WELDING PROCESSES

Physics of Welding

Power density

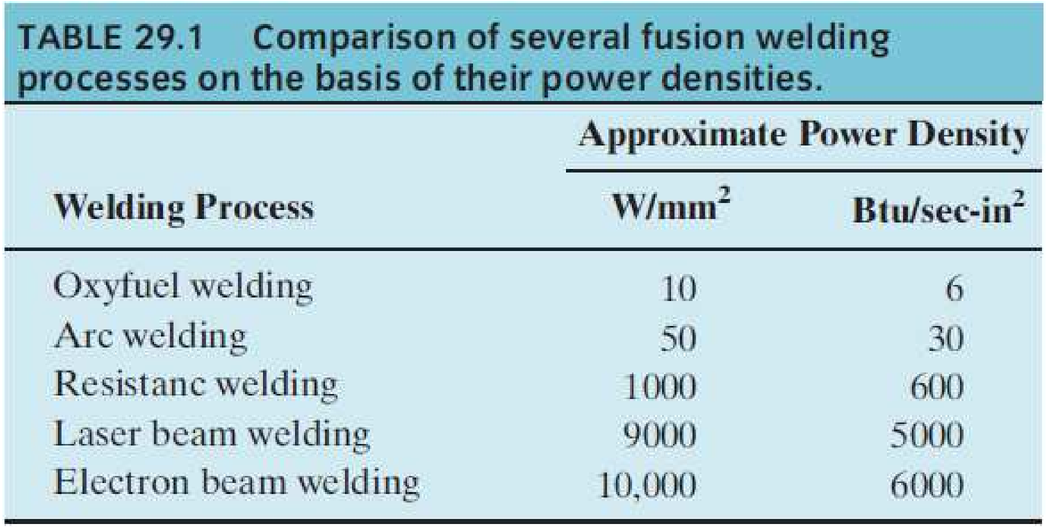
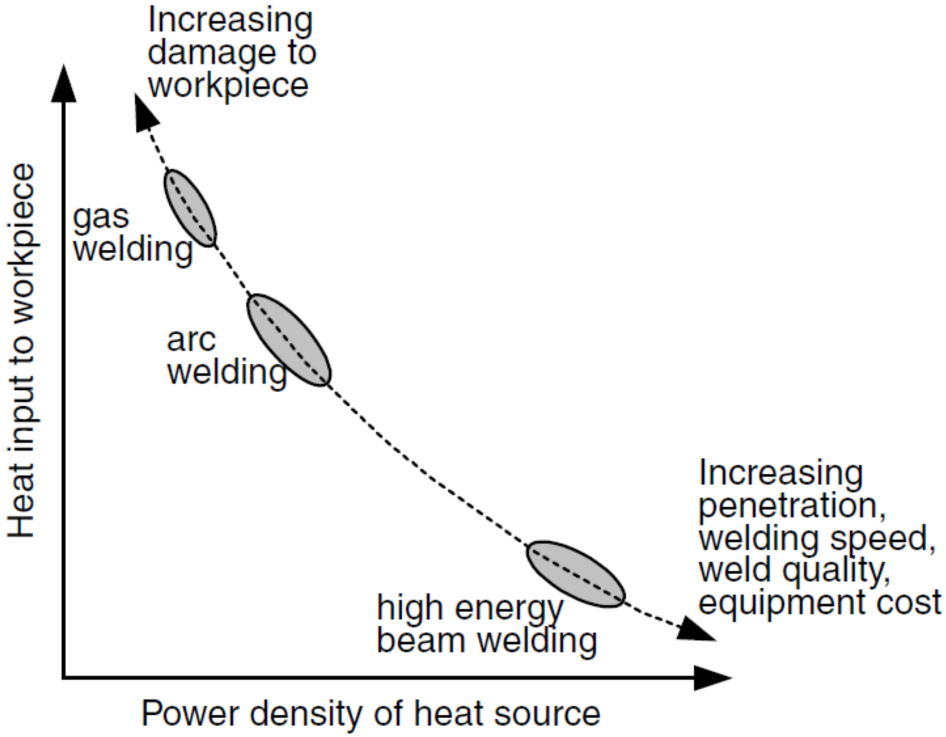


TABLE 29.1 **Comparison of several fusion welding processes on the basis of their power densities.**

Welding Process	**Approximate Power Density** **W/mm²**	 **Btu/sec-in²**
Oxyfuel welding	10	6
Arc welding	50	30
Resistanc welding	1000	600
Laser beam welding	9000	5000
Electron beam welding	10,000	6000

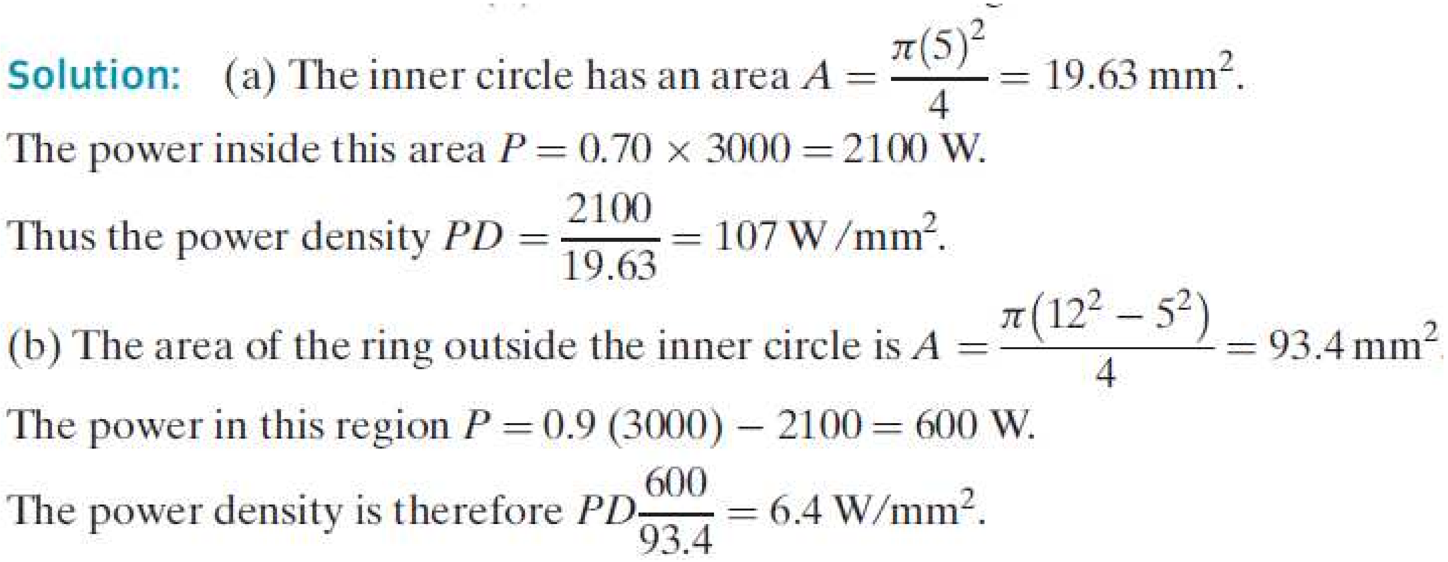
$$PD = \frac{P}{A}$$



Variation of heat input to the workpiece with power density of the heat source.

Example

A heat source transfers 3000Wto the surface of a metal part. The heat impinges the surface in a circular area, with intensities varying inside the circle.The distribution is as follows: 70% of the power is transferred within a circle of diameter¼5mm, and 90%is transferred within a concentric circle of diameter ¼ 12 mm. What are the power densities in (a) the 5-mm diameter inner circle and (b) the 12-mm-diameter ring that lies around the inner circle?



Solution: (a) The inner circle has an area $A = \frac{\pi(5)^2}{4} = 19.63\ \text{mm}^2$.

The power inside this area $P = 0.70 \times 3000 = 2100$ W.

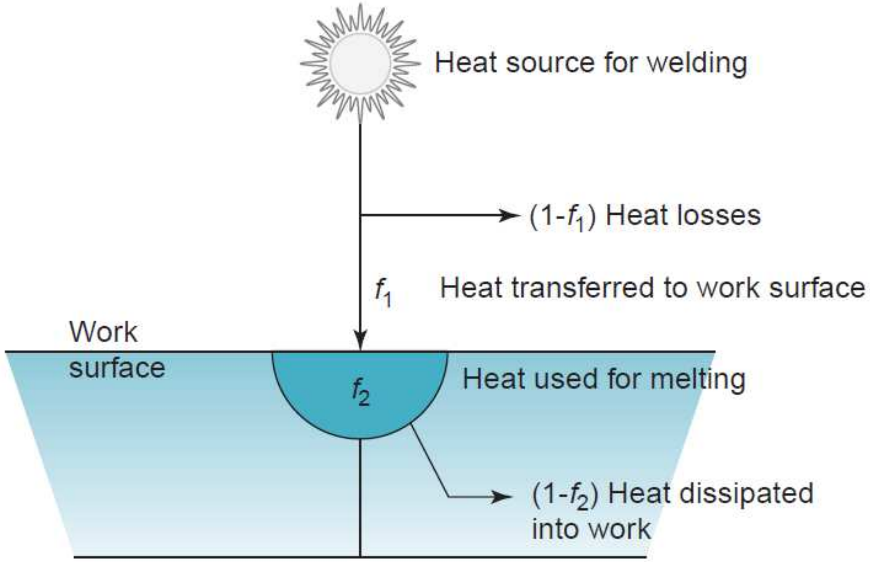
Thus the power density $PD = \frac{2100}{19.63} = 107\ \text{W/mm}^2$.

(b) The area of the ring outside the inner circle is $A = \frac{\pi\left(12^2 - 5^2\right)}{4} = 93.4\ \text{mm}^2$

The power in this region $P = 0.9\ (3000) - 2100 = 600$ W.

The power density is therefore $PD\frac{600}{93.4} = 6.4\ \text{W/mm}^2$.

Physics of Welding



Heat transfer mechanisms in fusion welding.

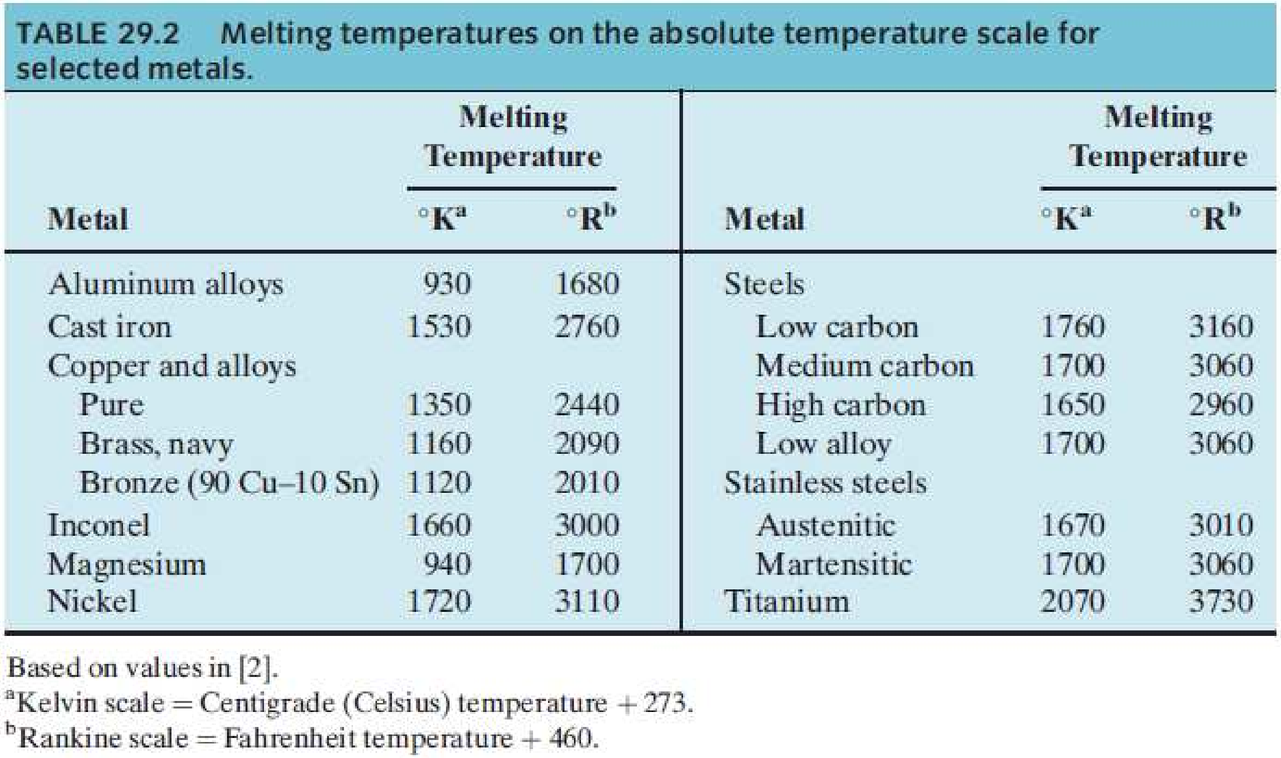


TABLE 29.2 Melting temperatures on the absolute temperature scale for selected metals.

	Melting Temperature			Melting Temperature	
Metal	**°K[a]**	**°R[b]**	**Metal**	**°K[a]**	**°R[b]**
Aluminum alloys	930	1680	Steels		
Cast iron	1530	2760	Low carbon	1760	3160
Copper and alloys			Medium carbon	1700	3060
Pure	1350	2440	High carbon	1650	2960
Brass, navy	1160	2090	Low alloy	1700	3060
Bronze (90 Cu–10 Sn)	1120	2010	Stainless steels		
Inconel	1660	3000	Austenitic	1670	3010
Magnesium	940	1700	Martensitic	1700	3060
Nickel	1720	3110	Titanium	2070	3730

Based on values in [2].

[a] Kelvin scale = Centigrade (Celsius) temperature + 273.

[b] Rankine scale = Fahrenheit temperature + 460.

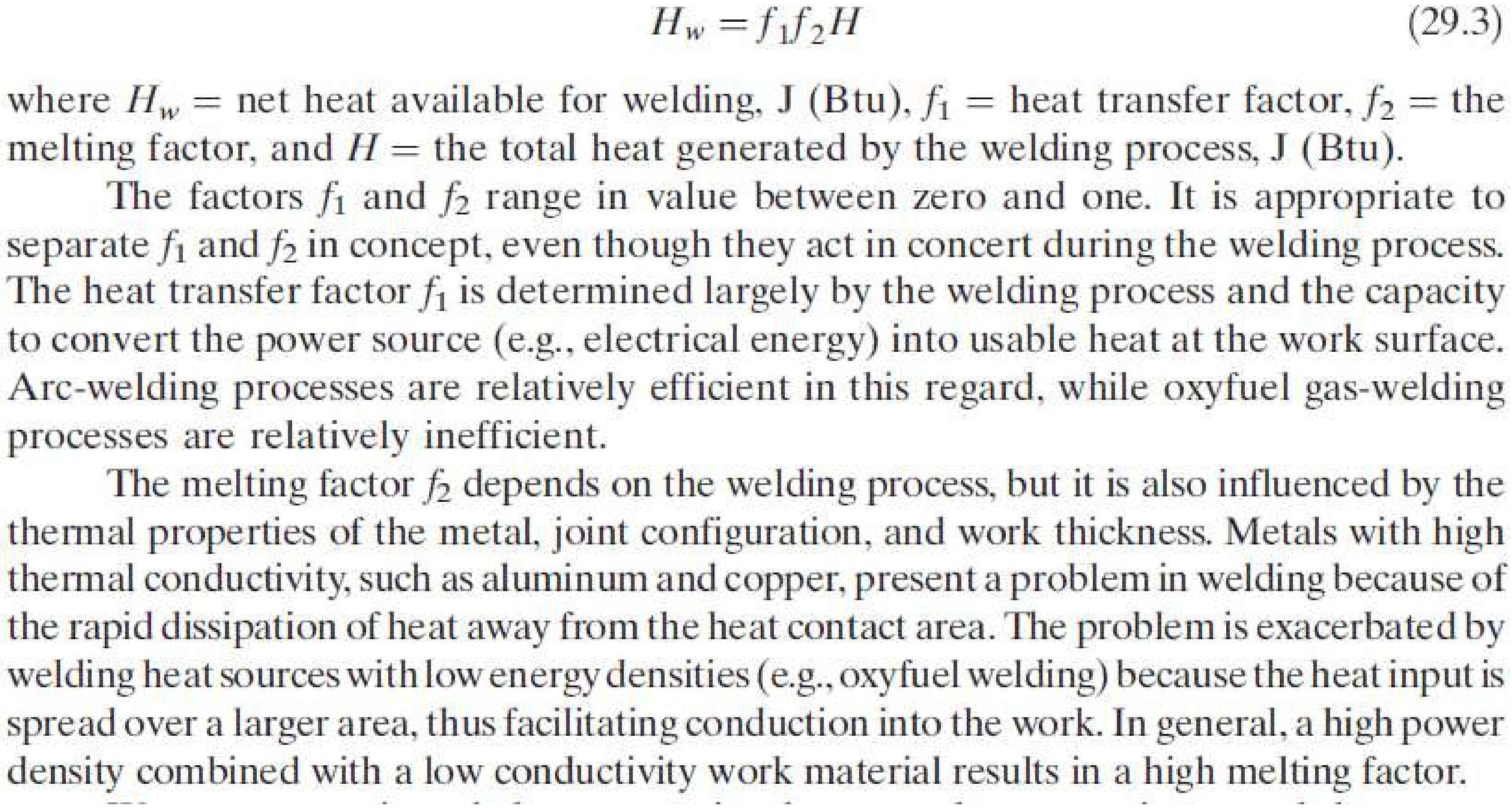
HEAT BALANCE IN FUSION WELDING

- The quantity of heat required to melt a given volume of metal depends on (1) the heat to raise the temperature of the solid metal to its melting point, which depends on the metal's volumetric specific heat, (2) the melting point of the metal, and (3) the heat to transform the metal from solid to liquid phase at the melting point, which depends on the metal's heat of fusion. To a reasonable approximation, this quantity of heat can be estimated by the following equation

$$U_m = KT_m^2$$

- where Um ¼ the unit energy for melting (i.e., the quantity of heat required to melt a unit volume of metal starting from room temperature), J/mm3 (Btu/in3); Tm ¼ melting point of the metal on an absolute temperature scale, °K(°R); and K=constant whose value is $3.33 \mathrm{x} 10^{-6}$ when the Kelvin scale is used (and K = $1.467 \mathrm{x}\ 10^{-5}$ for the Rankine temperature scale). Absolute melting temperatures for selected metals are presented in Table 29.2

HEAT BALANCE IN FUSION WELDING



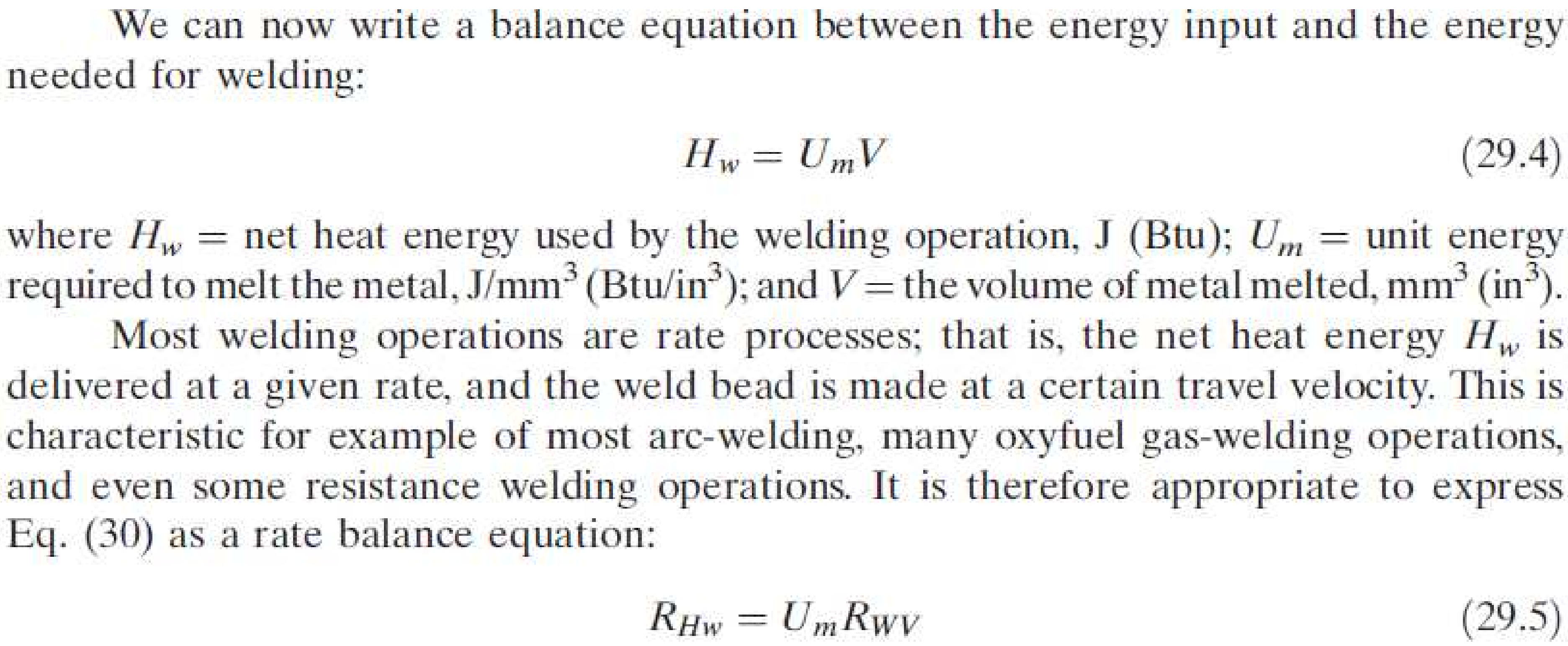
$$H_w = f_1 f_2 H \tag{29.3}$$

where H_w = net heat available for welding, J (Btu), f_1 = heat transfer factor, f_2 = the melting factor, and H = the total heat generated by the welding process, J (Btu).

The factors f_1 and f_2 range in value between zero and one. It is appropriate to separate f_1 and f_2 in concept, even though they act in concert during the welding process. The heat transfer factor f_1 is determined largely by the welding process and the capacity to convert the power source (e.g., electrical energy) into usable heat at the work surface. Arc-welding processes are relatively efficient in this regard, while oxyfuel gas-welding processes are relatively inefficient.

The melting factor f_2 depends on the welding process, but it is also influenced by the thermal properties of the metal, joint configuration, and work thickness. Metals with high thermal conductivity, such as aluminum and copper, present a problem in welding because of the rapid dissipation of heat away from the heat contact area. The problem is exacerbated by welding heat sources with low energy densities (e.g., oxyfuel welding) because the heat input is spread over a larger area, thus facilitating conduction into the work. In general, a high power density combined with a low conductivity work material results in a high melting factor.

HEAT BALANCE IN FUSION WELDING



We can now write a balance equation between the energy input and the energy needed for welding:

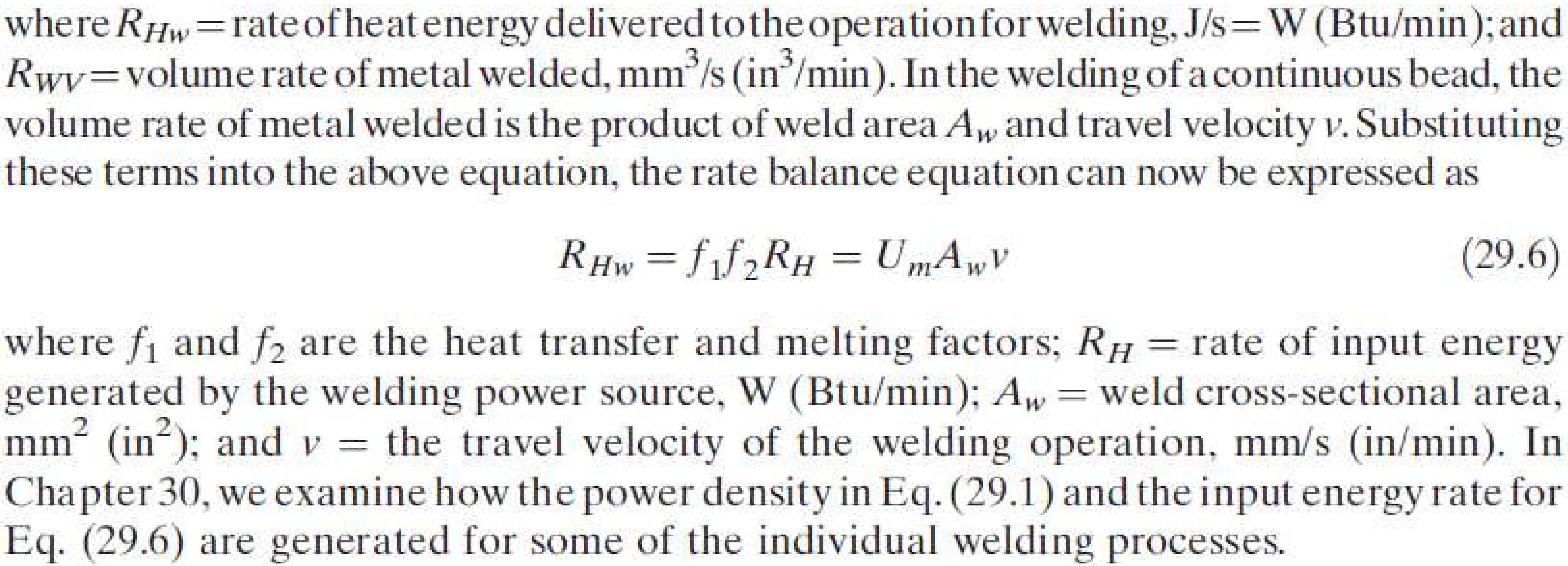
$$H_w = U_m V \tag{29.4}$$

where H_w = net heat energy used by the welding operation, J (Btu); U_m = unit energy required to melt the metal, J/mm^3 (Btu/in^3); and V = the volume of metal melted, mm^3 (in^3).

Most welding operations are rate processes; that is, the net heat energy H_w is delivered at a given rate, and the weld bead is made at a certain travel velocity. This is characteristic for example of most arc-welding, many oxyfuel gas-welding operations, and even some resistance welding operations. It is therefore appropriate to express Eq. (30) as a rate balance equation:

$$R_{Hw} = U_m R_{WV} \tag{29.5}$$

HEAT BALANCE IN FUSION WELDING

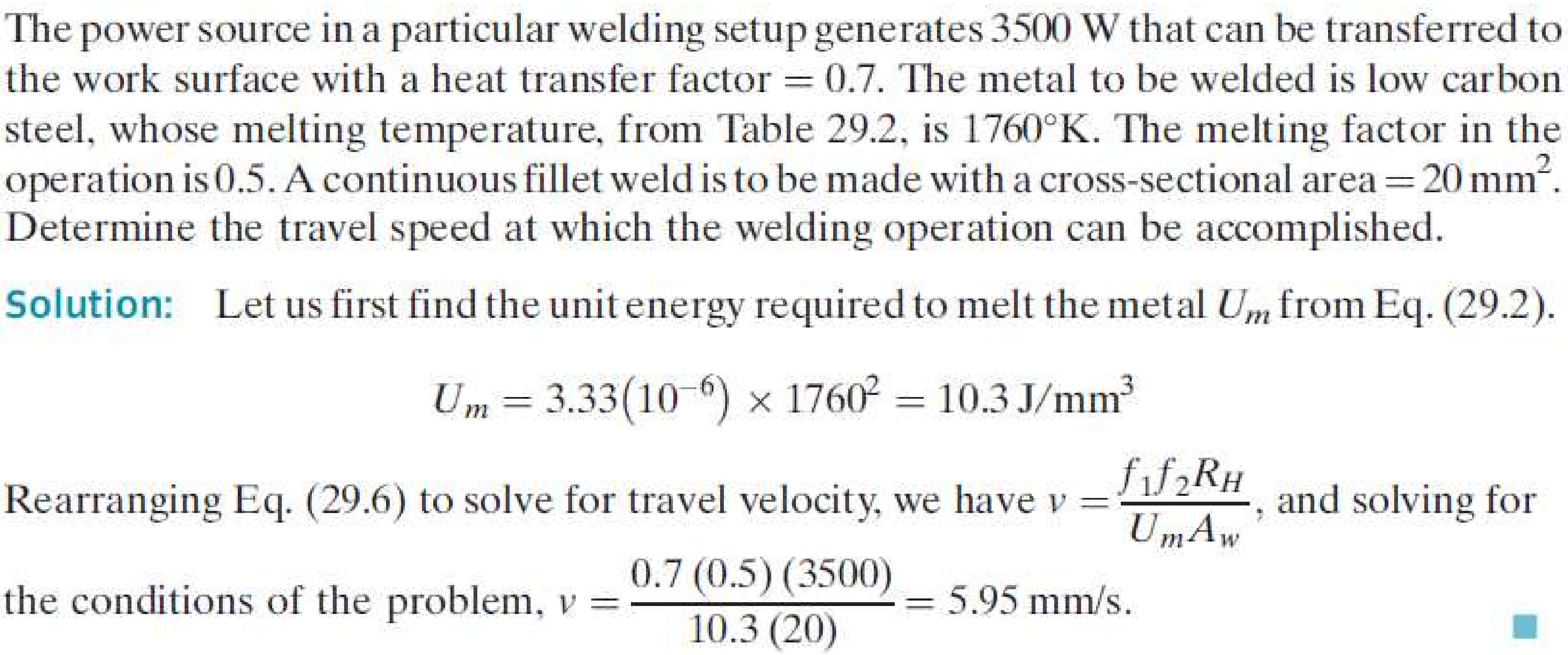


where R_{Hw} = rate of heat energy delivered to the operation for welding, J/s = W (Btu/min); and R_{WV} = volume rate of metal welded, mm^3/s (in^3/min). In the welding of a continuous bead, the volume rate of metal welded is the product of weld area A_w and travel velocity v. Substituting these terms into the above equation, the rate balance equation can now be expressed as

$$R_{Hw} = f_1 f_2 R_H = U_m A_w v \tag{29.6}$$

where f_1 and f_2 are the heat transfer and melting factors; R_H = rate of input energy generated by the welding power source, W (Btu/min); A_w = weld cross-sectional area, mm^2 (in^2); and v = the travel velocity of the welding operation, mm/s (in/min). In Chapter 30, we examine how the power density in Eq. (29.1) and the input energy rate for Eq. (29.6) are generated for some of the individual welding processes.

Example



The power source in a particular welding setup generates 3500 W that can be transferred to the work surface with a heat transfer factor = 0.7. The metal to be welded is low carbon steel, whose melting temperature, from Table 29.2, is 1760°K. The melting factor in the operation is 0.5. A continuous fillet weld is to be made with a cross-sectional area = 20 mm^2. Determine the travel speed at which the welding operation can be accomplished.

Solution: Let us first find the unit energy required to melt the metal U_m from Eq. (29.2).

$$U_m = 3.33(10^{-6}) \times 1760^2 = 10.3\ \text{J/mm}^3$$

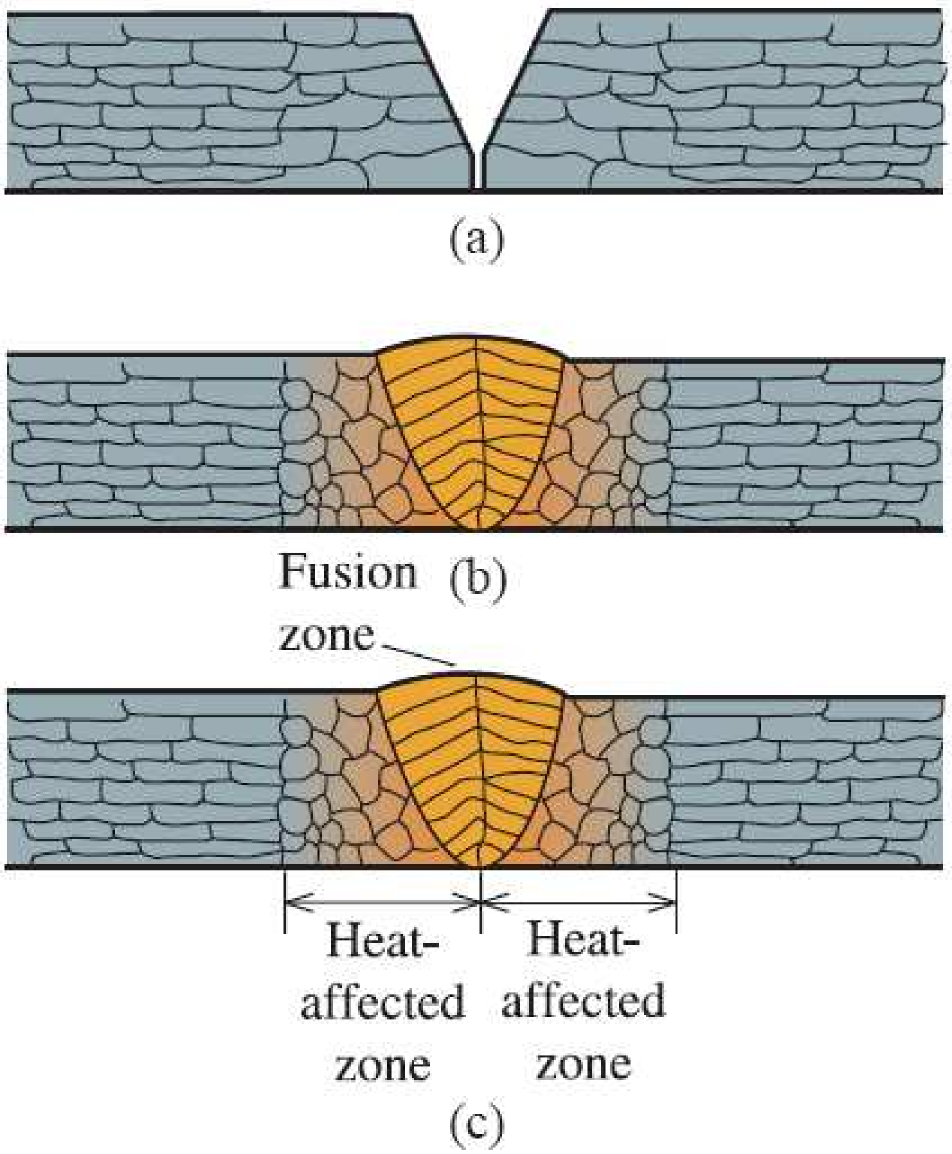
Rearranging Eq. (29.6) to solve for travel velocity, we have $v = \dfrac{f_1 f_2 R_H}{U_m A_w}$, and solving for the conditions of the problem, $v = \dfrac{0.7\,(0.5)\,(3500)}{10.3\,(20)} = 5.95$ mm/s.

Features of a Fusion-Welded Joint

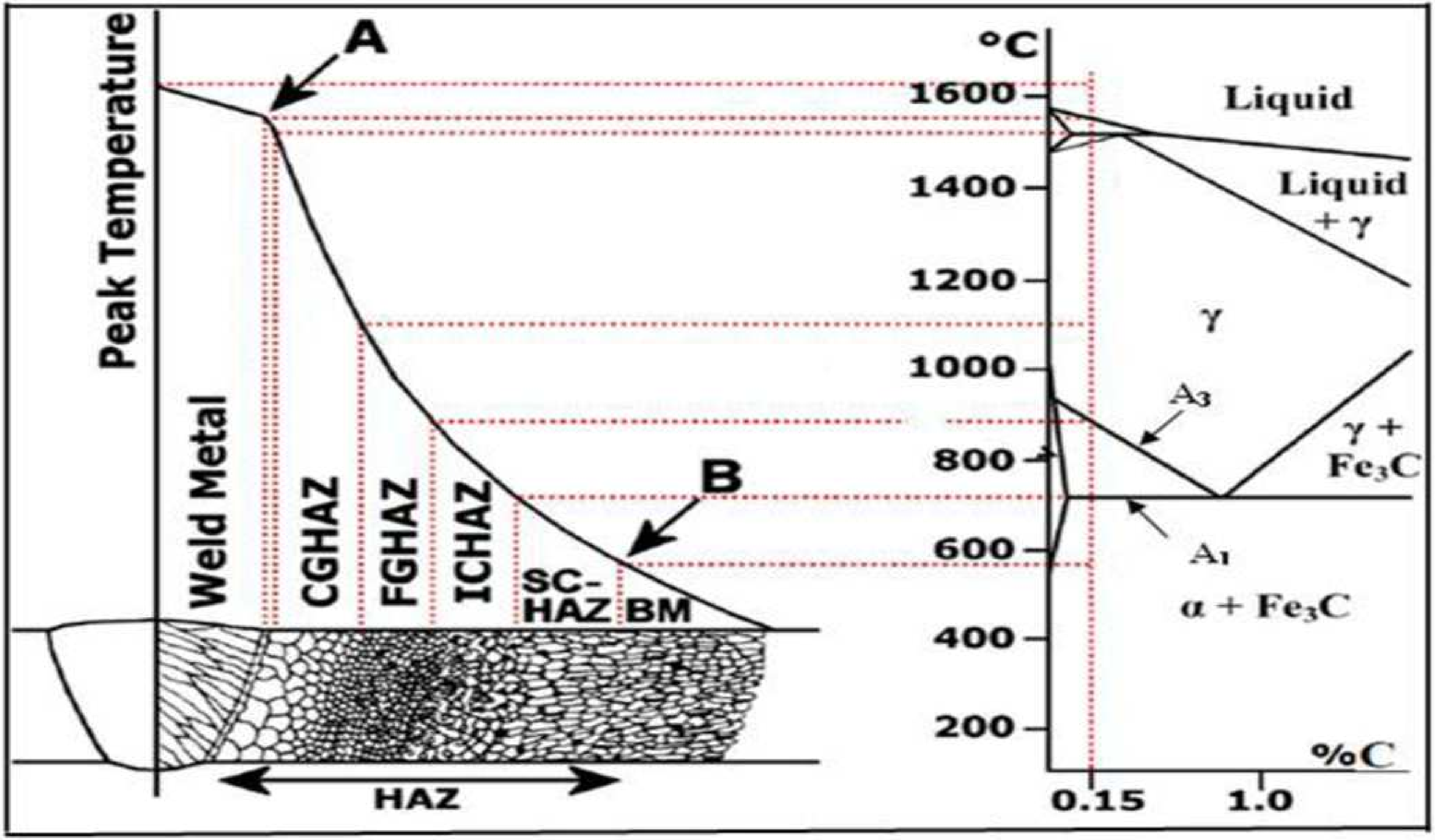
- A typical fusion-weld joint in which filler metal has been added consists of several zones: (1) fusion zone, (2) weld interface, (3) heat-affected zone, and (4) unaffected base metal zone.
- The fusion zone consists of a mixture of filler metal and base metal that have completely melted. This zone is characterized by a high degree of homogeneity among the component metals that have been melted during welding. The grain structure depends on various factors, including welding process, metals being welded (*e.g., identical metals vs. dissimilar metals welded*), whether a filler metal is used, and the feed rate at which welding is accomplished. The resulting structure in the solidified fusion zone tends to feature coarse columnar grains.
- The second zone in the weld joint is the weld interface, a narrow boundary that separates the fusion zone from the heat-affected zone. The interface consists of a thin band of base metal that was melted or partially melted (localized melting within the grains) during the welding process but then immediately solidified before any mixing with the metal in the fusion zone. Its chemical composition is therefore identical to that of the base metal.

- The third zone in the typical fusion weld is the heat-affected zone (HAZ). The metal in this zone has experienced temperatures that are below its melting point, yet high enough to cause microstructural changes in the solid metal. The chemical composition in the heat-affected zone is the same as the base metal, but this region has been heat treated due to the welding temperatures so that its properties and structure have been altered. The amount of metallurgical damage in the HAZ depends on factors such as the amount of heat input and peak temperatures reached, distance from the fusion zone, length of time the metal has been subjected to the high temperatures, cooling rate, and the metal’s thermal properties. The effect on mechanical properties in the heat-affected zone is usually negative, and it is in this region of the weld joint that welding failures often occur.

Solidification and Metal Joining



A schematic diagram of the fusion zone and solidification of the weld during fusion welding:
(a) initial prepared joint,
(b) weld at the maximum temperature, with joint filled with filler metal, and
(c) weld after solidification.

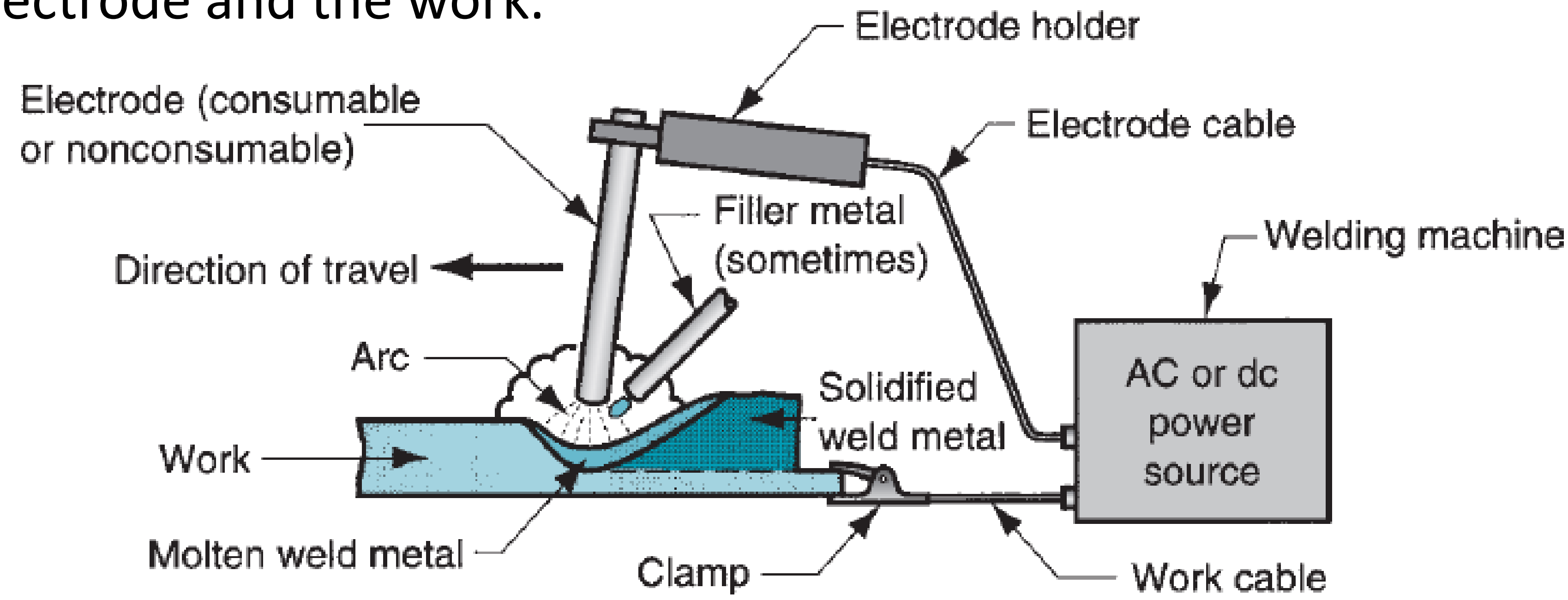

Peak Temperature
A
B
Weld Metal
CGHAZ
FGHAZ
ICHAZ
SC-HAZ
BM
HAZ
°C
1600
1400
1200
1000
800
600
400
200
Liquid
Liquid + γ
γ
A3
γ + Fe3C
A1
α + Fe3C
%C
0.15
1.0

Welding Processes

- Welding processes divide into two major categories: **(1) fusion welding**, in which coalescence is accomplished by melting the two parts to be joined, in some cases adding filler metal to the joint; and **(2) solid-state welding**, in which heat and/or pressure are used to achieve coalescence, but no melting of the base metals occurs and no filler metal is added.
- Fusion welding is by far the more important category. It includes (1) arc welding, (2) resistance welding, (3) oxyfuel gas welding, and (4) other fusion welding processes.

ARC WELDING

- Arc welding (AW) is a fusion-welding process in which coalescence of the metals is achieved by the heat of an electric arc between an electrode and the work.



The basic configuration and electrical circuit of an arcwelding process.

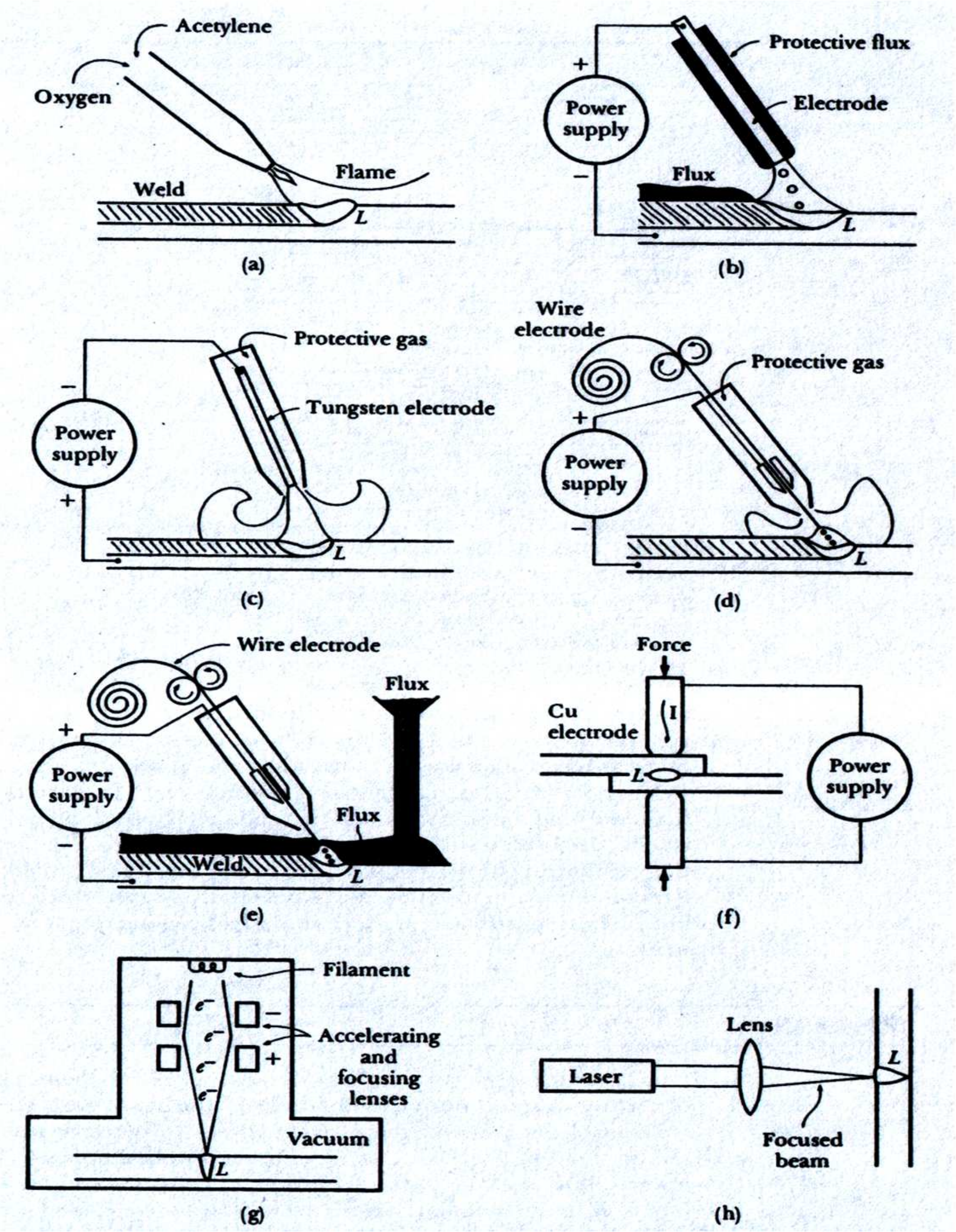
ARC WELDING

- An electric arc is a discharge of electric current across a gap in a circuit. It is sustained by the presence of a thermally ionized column of gas (called a plasma) through which current flows. To initiate the arc in an AW process, the electrode is brought into contact with the work and then quickly separated from it by a short distance. The electric energy from the arc thus formed produces temperatures of 5500C or higher, sufficiently hot to melt any metal. A pool of molten metal, consisting of base metal(s) and filler metal (if one is used) is formed near the tip of the electrode. In most arc welding processes, filler metal is added during the operation to increase the volume and strength of the weld joint. As the electrode is moved along the joint, the molten weld pool solidifies in its wake

Electrodes

- **Electrodes** used in AW processes are classified as consumable or **nonconsumable**. Consumable electrodes provide the source of the filler metal in arc welding. These electrodes are available in two principal forms: rods (also called sticks) and wire. Welding rods are typically 225 to 450 mm long and 9.5 mm or less in diameter. The problem with consumable welding rods, at least in production welding operations, is that they must be changed periodically, reducing arc time of the welder.
- **Consumable** weld wire has the advantage that it can be continuously fed into the weld pool from spools containing long lengths of wire, thus avoiding the frequent interruptions that occur when using welding sticks. In both rod and wire forms, the electrode is consumed by the arc during the welding process and added to the weld joint as filler metal. Nonconsumable electrodes are made of tungsten (or carbon, rarely), which resists melting by the arc. Despite its name, a nonconsumable electrode is gradually depleted during the welding process (vaporization is the principal mechanism), analogous to the gradual wearing of a cutting tool in a machining operation. For AW processes that utilize nonconsumable electrodes, any filler metal used in the operation must be supplied by means of a separate wire that is fed into the weld pool.

- Electrode coating (e.g. cellulose + titania) vaporizes and provides a protective gas shield around arc and weld pool to prevent oxidization
- Electric arc generated by touching the electrode tip against workpiece
- Sufficient distance between workpiece and electrode is required to maintain arc
- Parent material, electrode metal and some material from coating solidify in the weld
- Globular or short circuit mode of metal transfer
- Current ranges from 50 – 300 A



Typical-fusion
(a) Oxyacetylene welding,
(b) Shielded metal arc welding
(c) Gas tungsten arc welding,
(d) gaz-metal arc welding,
(e) Submerge arc welding
(f) Resistance welding,
(g) Electron beam welding,
(h) Laser welding