this case, section sizes up to 120 x 60 x 45 mm can be accommodated in Struers UnoForm, rectangular moulds for cold mounting (Fig. 3.18.).

Fig. 3.18. Rectangular mounts of various welds.

Macro sections

Traditionally, welded sections for macro examination are prepared manually on successively finer grades of silicon carbide paper to a 1200 grit finish. This is usually sufficient for hardness traverse through parent material, heat affected zone, and weld metal, as well as being suitable for macro etching to facilitate weld macro examination. Silicon carbide paper is limited in respect of its cutting life (1.0-1.5 mins) and this is exacerbated with increasing section size. As an alternative grinding/fine grinding media for manual preparation the Struers MD-Piano discs offer a number of advantages:

- A longer cutting life.
- A constant removal rate over a longer time period.
- Suitable for a wide range of materials hardness (HV150-2000).
- Less waste.

MD-Piano discs are resin bonded diamond discs which have been developed for coarse and fine grinding of materials in the hardness range HV150-2000 and they are available in comparable grain size to SiC-Paper 80,120, 220, 600, and 1200.

Micro sections

Weld specimens can involve wide variations in material hardness across the specimen either because of a phase changes during welding, or because the joint incorporates dissimilar metals. The weld metal may contain hard precipitates or some indigenous weld defect. As a consequence, it is important that the preparation method should ensure that polish relief between microstructural features is minimal and all microstructural elements are retained. In this respect, semiautomatic or automatic preparation equipment is preferred as it provides a consistency and reproducibility of polish which facilitates accurate microstructural analysis. Preparation methods for the wide range of welded materials which can be experienced cannot be covered in this document.

Etching

It is not uncommon, in shop floor production control applications, to find electrolytic polishing/etching being used as a method for obtaining prepared weld cross sections for macro examination. Here the sections are cut on an abrasive cut off machine, then after a single grinding stage, the specimens are electrolytically polished and etched to provide a section suitable for macro examination. The advantages of this technique are:

- Its speed.
- Its ease of operation.
- Minimizes user contact with acidic etchants.
- A more suitable option for a wide range of stainless steel types and other metals difficult to etch just chemically.

For applications where detailed microstructural analysis is required the specimens for electrolytic polishing and etching should be ground to 1000 grit.

Some of the more common chemical and electrolytic etching reagents for welded joints in a variety of materials are listed in Table 3.1 below.

Table 3.1 Chemical and electrolytic etching reagents for welded joints

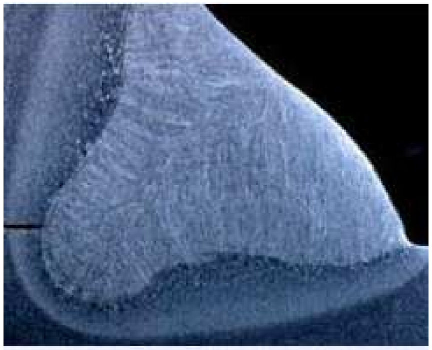
Material	Etchant	Comment
Carbon and low alloy steels	100 ml ethanol (95%) or methanol (95%) 1-5 ml nitric acid (Nital)	Good general purpose reagent; can be increased to 15 ml nitric acid for macro etching.
	100 ml distilled water 10 g ammonium persulphate	Good macro etching
Stainless steels	480 ml distilled water 120 ml hydrochloric acid (32%) 50 g iron (III) choride,	Macro etching
	100 ml distilled water 10 g oxalic acid	Electrolytic etching 4-6 volts for a few secs.
	100 ml distilled water 5 ml sulphuric acid (95-97%)	Electrolytic etching 2-4 volts for a few secs
Nickel alloys	100 ml distilled water 5 ml sulphuric acid (95-97%)	Electrolytic etching 3-6 volts for a few secs.
Copper alloys	100 ml distilled water 10 ml ammonium hydroxide (25%) with a few drops of aqueous hydrogen peroxide (3%)	Use freshly made
Aluminium alloys	100 ml distilled water 15 g sodium hydroxide	Macro etching

3.5.2. Metallography.

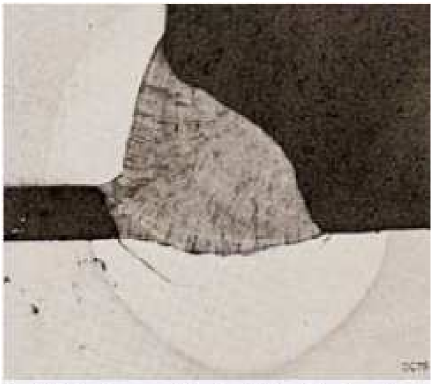
Macro sections

Etched macro sections allow the identification of the boundaries of the weld metal, heat affected zone, fusion boundary, grain growth and the individual runs in multi-run welds. In addition weld defects such as cracks, pores/voids, lack of fusion, and lack of penetration can be identified. Fig 3.18 is given for examples of macro sections.

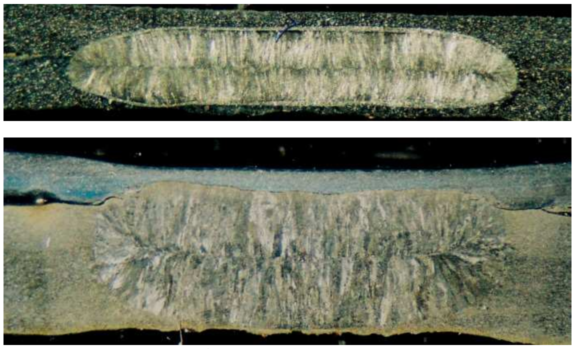
Polished and colour etched section through a multi pass austenitic stainless steel weld. Colour etched according to Lichtenberger and Bloech. Bright field, 6.5x.



Macro section through deep penetration fillet weld in carbon steel. Section was etched with 5% Nital. Bright field, 2.5x.



Heat affected zone crack below fillet weld in low alloy steel. Bright field, 5x.



Macro section of spot welded similar SUS304 and dissimilar SUS304-SS400

Fig 3.18 Examples of macro sections

Micro sections

Some of the more common metallographic tests carried out on welded joints are detailed below:

Area fraction of a constituent – identification of individual phases and determination of area fraction by point counting, e.g. deltaferrite in austenitic stainless steel welds (Fig. 3.19).

Grain size / grain size measurements of grain coarsened / grain refined regions in weld metal and heat affected zone (Fig. 3.20).

Microstructure type / morphology / identification of microstructural transformation products in weld metal and heat affected zone (Fig. 3.21)

Defect analysis / identification and characterization of indigenous weld defects (Fig. 3.22).

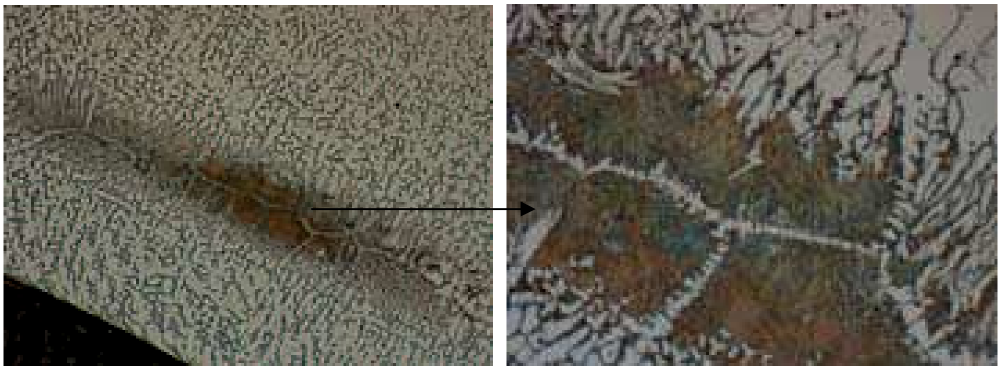


Fig 3.19 Islands of delta ferrite and small area of pearlite in austenitic stainless steel weld

Hardness survey - normally a hardness / microhardness traverse across parent material heat affected zone and weld metal is carried out to ensure whether weld and heat affected zone properties are satisfactory (Fig.3.23).

Fig 3.20 Aluminum weld showing assortment of microstructures in weld, base metal and heat affected zone. Etchant: 100 ml distilled water +2 ml hydrofluoric acid. Bright field, 100x.

Fig 3.21 Heat affected zone in duplex stainless steel weld. Etched electrolytically with 40% aqueous sodium hydroxide solution. 200x.

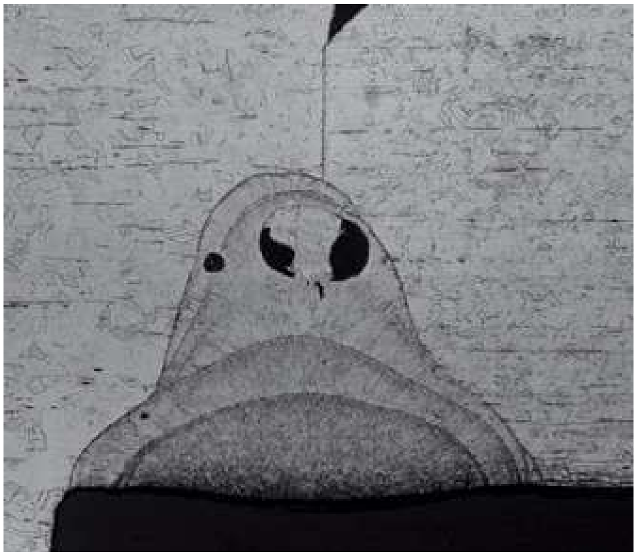


Fig 3.22 Pores in an austenitic stainless steel weld. 100x.

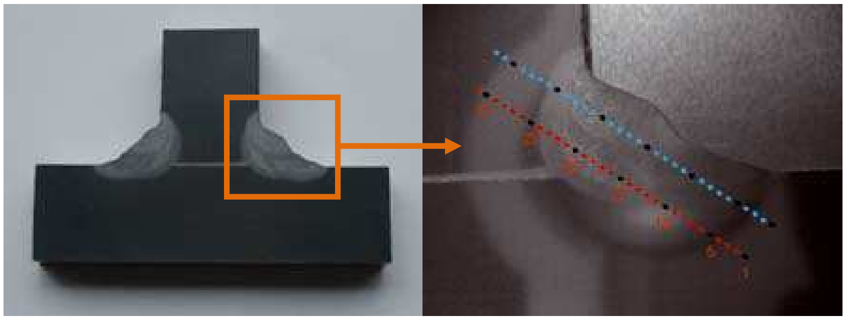


Fig 3.23 Weld with hardness indentations.

3.6. NON DESTRUCTIVE TEST OF WELDS

Non-destructive tests of weld commonly used in industries are summarised in Table 3.2 . They include Visual examination, Dye-penetrant inspection, Magnetic-particle inspection. Radiography and ultrasonics. The last three tests are more common and will be described in the following paragraphs.

Table 3.1 Summary of the methods of non-destructively testing weld

Method	*Defects detected*	*Advantages*	*Limitations*
Visual	Inaccuracies in size and shape. Surface cracks and porosity, undercut, overlap, crater faults.	Easy to apply at any stage of fabrication and welding. Low cost both in capital and labour.	Does not provide a permanent record. Provides positive information only for surface defects.
Dye-penetrant	Surface cracks which may be missed by naked eye.	Easy to use. No equipment required. Low cost both in materials and labour.	Only surface cracks detected with certainty. No permanent record.
Magnetic-particle	Surface cracks which may be missed by naked eye. May give indication of subsurface flaws.	Relatively low cost. Portable. Gives clear indication.	Only surface cracks detected with certainty. Can be used only on ferromagnetic metals. Can give spurious indications. No permanent record.
Radiography	Porosity, slag inclusions, cavities, and lack of penetration. Cracks and lack of fusion if correctly orientated with respect to beam.	Can be controlled to give reproducible results. Gives Gives permanent record.	Expensive equipment. Strict safety precautions required. Better suited to butt joins - not very satisfactory with fillet-welded joints. Requires high level of skill in choosing conditions and interpreting results.
Ultrasonics	All sub-surface defects, Laminations.	Very sensitive - can detect defects too small to be discovered by other methods. Equipment is portable. Access required to only one side.	Permanent record is difficult to obtain. Requires high level of skill in interpreting cathode-ray-tube indications.

3.6.1. Magnetic Particle Inspection

Magnetic particle inspection, as the name implies, requires the use of a magnetic field. The work to be checked must be able to accept magnetism. This process is therefore limited to magnetic metals. It is also limited to surface or near-surface faults. Steel castings, forgings, and sections that have been welded are the most common parts to be inspected by the magnetic particle process. There are several variations of this process.

Longitudinal Magnetization

By using a coil it is possible to include a magnetic field in a part that has the lines of force running through the length of the shaft as seen in Fig. **3.24**.

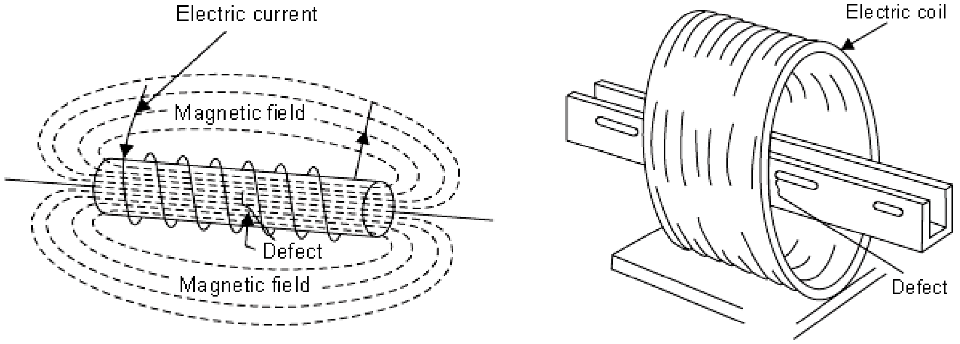


Fig 3.24 Longitudinal Magnetic Inspection.

3.6.2. Radiographic Inspection

Radiography uses X-rays or gamma rays, which have the ability to penetrate materials that absorb or reflect ordinary light. X-rays are created under controlled conditions by bombarding a specific area with a flow of electrons. Gamma rays are produced by radioactive isotopes. These isotopes never stop giving off radiation; therefore, they must be stored in special shielded containers.

The ability of a material to absorb radiation is dependent upon its density and the wavelength of radiation being used. Lead absorbs more radiation than iron and iron absorbs more than aluminium. This absorption of radiation also varies with the thickness of a piece of material. A thinner piece of material will absorb less radiation as the rays pass through the object; therefore, more radiation will escape through the object. A film placed behind the object to be inspected will be affected more in thin sections than thick sections. Defects in the part being examined will allow more radiation to pass through it and the defect will then be visible on the film.

A radiograph is the recorded image produced on a photographic plate by X-ray. A simplified version of the process is shown in Fig. **3.25** The flaw in the specimen will not absorb as much radiation as does the rest of the part. Therefore, a darker image is present on the film where the flaw exists.

One of the most important facts to remember when working in the area where X-ray or gamma ray equipment is being used is that this process is very dangerous. If excessive radiation is absorbed by the body, sickness and even death can be the result.

The X-ray inspection process has become a very common method of inspection in industry today. Aircraft inspection of major sections of the aircraft are successfully accomplished by X-ray. The pipeline industry is very dependent upon the X-ray process to ensure that each weld on the pipe is sound.

The pipeline industry uses X-ray units that will swing completely around the circumference of a weldment on the pipe. On completion of the travel around the pipe, complete picture of that entire weld is presented on the radiogram (X-ray film). The films are maintained as a permanent record of the inspection. They are numbered to identify each weld on an entire pipeline and may be referred to at a later date if a breakdown of the pipe occurs.

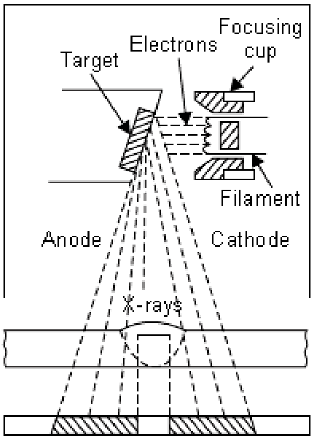


Fig 3.25 Operation of an X-ray device.

3.6.3. Ultrasonic Inspection

Ultrasonic Inspection makes use of the science of acoustics in frequencies above the upper audible limit of approximately 15,000 cycles per second.

The basic operation of ultrasonic inspection is the conversion of pulsating electronic waves into ultrasonic sound. These sound waves are introduced into the material to be tested through a quartz crystal. The crystal is set into a special search unit that not only sends out the sound but also acts as a receiver to accept reflections of that sound on its return. If the signal sent out runs into a defect in the material, a return signal comes back to the receiver in less time than it would have had it travelled the full distance to the other side of the part and back.

A cathode ray tube (CRT) is incorporated in the ultrasonic equipment to provide a visual indication on the screen of the initial signal and reflected signals. Fig 10.24 shows a diagram of the CRT screen with pips of the initial pulse, discontinuity, and back surface reflection. Fig. 3.26 shows the basic cathode ray tube construction.

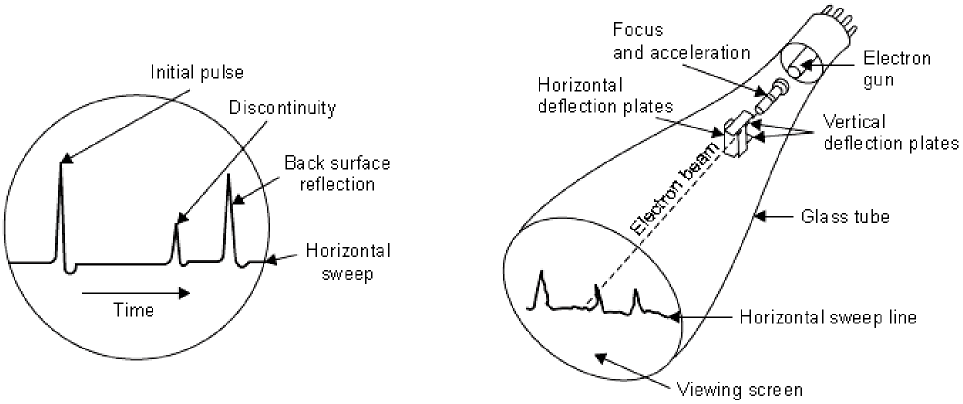


Fig 3.26 Cathode ray tube and cathode tube construction.

The pulses that are sent out by the quartz crystal may span a time of two millionths of a second or less and may vary in cycles of transmission from 60 to 1000 times per second. The return signals, shown as pips on the CRT, will be spaced in proportion to the distance between the points in the material they represent. For example, a pip representing a defect close to the back surface reflection indicates a defect that is close to the far edge of the part being inspected.

As with all electronic non-destructive testing methods, a considerable amount of skill is required to operate the ultrasonic inspection unit. As is the case with many skilled tasks, technique, practice, and experience determine the efficiency with which the inspection is completed. This inspection method is becoming more useful in the welding industry as new techniques for scanning welds are being perfected.

■ QUESTIONS

10.1 Briefly discuss the necessity of conducting destructive testing of welds. Why standard specimen are used for testing? State the basic considerations in choosing a test of mechanical properties.

10.2 What tests do you suggest to determine the strength and ductility of a welded joint? Why several different tests are carried out to determine correct strength and ductility of a welded joint?

10.3 With neat sketches explain the weld-tension tests all weld-metal tension test, transverse butt-weld test, longitudinal butt-weld-test.

10.4 With meat sketches explain the various types of tension shear tests for fillet welds.

10.5 With neat sketches discuss the various tests carried out to assess the strength properties of spot welds. What is cross-tension test? How is it carried out?

10.6 Explain the difference between free bend and guided bend tests. How their specimen are prepared. Differentiate between root-bend and face-bend specimen, pipe root and face bend and plate root and face bend tests. How their specimen are prepared?

10.7 Name the tests commonly used for the inspection of welds. For each test summarise the defect it detects, its advantages and limitations.

10.8 With neat sketches describe briefly the following non-destructive tests:

(*a*) Magnetic particle inspection

(*b*) Radiographic inspection

(*c*) Ultrasonic inspection.