PHYSICS OF WELDING

Although several coalescing mechanisms are available for welding, fusion is by far the most common means. **To accomplish fusion, a source of high-density heat energy is applied to the faying surfaces, and the resulting temperatures are sufficient to cause localized melting of the base metals.** If a filler metal is added, the heat density must be high enough to melt it also. **Heat density can be defined as the power transferred to the W per unit surface area, W/mm^2.** The time to melt the metal is inversely proportional to the power density. At low power densities, a significant amount of time is required to cause melting. If power density is too low, the heat is conducted into work as rapidly as it is added at the surface, and melting never occurs. It has been found that the minimum power density required to melt most metals in welding is about 10 W/mm^2. As heat density increases, melting time is reduced. If power density is too high-above around 10^5 W/mm^2-the localized temperatures vaporize the metal in the affected region.

Thus, there is a practical range of values for power density within which welding can be performed. Differences among welding processes in this range are (1) the rate at which welding can be performed and / or (2) the size of the region that can be welded. Table 1 provides a comparison of power densities for the major groups of fusion welding processes. Oxyfuel gas welding is capable of developing large amounts of heat, but the heat density is relatively low because it is spread over a large area. Oxyacetylene gas, the hottest of the OFW fuels, burns at a top temperature of around 3500°C.

By comparison, arc welding produces high energy over a smaller area, resulting in local temperatures of 5500° to 6600°C. For metallurgical reasons, it is desirable to melt the metal with minimum energy, and high heat densities are generally preferable.

TABLE 1 Comparison of several fusion-welding processes on the basis of their power densities.

Welding Process	Approximate Power Density W/mm²
Oxyfuel welding	10
Arc welding	50
Resistance welding	1,000
Laser beam welding	9,000
Electron beam welding	10,000

Power density can be computed as the power entering the surface divided by the corresponding surface area:

$$PD = P / A \qquad (1)$$

where PD = power density, W/mm^2; P = power entering the surface, W; and A = surface area over which the energy is entering, mm^2. The issue is more complicated than indicated by Eq. (1). One complication is that the power source (e.g., the arc) is moving in many welding processes, which results in preheating ahead of the operation and postheating behind it. Another complication is that power density is not uniform throughout the affected surface; it is distributed as a function of area, as demonstrated by the following example.

Example:

A heat source is capable of transferring 3000 W to 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 diameter = 5 mm, and 90% is transferred within a concentric circle of diameter = 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 $A = \pi (5)^2 / 4 = 19.63$ mm^2.

The power inside this area P = 0.70 X 3000 = 2100 W

Thus the power density PD = 2100 / 19.63 = 107 W/ mm^2

(b) The area of the ring outside the inner circle is $A = \pi (12^2 - 5^2) /4 = 93.4$ mm^2

The power in this region P = 0.9 X 3000 – 2100 = 600 W

The power density is therefore PD = 600 / 93.4 = 6.4 W/mm^2.

Observation: The power density seems high enough for melting in the inner circle, but probably not sufficient in the ring that lies outside this inner circle.

The quantity of heat required to melt a given volume of metal is the sum of (1) the heat to raise the temperature of the solid metal to its melting point, which depends on the metal's volumetric specific heat, and (2) 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:

$$U_m = KT_m^2 \qquad (2)$$

where U_m is the unit energy for melting - the quantity of heat required to melt a unit volume of metal starting from room temperature, J/mm^3; T_m = melting point of the metal on an absolute temperature scale, °K; and K = constant whose value is 3.33 x 10^{-6} when the Kelvin scale is used. Absolute melting temperatures for selected metals are presented in Table 2.

Not all of the input energy is used to melt the weld metal. There are two heat transfer mechanisms at work, both of which reduce the amount of heat available to the welding process. The first mechanism is the transfer of heat between the heat source and the surface of the work. This process has a certain heat transfer efficiency, f_1, defined as the ratio of the actual heat received by the workpiece divided by the total heat gen-

erated at the source. The second mechanism involves the conduction of heat away from the weld area to be dissipated throughout the work metal, so that only a portion of the heat transferred to the surface is available for melting. This melting efficiency, f_2, is the proportion of heat received at the work surface that can be used for melting.

The combined effect of these two efficiencies is to reduce the heat energy available for welding as follows:

$$H_w = f_1 f_2 H \qquad (3)$$

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

Table 2: Melting temperatures on the absolute temperature scale for selected metals.

	Melting Temperature				
Metal	°K[a]	°R[b]	Metal	°K[a]	°R[b]
Aluminium 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		
Lnconel	1660	(3000)	Austenitic	1670	(3010)
Magnesium	940	(1700)	Martensitic	1700	(3060)
Nickel	1720	(3110)	Titanium	2070	(3730)
Based on values					
a Kelvin scale = Centigrade (Celsius) temperature + 273.					
b Rankine scale = Fahrenheit temperature + 460.					

It is appropriate to separate f_1 and f_2 in concept, even though they act in concert during the welding process. Heat transfer efficiency 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. Oxyfuel gas welding processes are relatively inefficient in this regard, while arc welding processes are relatively efficient.

Melting efficiency 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 aluminium 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-intensity welding heat source, combined with a low conductivity work material, results in a high melting efficiency.

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

$$H_w = U_m V \qquad (4)$$

where H_w = net heat energy delivered to the operation, J; U_m = unit energy required to melt the metal, J/mm^3; and V = the volume of metal melted, mm^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 and many oxyfuel gas welding operations. It is therefore appropriate to express Eq. (4) in the form of a rate balance equation:

$$HR_w = U_m WVR \qquad (5)$$

where HR_w = rate of heat energy delivered to the operation, J/s = W; and WVR = volume rate of metal welded, mm^3/s. In the welding of a

continuous bead, the volume rate of metal welded is the product of weld area Aw and travel velocity v. Substituting these terms into the above equation, the rate balance equation can now be expressed as

$$HR_w = f_1 f_2 HR = U_m A_w v \qquad (6)$$

Where f_1 and f_2 are the heat transfer and melting efficiencies; HR = rate of input energy generated by the welding power source, W; A_w = weld cross-sectional area, mm^2; and v = the travel velocity of the welding operation, mm/s.

Example

The power source in a particular welding setup is capable of generating 3500 W that can be transferred to the work surface with an efficiency f_1= 0.7. The metal to be welded is low carbon steel, whose melting temperature, from Table 2, is T_m = 1760°K. Melting efficiency in the operation is f_2 = 0.5. A continuous fillet weld is to be made with a cross sectional area A_w= 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. (2).

$$U_m = 3.33(10^{-6}) \times 17602 = 10.3 \ J/mm^3$$

Rearranging Eq. (6) to solve for travel velocity, we have $v = \frac{f_1 \ f_2 \ HR}{U_m \ A_w}$

and solving for the conditions of the problem, $v = \frac{0.7 \ (0.5)(3500)}{10.3 \ (20)} = 5.95$ mm/s

Power Source in Arc Welding Both direct current (DC) and alternating current (AC) are used in arc welding. AC machines are less expensive to purchase and operate, are generally restricted to welding of ferrous metals. DC equipment can be used on metals with good results and is generally noted for better arc control.

In all AW processes, power to drive the operation is the product of the current passing through the arc and the voltage 'E' across it. This power is converted into heat, but not

all of the heat is transferred to the surface of the work. Convection, conduction, radiation, and spatter account for losses that reduce the amount of usable heat. The effect of the losses is expressed by the heat transfer efficiency f_1. Some representative values of f_1 for several AW processes are given in Table 3. Heat transfer efficiency is greater for AW processes that use consumable electrodes because most of the heat consumed in melting the electrode is subsequently transferred to the work as molten metal. The process with the lowest f_1 value in Table 3 is gas tungsten arc welding, which uses a non-consumable electrode. Melting efficiency f_2 further reduces the available heat for welding. The resulting power balance in arc welding is defined by

$$HR_w = f_1 f_2 I E = U_m A_w v$$

where E = voltage, V; I = current, A; and the other terms were defined earlier. The units of HR_w that result from product of amps x voltage are watts, which equal joule/sec. This can be converted to Btu/sec by recalling that 1 Btu = 1055 joule.

TABLE 3: Heat transfer efficiencies for several arc-welding processes.

Arc Welding Process.	Typical Heat Transfer Efficiency f_1
Shielded metal arc welding	0.9
Gas metal arc welding	0.9
Flux-cored arc welding	0.9
Submerged arc welding	0.95
Gas tungsten arc welding	0.7

Example:

A gas tungsten AW operation is performed at a current of 300 A and voltage of 20 V. The melting efficiency f_2 = 0.5, and the unit melting energy for the metal U_m = 10 J/mm^3. Determine (a) power in the operation, (b) rate of heat generation at the weld, and (c) volume rate of metal welded.

Solution: (a) The power in this arc-welding operation is

P = IE = (300 A)(20 V) = 6000 W

(b) From, the heat transfer efficiency f_1 = 0.7. The rate of heat used for welding is given by

$$HR_w = f_1 f_2 IE = (0.7)(0.5)(6000) = 2100 \text{ W} = 2100 \text{ J/s}$$

(c) The volume rate of metal welded is

$$WVR = (2100\ J/s)/(10\ J/mm^3) = 210\ mm^3/s$$

Power Source in Resistance Welding

The heat energy supplied to the welding operation depends on current flow, resistance of the circuit, and length of time the current is applied. This can be expressed by the equation

$$H = I^2 R t$$

where H = heat generated, J (to convert to Btu divide by 1055);

I = current, A; R = electrical resistance, ohm; and t = time, s.

The current used in resistance welding operations is very high (5,000 to 20,000 A, typically), although voltage is relatively low (usually below 10 V). The duration t of the current is short in most processes, perhaps lasting 0.1 to 0.4 s in a typical spot welding operation.

Current is so high in RW because the squared term in Eq. amplifies the effect of current, and resistance is very low (around 0.0001 ohm). Resistance in the welding circuit is the sum of **(1) resistance of the electrodes, (2) resistances of the work parts, (3) contact resistances between electrodes and work parts, and (4) contact resistance of the faying surfaces.**

The ideal situation is for the faying surfaces to be the largest resistance in the sum, since this is the desired location of the weld. The resistance of the electrodes is minimized by using metals with very low resistivities, such as copper. The resistances of the work parts are a function of the resistivities of the base metals involved and the thicknesses of the parts. The contact resistance between the electrodes and the parts is determined by the contact areas (i.e., size and shape of the electrode) and the condition of the surfaces (e.g., cleanliness of the work surfaces and scale on the electrode). Finally, the resistance at the faying surfaces

depends on surface finish, cleanliness, contact area, and pressure. No paint, oil, dirt, or other contaminants should be present to separate the contacting surfaces.

EXAMPLE

A resistance spot welding operation is performed on two pieces of 1.5 mm thick sheet steel using 12,000 amps for a 0.20 second duration. The electrodes are 6 mm in diameter at the contacting surfaces. Resistance is assumed to be 0.0001 ohms, and the resulting weld nugget is 6 mm in diameter and 2.5 mm thick. The unit melting energy for the metal U_m = 12.0 J/mm³. What portion of the heat generated was used to form the weld, and what portion was dissipated into the surrounding metal?

Solution: The heat generated in the operation is given by Eq. as

$$H = (12{,}000)^2\,(0.0001)\,(0.2) = 2880\text{ J}$$

The volume of the weld nugget (assumed disc-shaped) is $V = 2.5\,\pi\,(6)^2 = 70.7\text{ mm}^3$.

The heat required to melt this volume of metal is $H_m = 70.7(12.0) = 848$ J.

The remaining heat, 2880 - 848 = 2032 J (70.6% of the total), is absorbed into the surrounding metal.

Success in resistance welding depends on pressure, as well as heat. The principal functions of pressure in RW are to (1) force contact between the electrodes and the workparts and between the two work surfaces prior to applying current; and (2) press the faying surfaces together to accomplish coalescence when the proper welding temperature has been reached. There are some general advantages of resistance welding: (1) no filler metal is required, (2) high production rates are possible, (3) it lends itself to mechanization and automation, (4) operator skill level is lower than that required for arc welding, and (5) good repeatability and reliability. Drawbacks are that initial equipment cost is high- usually much higher than AW operations, and the types of joints that can be welded are limited to lap joints for most RW processes.

Electron beam welding (EBW) is a fusion-welding process in which the heat for

welding is provided by a highly focused, high-intensity stream of electrons impinging against the work surface. The equipment is similar to that used for electron-beam machining. The electron beam gun operates at high voltage to accelerate the electrons (e.g., 10 to 150 kV typical), and beam currents are low (measured in milliamps). High-power density is achieved by focusing the electron beam on a very small area of the work surface, so that the power density PD is based on

$$PD = f_1 E I / A$$

where PD = power density, W/mm^2; f_1 = heat transfer efficiency (typical values for EBW range from 0.8 to 0.95); E = accelerating voltage, V; I = beam current, A; and A = the work surface area on which the electron beam is focused, mm^2. Typical weld areas for EBW range from 13 X 10^{-3} to 2000 x 10^{-3} mm^2.

The process had its beginnings in the 1950s in the atomic power field. When first developed, welding had to be carried out in a vacuum chamber to minimize the disruption of the electron beam by air molecules. This requirement was, and still is, a serious inconvenience in production, due to the time required to evacuate the chamber prior to welding. The pump-down time, as it is called, can take as long as an hour, depending on the size of the chamber and the level of vacuum required. Today, EBW technology has progressed to where some operations are performed without a vacuum. Three categories can be distinguished: (1) *high-vacuum welding* (EBW-HV), in which welding is carried out in the same vacuum as beam generation; (2) *medium- : vacuum welding* (EBW-MV), in which the operation is performed in a separate cham- . ber where only a partial vacuum is achieved; and (3) *non vacuum welding* (EBW-NV), in which welding is accomplished at or near atmospheric pressure. The pump-down time during workpart loading and unloading is reduced in medium-vacuum EBW and minimized in nonvacuum EBW, but there is a price paid for this advantage. In the latter two operations, the equipment must include one or more vacuum dividers (very small orifices that impede air flow but permit passage of the electron beam) to separate the beam generator (which requires a high vacuum) from the work chamber. Also, in non vacuum EBW, the work must be located close to the orifice of the electron beam gun, approximately 13 mm (0.5 in.) or less. Finally, the lower vacuum processes cannot achieve the high weld qualities and depth-to-width ratios accomplished by EBW-HY. Any metals that can be arc welded can be welded by EBW, as well as certain refractory and difficult-to-weld metals that are not suited to AW. Work sizes range from thin foil to thick plate. EBW is applied mostly in the automotive, aerospace, and nuclear industries. In the automotive industry, EBW assembly includes aluminum manifolds, steel torque converters, catalytic converters, and transmission components. In these and other