29 WELDING PROCESSES

Review Questions

29.1 Name the principal groups of processes included in fusion welding.

Answer. The principal groups of processes included in fusion welding are (1) arc welding, (2) resistance welding, (3) oxyfuel welding, and (4) other. The "other" category includes EBW, LBW, thermit welding, and others.

29.2 What is the fundamental feature that distinguishes fusion welding from solid-state welding?

Answer. In fusion welding, melting occurs at the faying surfaces; in solid state welding, no melting occurs.

29.3 What is an electrical arc?

Answer. An electrical arc is a discharge across a gap in a circuit; the arc is sustained by a thermally ionized column of gas through which the current flows.

29.4 What does the term *arc-on time* mean?

Answer. The text gives four alternative definitions: (1) Arc-on time = minutes per work cycle during which arc is on; (2) Arc-on time = fraction of time per work cycle during which arc is on; (3) Arc-on time = hours per shift during which arc is on; and (4) Arc-on time = fraction of time per shift during which arc is on

29.5 Electrodes in arc welding are divided into two categories. Name and define them.

Answer. The two categories are consumable and nonconsumable. The consumable type, in addition to being the electrode for the process, also provides filler metal for the welding joint. The nonconsumable type is made of materials that resist melting, such as tungsten or carbon.

29.6 What are the two basic methods of arc shielding?

Answer. (1) Shielding gas, such as argon and helium; and (2) flux, which covers the welding operation and protects the molten pool from the atmosphere.

29.7 Why is the heat transfer factor in arc-welding processes that utilize consumable electrodes greater than in those that use nonconsumable electrodes?

Answer. Because molten metal from the electrode is transferred across the arc and contributes to the heating of the molten weld pool in arc-welding processes that utilize consumable electrodes.

29.8 Describe the shielded metal arc-welding (SMAW) process.

Answer. SMAW is an arc-welding process that uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding.

29.9 Why is the shielded metal arc-welding (SMAW) process difficult to automate?

Answer. Because the stick electrodes used in SMAW must be changed frequently, which would be difficult to do automatically. It is much easier to automate the feeding of continuous filler wire, such as in GMAW, FCAW, SAW, or GTAW.

29.10 Describe submerged arc welding (SAW).

Answer. SAW is an arc-welding process that uses a continuous, consumable bare wire electrode, and arc shielding is provided by a cover of granular flux.

29.11 Why are the temperatures much higher in plasma arc welding than in other AW processes?

Answer. Because the arc is restricted in diameter, thus concentrating the heat energy into a smaller area, resulting in much higher power densities.

29.12 Define resistance welding.

Answer. RW consists of a group of fusion welding processes that utilize a combination of heat and pressure to accomplish coalescence of the two faying surfaces. Most prominent in the group is resistance spot welding.

29.13 What are the desirable properties of a metal for resistance welding?

Answer. High resistivity, low electrical and thermal conductivity, and low melting point.

29.14 Describe the sequence of steps in the cycle of a resistance spot-welding operation.

Answer. The steps are (1) insert parts between electrodes, (2) squeeze parts between the electrodes, (3) weld, in which the current is switched on for a brief duration (0.1 to 0.4 sec), (4) hold, during which the weld nugget solidifies, and (5) open electrodes and remove parts.

29.15 What is resistance-projection welding?

Answer. RPW is a resistance welding process in which coalescence occurs at one or more relatively small points on the parts; the contact points are designed into the geometry of the parts as embossments or projections.

29.16 What is cross-wire welding?

Answer. Cross-wire welding is a form of resistance projection welding used to fabricate welded wire products such as shopping carts and stove grills.

29.17 Why is the oxyacetylene welding process favored over the other oxyfuel welding processes?

Answer. Because acetylene and oxygen burn hotter than other oxyfuels.

29.18 Define pressure gas welding.

Answer. PGW is a fusion welding process in which coalescence is obtained over the entire contact surfaces of the two parts by heating them with an appropriate fuel mixture and then applying pressure to bond the surfaces.

29.19 Electron-beam welding has a significant disadvantage in high-production applications. What is that disadvantage?

Answer. EBW must usually be carried out in a vacuum for a high quality weld. The time to draw the vacuum adds significantly to the production cycle time.

29.20 Laser-beam welding and electron-beam welding are often compared because they both produce very high power densities. LBW has certain advantages over EBW. What are they?

Answer. Advantages of LBW over EBW are (1) no vacuum chamber is required in LBM, (2) no x-rays are emitted in LBM; and (3) the laser beam can be focused and directed with conventional optical mirrors and lenses.

29.21 Name several modern-day variations of forge welding, the original welding process from ancient times.

Answer. Variations of forge welding are (1) cold welding, (2) roll welding, (3) and hot pressure welding.

29.22 There are two basic types of friction welding (FRW). Describe and distinguish the two types.

Answer. The two types of FRW are (1) continuous-drive friction welding and (2) inertia friction welding. In continuous-drive friction welding, one part is rotated at a constant speed and forced into contact against a stationary part with a certain force so that friction heat is generated at the interface; when the right temperature is reached, the rotating part is stopped abruptly and the two parts are forced together at forging pressures. In inertia friction welding, the rotating part is connected to a flywheel which is brought up to proper speed; then the flywheel is disengaged from the drive motor and the parts are forced together, so that the kinetic energy of the flywheel is converted to friction heat for the weld.

29.23 What is friction stir welding (FSW), and how is it different from friction welding?

Answer. Friction stir welding (FSW) is a solid state welding process in which a rotating tool is fed along the joint line between two work parts, generating friction heat and mechanically stirring the metal to form the weld seam. FSW is distinguished from conventional friction welding (FRW) by the fact that friction heat is generated by a separate wear-resistant tool rather than by the parts themselves.

29.24 What is a *sonotrode* in ultrasonic welding?

Answer. It is the actuator which is attached to one of the two parts to be welded with USW and which provides the oscillatory motion that results in coalescence of the two surfaces. It is analogous to an electrode in resistance welding.

29.25 Distortion (warping) is a serious problem in fusion welding, particularly arc welding. What are some of the techniques that can be used to reduce the incidence and extent of distortion?

Answer. The following techniques can be used to reduce warping in arc welding: (1) Welding fixtures can be used to physically restrain movement of the parts during welding. (2) Heat sinks can be used to rapidly remove heat from sections of the welded parts to reduce distortion. (3) Tack welding at multiple points along the joint can create a rigid structure prior to continuous seam welding. (4) Welding conditions (speed, amount of filler metal used, etc.) can be selected to reduce warping. (5) The base parts can be preheated to reduce the level of thermal stresses experienced by the parts. (6) Stress relief heat treatment can be performed on the welded assembly, either in a furnace for small weldments, or using methods that can be used in the field for large structures. (7) Proper design of the weldment itself can reduce the degree of warping.

29.26 What are some important welding defects?

Answer. Some of the important welding defects are (1) cracks, (2) cavities, (3) solid inclusions, (4) incomplete fusion, and (5) imperfect shape or contour of weld cross section.

29.27 What are the three basic categories of inspection and testing techniques used for weldments? Name some typical inspections and/or tests in each category.

Answer. The three categories are: (1) visual inspection, which includes dimensional checks and inspection for warping, cracks, and other visible defects; (2) nondestructive evaluation, which includes dye-penetrant, magnetic particle, ultrasonic, and radiographic tests; and (3) destructive tests, which includes conventional mechanical and metallurgical tests adapted to weld joints.

29.28 What are the factors that affect weldability?

Answer. Factors affect weldability include (1) welding process, (2) base metal properties such as melting point, thermal conductivity, coefficient of thermal expansion, and whether the base metals are similar or dissimilar - dissimilar base metals are generally more difficult to weld, (3) filler metal and its composition relative to the base metals, and (4) surface condition - surfaces should be clean and free of oxides, moisture, etc.

29.29 Why are the values of electric power cost in arc welding so low compared with the other costs of arc welding?

Answer. Although the power in arc welding is high, the arc-on time during each work cycle is usually short relative to the other elements in the work cycle, so the total amount of electricity used per weldment or per hour is modest. The significant contributors to welding costs are labor and equipment; labor cost is more significant in manual welding and equipment cost is more significant in automated and robotic welding.

Problems

Answers to problems labeled **(A)** are listed in the Appendix at the back of the book.

Arc Welding

29.1 **(A)** (SI units) A shielded metal arc-welding operation is performed on low-carbon steel plates at a voltage = 25 volts and current = 150 amps. The heat transfer factor = 0.90, and the melting factor = 0.75. The melting temperature of low-carbon steel = 1487°C, and the unit melting energy can be determined by the methods of the previous chapter. Using SI units, determine the (a) rate of heat generation at the weld and (b) volume rate of metal welded.

Solution: (a) $R_{HW} = f_1 f_2 EI$ = (0.90)(0.75)(25)(150) = **2531.25 J/s = 2531.25 W**

(b) On the Kelvin scale, T_m = 1487 + 273 = 1760°K, which is the value in Table 28.2
$U_m = KT_m^2 = 3.33(10^{-6})(1760)^2$ = 10.3 J/mm^3
R_{WV} = (2531.25 J/s)/(10.3 J/mm^3) = **245.8 mm^3/s**

29.2 (USCS units) Solve the previous problem only using USCS units. The melting temperature of low-carbon steel = 2700°F, and the unit melting energy can be determined by the methods of the previous chapter.

Solution: (a) $R_{HW} = f_1 f_2 EI = (0.90)(0.75)(25)(150) = 2531.25$ J/s
Converting J/s to Btu/sec (1 Btu = 1055 J), $R_{HW} =$ **2.4 Btu/sec**

(b) On the Rankine scale, $T_m = 2700 + 460 = 3160$°K, which is the value in Table 28.2
$U_m = KT_m^2 = 1.467(10^{-5})(3160)^2 = 146.5$ Btu/in^3
$R_{WV} = (2.4$ Btu/sec$)/(146.5$ Btu/in$^3) =$ **0.0164 in^3/s = 0.983 in^3/min**

29.3 (SI units) Flux-cored arc welding is used to butt-weld two austenitic stainless steel plates together. Welding voltage = 20 volts, and current = 175 amps. The cross-sectional area of the weld seam = 45 mm^2, the heat transfer factor = 0.9, and the melting factor of the stainless steel = 0.60. Using tabular data and equations in this and the preceding chapter, determine the value for travel speed in the operation.

Solution: Given the heat transfer factor for FCAW $f_1 = 0.9$ and f_2 for SS = 0.60
From Table 28.2, $T_m = 1670$°K for austenitic stainless steel.
$U_m = 3.33 \times 10^{-6} (1670)^2 = 9.29$ J/mm^3
$f_1 f_2 EI = U_m A_w v$
Travel speed $v = f_1 f_2 EI/U_m A_w = 0.9(0.6)(20)(175)/(9.29 \times 45) =$ **4.5 mm/s**

29.4 (SI units) A submerged arc-welding operation under automatic control is used to butt weld two round steel tubes with diameters = 2.0 m. The tubes are slowly rotated under a stationary welding head to complete the weld seam. Welding voltage = 25 volts, and current = 300 amps. The heat transfer factor for SAW = 0.95, and the melting factor = 0.7. Cross-sectional area of the weld bead = 45.0 mm^2. If the melting temperature of the steel = 1490°C, and its unit melting energy = 10.3 J/mm^3, determine the (a) rotational speed of the tubes and (b) time required to weld the seam.

Solution: (a) Given the heat transfer factor for SAW $f_1 = 0.95$ and melting factor = 0.7
Energy balance equation: $f_1 f_2 EI = U_m A_w v$
$v = f_1 f_2 EI/U_m A_w$
Travel speed $v = 0.95(0.7)(25)(300)/(10.3 \times 45.0) = 10.76$ mm/s
Circumference $C = \pi D = 2000\pi = 6{,}283$ mm/rev
Rotational speed $N = (10.76$ mm/s$)/(6{,}283$ mm/rev$) =$ **1.7126(10^{-3}) rev/s**

(b) Time to weld seam = C/v = (6,283 mm/rev)/(10.76 mm/s) = **584 s = 9.73 min**

29.5 **(A)** (USCS units) A flux-cored arc-welding process is used to join two low-alloy steel plates at a 90° angle. The joint is an outside fillet weld. The plates are ¼-in thick. The weld bead consists of 55% metal from the electrode and 45% from the steel plates. The heat transfer factor for FCAW = 0.9, and the melting factor = 0.65. Welding current = 120 amps, and voltage = 20 volts. Velocity of the welding head = 25 in/min. Electrode wire diameter = 0.125 in. A core of flux (compounds that do not become part of the weld bead) runs through the center of the electrode. The diameter of the core = 0.0625 in. (a) What is the cross-sectional area of the weld bead? (b) How fast must the electrode wire be fed into the welding operation?

Solution: (a) Given the heat transfer factor for FCAW $f_1 = 0.9$ and melting factor $f_2 = 0.65$
T_m from Table 28.2 is 3060°R
$U_m = KT_m^2 = 1.467(10^{-5})(3060)^2 = 137.4$ Btu/in^3
$R_{HW} = f_1f_2EI = U_mA_wv$, rearranging, $A_w = f_1f_2EI/U_mv$
$f_1f_2EI = 0.90(0.65)(20)(120) = 1404$ J/sec
$U_mv = (137.4$ Btu/in$^3)(25$ in/min$) = 3435$ Btu/in^2-min
Conversions: 1 Btu = 1055 J and 1 min = 60 sec
$U_mv = (3435$ Btu/in^2-min)(1055 J/Btu)(min/60 sec) = 60,399 J/in^2-sec
$A_w = (1404$ J/sec)/(60,399 J/in^2-sec) = **0.0232 in^2**

(b) Volume rate of welding = $A_wv = 0.0232(25) = 0.58$ in^3/min
Electrode $A = \pi D^2/4 = \pi(0.125)^2/4 = 0.01227$ in^2
Flux $A = \pi D^2/4 = \pi(0.0625)^2/4 = 0.00307$ in^2
Metal in electrode $A = 0.01227 - 0.00307$ in$^2 = 0.0092$ in^2
At 55% electrode metal,
Feed rate of electrode wire = (0.58 in^3/min)(0.55)/0.0092 = **34.7 in/min**

29.6 (USCS units) A gas metal arc-welding test is performed to determine the value of melting factor f_2 for a certain metal and operation. Welding voltage = 25 volts, current = 200 amps, and heat transfer factor = 0.90. The rate at which the filler metal is added to the weld = 0.90 in^3/min, and the final weld bead consists of 70% filler metal and 30% base metal. The compositions of the base and filler metals are the same, the melting temperature = 2460°F, and unit melting energy = 125 Btu/in^3. Determine the (a) melting factor and (b) travel speed if the cross-sectional area of the weld bead = 0.05 in^2.

Solution: (a) $f_1f_2EI = U_mA_wv$
A_wv = welding volume rate = R_{WV} = (0.90 in^3/min)/0.70 = 1.286 in^3/min = 0.0214 in^3/sec
Therefore, $f_1f_2EI = U_m(R_{WV})$
1 Btu = 1055 J, so 125 Btu/in^3 = 131,875 J/in^3
$f_2 = U_m(R_{WV})/f_1EI = 131{,}875(0.0214)/(0.9 \times 25 \times 200)$ = **0.627**

(b) Given that $A_w = 0.05$ in^2, travel speed $v = (R_{WV})/A_w = 1.286/0.05$ = **25.7 in/min**

Resistance Welding

29.7 **(A)** (SI units) A resistance spot-welding operation makes a series of spot welds between two sheets of aluminum, each 3.0 mm thick. The unit melting energy for aluminum = 2.90 J/mm^3. Welding current = 5000 amps, resistance = 75 micro-ohms, and time duration = 0.15 sec. Each weld nugget = 5.0 mm in diameter with an average thickness = 2.5 mm. How much of the total energy generated is used to form the weld nugget?

Solution: $H = I^2Rt = (5000)^2(75 \times 10^{-6})(0.15) = 281.1$ W-sec = 281.1 J
Weld nugget volume $V = \pi D^2d/4 = \pi(5)^2(2.5)/4 = 49.1$ mm^3
Heat required for melting = $U_mV = (2.9$ J/mm$^3)(49.1$ mm$^3) = 142.2$ J
Proportion of heat for welding =142.2/281.1 = **0.507 = 50.7%**

29.8 (USCS units) A resistance spot-welding operation performs a series of spot welds between two parts of sheet steel that are each 1/8 in thick. The steel has a unit melting energy = 130 Btu/in^3. Weld duration is set at 0.25 sec, and current = 11,000 amp. The weld nugget has a diameter = 0.30 in. Experience has shown that 40% of the supplied heat melts the nugget and the rest is dissipated. If the electrical resistance between the surfaces is 125 micro-ohms, what is the average thickness of the weld nugget assuming that it is disk-shaped?

Solution: $H = I^2Rt = 11{,}000^2(0.000125)(0.25) = 3{,}782$ J = 3,782/1055 = 3.584 Btu
$V = H_w/U_m = (0.4)(3.584/130) = 0.011$ in^3
$V = (d)\pi D^2/4$; $d = V/(\pi D^2/4) = 0.011/(0.25\pi(0.30^2)) =$ **0.156 in**

29.9 (SI units) The unit melting energy for a certain sheet metal is 9.5 J/mm^3. The thickness of each of the two sheets to be spot-welded is 3.5 mm. To achieve required strength, it is desired to form a weld nugget that is 5.5 mm in diameter and 4.0 mm thick. The weld duration will be set at 0.3 sec. If the electrical resistance between the surfaces is 140 micro-ohms, and only one-third of the electrical energy generated will be used to form the weld nugget (the rest being dissipated), determine the minimum current level required in this operation.

Solution: $H_m = U_mV$
$V = \pi D^2d/4 = \pi(5.5)^2(4.0)/4 = 95.0$ mm^3
$H_w = 9.5(95.0) = 902.8$ J
Required heat for the RSW operation $H = 902.8/(1/3) = 2708$ J
$H = I^2Rt = I^2(140 \times 10^{-6})(0.3) = 42 \times 10^{-6}\, I^2 = 2708$ J
$I^2 = 2708/(42 \times 10^{-6}) = 64.5 \times 10^6$ A^2
$I = 8.03 \times 10^3 =$ **8,030 A**

29.10 **(A)** (USCS units) A resistance spot-welding operation is performed on two pieces of 0.047-in-thick low-carbon sheet steel. The unit melting energy for this steel = 150 Btu/in^3. Current = 9500 A, time duration = 0.2 sec, and resistance = 120 micro-ohms. This results in a weld nugget with diameter = 0.22 in, and average thickness = 0.15 in. Determine the (a) average power density in the interface area defined by the weld nugget and (b) proportion of total energy used to form the weld nugget.

Solution: (a) $PD = I^2R/A$
$A = \pi D^2/4 = \pi(0.22)^2/4 = 0.038$ in^2
$I^2R = (9500)^2\,(120 \times 10^{-6}) = 10{,}830$ W
1 Btu/sec = 1055 W, so 10,830 W = 10.265 Btu/sec
$PD = 10.265/0.038 =$ **270 Btu/sec-in^2**

(b) $H = I^2Rt = (9500)^2\,(120 \text{ x } 10^{-6})(0.2) = 2166$ W-sec = 2.053 Btu
Weld nugget volume $V = \pi D^2d/4 = \pi(0.22)^2(0.15)/4 = 0.0057$ in^3
Heat required for melting = U_mV = (150 Btu/in^3)(0.0057) = 0.855 Btu
Proportion of heat used for welding = 0.855/2.053 = **0.416 = 41.6%**

29.11 (SI units) A resistance seam-welding operation is performed on two pieces of 2.5-mm-thick austenitic stainless steel to fabricate a container. Current in the operation = 10,000 amps, weld duration = 0.2 sec, and the resistance at the interface is 75 micro-ohms. Continuous motion welding is used with 200-mm-diameter electrode wheels. The individual weld nuggets formed in this RSEW operation have diameter = 6.0 mm, and average thickness = 3.0 mm (assume that the weld nuggets are disk-shaped). The weld nuggets must be contiguous to form a sealed seam. The power unit driving the process requires an off-time between spot welds of 1.0 s. The unit melting energy of stainless steel = 9.3 J/mm^3.

Determine the (a) proportion of total energy used to form the weld nugget and (b) rotational speed of the electrode wheels.

Solution: (a) $H_w = U_m V$
$V = \pi D^2 d/4 = \pi(6.0)^2(3.0)/4 = 84.82$ mm^3
$H_w = (9.3$ J/mm$^3)(84.82$ mm$^3) = 789$ J
$H = I^2Rt = (10{,}000)^2(75 \times 10^{-6})(0.2) = 1500$ J
Proportion of heat for welding =789/1500= **0.526 = 52.6%**

(c) Total cycle time per weld $T_c = 0.2 + 1.0 = 1.2$ sec.
Distance moved per spot weld in order to have contiguous spot welds for the seam = 6 mm.
Therefore, surface speed of electrode wheel $v = 6.00$ mm/1.2 sec = 5.0 mm/s = 300 mm/min.
$N = v/\pi D$ = (300 mm/min)/(200π mm/rev) = **0.477 rev/min**

29.12 Quality problems are occurring in a resistance spot-welding operation in the fabrication of steel containers. The steel is 2.4-mm-thick (0.094-in-thick) low-carbon sheet steel. The main problem is incomplete fusion of the spot welds, in which the weld nuggets are very small and susceptible to separation. In some cases, weld nuggets do not even form. Without knowing any more about the operation, make several recommendations that might solve the problem.

Solution: The physics of a spot-welding operation are captured in Equation (29.3): $H = I^2Rt$. The problem of incomplete fusion suggests that insufficient heat is being used to form the weld nuggets. The possible remedies indicated by the heat equation are: (1) increase the welding current I, (2) increase the duration t of the cycle, and (3) make sure the faying surfaces are clean so that as much of the heat as possible is applied to form the weld nugget rather than dissipated into the surrounding metal, electrodes, and air.

Oxyfuel Welding

29.13 **(A)** (SI units) Suppose in Example 29.3 in the text that the fuel used in the welding operation is MAPP instead of acetylene and the proportion of heat concentrated in the 9 mm circle = 60% instead of 75 %. Compute the (a) rate of heat liberated during combustion, (b) rate of heat transferred to the work surface, and (c) average power density in the circular area.

Solution: (a) Rate of heat generated by the torch $R_H = (0.3$ m^3/hr$)(91.7 \times 10^6$ J/m$^3)$
$= 27.5 \times 10^6$ J/hr = **7642 J/s**

(b) Rate of heat received at work surface = $f_1 R_H = 0.25(7642) =$ **1910 J/s**

(c) Area of circle in which 60% of heat is concentrated $A = \pi D^2/4 = \pi(9.0)^2/4 = 63.6$ mm^2
Power density $PD = 0.60(1910)/63.6 =$ **18.0 W/mm^2**

29.14 (USCS units) An oxyacetylene torch supplies 8.5 ft^3 of acetylene per hour and an equal volume rate of oxygen for an OAW operation on ¼-in steel. Heat generated by combustion is transferred to the work surface with a heat transfer factor = 0.3. If 80% of the heat from the flame is concentrated in a circular area on the work surface whose diameter = 0.40 in, determine the (a) rate of heat liberated during combustion, (b) rate of heat transferred to the work surface, and (c) average power density in the circular area.

Solution: (a) Rate of heat generated by the torch R_H = (8.5 ft^3/hr)(1470 Btu/ft^3)
= **12,500 Btu/hr = 3.47 Btu/sec**

(b) Rate of heat received at work surface = f_1R_H = 0.30(3.47 Btu/sec) = **1.04 Btu/sec**

(c) Area of circle in which 80% of heat is concentrated $A = \pi D^2/4 = \pi(0.4)^2/4 = 0.1257$ in^2
Power density PD = 0.80(1.04 Btu/sec)/(0.1257 in^2) = **6.63 Btu/sec-in^2**

29.15 (SI units) An oxyacetylene welding operation is used to weld a corner joint formed by two 7.5-mm-thick low-carbon steel plates. A fillet weld is made in the joint, adding filler metal of the same composition with the base metal, and the cross-sectional area of the weld bead = 75 mm^2. Travel speed at which the bead is formed = 5 mm/s. The unit melting energy of the steel = 10.3 J/mm^3. From previous OAW operations, it is known that only 40% of the energy generated by the torch is used to melt the metal; the rest is dissipated. Determine the volume flow rate of acetylene required to perform this OAW operation. An equal volume flow rate of oxygen will be used.

Solution: (a) Rate of heat input required to form the weld bead $R_{Hw} = AvU_m$
$R_{Hw} = AvU_m$ = (75 mm^2)(5 mm/s)(10.3 J/mm^3) = 3862.5 J/s
Power required by torch $R_H = R_{Hw}/0.40$ = 3862.5/0.40 = 9,656 J/s
Let R_{Vf} = volume flow rate of fuel (acetylene) to the process, m^3/s
From Table 29.2, the heat of combustion of acetylene = 54.8 MJ/m^3
Power generated by torch $R_H = R_{Vf}(54.8 \times 10^6$ J/m^3) = 9,656 J/s
R_{Vf} = (9,656 J/s)/(54.8 × 10^6 J/m^3) = 176.2 × 10^{-6} m^3/s
Converting to an hourly rate, R_{Vf} = (176.2 × 10^{-6} m^3/s)(3600 s/hr) = **0.634 m^3/hr**

Electron-Beam Welding

29.16 **(A)** (SI units) The voltage in an EBW operation is 45 kV. The beam current is 50 milliamp. The electron beam is focused on a circular area that is 0.50 mm in diameter. The heat transfer factor is 0.87. Calculate the average power density in the area in watt/mm^2.

Solution: Power density $PD = f_1EI/A$
Power $P = f_1EI = 0.87(45 \times 10^3)(50 \times 10^{-3}) = 1957$ W
Area $A = \pi D^2/4 = \pi(0.5)^2/4 = 0.196$ mm^3
PD = 1957/0.196 = **9,985 W/mm^2**

29.17 (SI units) An EBW operation is used to butt-weld two sheet metal parts that are 3 mm thick. The unit melting energy = 8.0 J/mm^3. The weld joint is 0.35 mm wide, so that the cross section of the fused metal = 0.35 mm by 3.0 mm. If accelerating voltage = 25 kV, beam current = 30 milliamp, heat transfer factor f_1 = 0.85, and melting factor f_2 = 0.75, determine the travel speed at which this weld is made along the seam.

Solution: Available heat for welding $R_{HW} = f_1f_2EI = U_mA_wv$
Travel velocity $v = f_1f_2EI/U_mA_w$
Cross-sectional area of weld seam A_w = (0.35)(3.0) = 1.05 mm^2
$v = 0.85(0.75)(25 \times 10^3)(30 \times 10^{-3})/(8.0 \times 1.05)$ = **56.9 mm/s**

Welding Economics

29.18 **(A)** (SI units) A shielded metal arc-welding operation is accomplished in a work cell by a fitter and a welder. The fitter takes 5.5 min to load components into the welding fixture at the beginning of the work cycle, and 1.5 min to unload the completed weldment at the end of the cycle. The total length of the weld seams = 1200 mm, and the travel speed used by the welder averages 300 mm/min. Every 600 mm of seam length, the welding stick must be changed, which takes 0.8 min. While the fitter is working, the welder is idle (resting); while the welder is working, the fitter is idle. (a) Determine the average arc-on time as a fraction of the work cycle time. (b) How much improvement in arc-on time would result if the welder used flux-cored arc welding (manually operated), given that the spool of weld wire must be changed every 10 weldments, and it takes the welder 5.0 min to accomplish the change? (c) What are the production rates for these two cases (weldments completed per hour)?

Solution: (a) SMAW cycle time T_c = 5.5 + 1200/300 + (1200/600)(0.8) + 1.5 = 5.5 + 4.0 + 1.6 + 1.5 = 12.6 min
Arc-on time = 4.0/12.6 = 0.317 = **31.7%**

(b) In the FCAW work cycle, assume the work is organized so that the welder changes the spool (5.0 min) at the same time the fitter unloads and loads parts into the welding fixture (5.5 min). Thus, when the spool needs to be changed, the fitter's time dominates the cycle.
Thus, FCAW cycle time T_c = 5.5 + 1200/300 + 1.5 = 5.5 + 4.0 + 1.5 = 11.0 min
Arc-on time = 4.0/11.0 = 0.364 = **36.4%**

(c) SMAW R_p = 60/12.6 = **4.76 pc/hr**
FCAW R_p = 60/11.0 = **5.45 pc/hr**. This is an increase in production rate of 14%.

29.19 (SI units) In the previous problem, a proposal has been made to install an industrial robot to replace the welder. The cell would consist of the robot, two welding fixtures, and the fitter who loads and unloads the parts. With two fixtures, the fitter and robot would work simultaneously, the robot welding at one fixture while the fitter unloads and loads at the other. At the end of each work cycle, they switch places. The robot would use gas metal arc welding instead of shielded-metal or flux-cored arc welding, but the welding speed would remain the same at 300 mm/min. The electrode wire spool must be changed every 10 work parts, which takes 5.0 min and is accomplished by the fitter. Determine the (a) arc-on time and (b) production rate for this work cell.

Solution: (a) Fitter: T_c = 5.5 + 1.5 + (1/10)(5.0) = 7.5 min
Robot: T_c = 1200/300 + (1/10)(5.0) = 4.5 min
Limiting cycle is the fitter: arc-on time = 4.0/7.5 = 0.533 **= 53.3%**

(b) R_p = 60/7.5 = **8.0 pc/hr**. This is an increase in production rate of 73% over the original SMAW cycle and 47% over the FCAW cycle in the previous problem.

29.20 (SI units) In Example 29.4, the welder works alone, performing not only the welding but also loading and unloading the parts. Suppose a fitter is used in the work cycle to load the starting parts and unload the weldment, and a two-position fixture is installed so that the welder and fitter can work simultaneously. The fixture is designed to index (rotate) between the two positions at the end of each work cycle; indexing time = 0.15 min. The fitter performs the work handling elements, and the welder performs all elements related to welding and changing electrodes. Determine the (a) work cycle time and (b) arc-on time as a fraction of the work cycle time. If the welder and fitter take 30 min of rest breaks during the 8-hr work shift, (c) how many weldments are produced during the shift and (d) what is the arc-on time as a fraction of the 8-hr shift?

Solution: (a) Using the results of Example 29.4, T_o = 0.728 min, T_h = 1.80 min, and T_t = 1.42 min. The fitter's time = 1.80 min and the welder's time = 0.728 + 1.42 = 2.15 min
T_c = Max (1.80 min, 2.15 min) + 0.15 = **2.30 min**

(b) Arc-on time as a fraction of the work cycle time = $\dfrac{0.728}{2.30}$ = 0.317 = **31.7%**

(c) Number of weldments produced = $\dfrac{(8.0-0.5)(60)}{2.30}$ = 195.6 rounded to **195**

(d) Arc-on time as a fraction of 8-hr shift = $\dfrac{195(0.728/60)}{8.0}$ = 0.296 = **29.6%**

Comment: These are significant improvements compared to the results of Example 29.4.

29.21 For the preceding problem, the labor rates for the welder and fitter are \$35.00/hr and \$25.00/hr, respectively, and the equipment cost rate = \$10.00/hr, which includes the cost of the new two-position fixture. All three rates include applicable overheads. Power during arc-on time = 6,000 W, and cost of electricity = \$0.128/kWH. Determine the (a) cost of each weldment produced in the operation and (b) cost of electric power per weldment. (c) Also, determine the hourly electric power cost in the operation.

Solution: (a) The cost rate of labor and equipment = 35.00 + 25.00 + 10.00 = \$70.00/hr
C_{pc} = 2.66 + $\left(\dfrac{70.00}{60}\right)2.30+0.85$ = 2.66 + 2.68 + 0.85 = **\$6.19/pc**

(b) Power P = 6,000 W = 6.0 kW
The arc-on time for each weldment T_o = 0.728 min = 0.01213 hr
The number of kilowatt-hours per weldment = 6.0(0.01213) = 0.073 kWH
At \$0.128/kWH, cost of power per weldment = 0.073(0.128) = **\$0.0093/pc**
Including this cost, C_{pc} = **\$6.20/pc**

(c) From the preceding problem, there are 195 weldments produced during the 8-hr shift.
The total cost of power for 195 weldments = 195(\$0.0093) = \$1.81/shift
On an hourly basis, electric power cost = \$1.81/8 = **\$0.227/hr**

29.22 (SI units) A submerged arc-welding operation is performed on a steel plate that has been roll formed to the shape of a tube whose diameter = 400 mm. The SAW operation is used to weld a longitudinal seam to join the two edges of the formed plate. The unwelded tube is loaded into a fixture so that the two edges are on top, and the SAW operation is performed over the length of the tube, which is 3.5 m. Loading the unwelded tube takes 4.0 min, and unloading the welded tube takes 2.5 min. Positioning the submerged arc-welding head before and after the work cycle takes a total of 3.0 min. The volume rate of metal welded = 236 mm^3/s, of which 75% is melting of the wire electrode and 25% is melting of the base metal. The diameter of the wire electrode = 3.2 mm. The spool of weld wire must be changed every 20 weldments, and this takes 7.0 min. The cross-sectional area of the resulting weld seam is 50 mm^2. Chipping away the slag from the granular flux is accomplished in a manual operation that is performed later and is not part of this welding cycle. Determine the (a) total work cycle time, (b) arc-on time as a fraction of the welding cycle time, and (c) length of electrode wire that is consumed in each weldment.

Solution: (a) The weld seam area that is from the electrode wire = 0.75(50) = 37.5 mm^2
The total volume of weld wire in the 3.5 m seam length = 37.5(3.5×1000) = 131,250 mm^3
At a deposition rate of 0.75(236 mm^3/s) = 177 mm^3/s, the arc-on time = 131,250/177 = 741.5 s = 12.36 min
The terms in Equation (1.1) for this operation are as follows: T_o = 12.36 min, T_h = 4.0 + 2.5 = 6.5 min, T_t = 3.0 + 7.0/20 = 3.0 + 0.35 = 3.35 min
T_c = 12.36 + 6.5 + 3.35 = **22.21 min**

(b) The arc-on time as a fraction of the work cycle = 12.36/22.21 = 0.557 = **55.7%**

(c) The cross-sectional area of the electrode wire = $\pi(3.2^2)$ = 32.17 mm^2
The length of wire consumed in each weldment = 131,250/32.17 = 4080 mm = **4.08 m**

29.23 It is desired to determine the cost of the submerged arc-welding operation in the preceding problem, including electric power cost but excluding work material costs. Power during arc-on time = 9000 W, and cost of electricity = \$0.15/kWH. The labor cost rate = \$33.00/hr and the SAW equipment cost = \$20.00/hr (including applicable overheads). The cost of each spool of electrode wire = \$50.00. The cost of granular flux used in each cycle = \$2.00. What is the welding cost of each completed tube?

Solution: From the previous problem, T_c = 22.21 min
C_o = 33.00 + 20.00 = \$53.00/hr
C_oT_c = (53.00/60)(22.21) = \$19.62/pc
The cost per spool of weld wire = \$50, and it can be used for 20 tubes. Adding the cost of flux, C_t = \$50.00/20 + 2.00 = \$4.50/pc
Power used per weldment = (9 kW)(22.21 min/60) = 3.33 kWH
Cost of electricity = (\$0.15/kWH)(3.33 kWH) = \$0.50/pc
Cost per weldment C_{pc} = 19.62 + 4.50 + 0.50 = **\$24.62/pc**

29.24 (SI units) In a manual gas metal arc-welding operation, a fillet weld is made to form an outside single corner joint, as in Figure 28.3(b), along a seam that is 1.5 m long. The design specifications call for a 6.4-mm fillet weld to be made, but the welder makes a 9.5-mm fillet weld instead. The volume rate of metal welded = 220 mm^3/s, of which 70% is melting of the bare wire electrode and 30% is melting of the base metal. The spool of weld wire must be changed every 20 weldments, and this takes 7.0 min. Power during arc-on time = 6000 W, and cost of electricity = \$0.14/kWH. The labor cost rate = \$36.00/hr and the GMAW equipment cost = \$6.00/hr (including applicable overheads). The diameter of the electrode wire = 1.5 mm, and its cost per length = \$0.90/m. Cost of supplying shielding gas = \$0.50/min. Considering only the arc-on time per cycle, (a) how much is the welding cycle time increased to perform the 9.5-mm fillet than it would for the 6.4-mm fillet and (b) how much more does it cost?

Solution: (a) Cross-sectional area of a 6.4-mm fillet = $A = bh/2 = (6.4^2)/2$ = 20.5 mm^2
Travel velocity of the welding operation v = (220 mm^3/s × 0.7)/(20.5 mm^2) = 7.51 mm/s

Time to complete the weld = L/v = (1.5×1000 mm)/(7.51 mm/s) = 199.7 s = 3.33 min
Cross-sectional area of a 9.5-mm fillet weld is $A = bh/2 = (9.5^2)/2 = 45.1$ mm^2
Travel velocity of the welding operation v = (220 mm^3/s × 0.7)/(45.1 mm^2) = 3.41 mm/s
Time to complete the weld = L/v = (1.5×1000 mm)/(3.41 mm/s) = 439.9 s = 7.33 min
The welding cycle time is increased by 7.33 – 3.33 = **4.0 min**, a 120% increase

(b) Cost rate of labor and equipment C_o = 36.00 + 6.00 = $42.00/hr
Additional cost of the 9.5-mm vs. 6.4-mm fillet weld = ($42/60)(4.0 min) = $2.80/pc
Additional cost of supplying shielding gas = ($0.50/min)(4.0 min) = $2.00/pc
Additional cost of electric power = ($0.14/kWH)(6.0 kW)(4.0 min/60) = $0.056 ≅ $0.06/pc
Given a weld wire diameter = 1.5 mm, cross-sectional area = $\pi(1.5)^2$ = 7.07 mm^2
For the 6.4-mm fillet weld, total volume of each seam = AL = (20.5 mm^2)(1500 mm) = 30,750 mm^3, and the volume of weld wire = 30,750(0.7) = 21,525 mm^3
The length of wire consumed in each weldment = 21,525/7.07 = 3045 mm = 3.045 m
Cost of weld wire per cycle = ($0.90/m)(3.045 m) = $2.74/pc
For the 9.5-mm fillet weld, total volume of each seam = AL = (45.1 mm^2)(1500 mm) = 67,650 mm^3, and the volume of weld wire = 67,650(0.7) = 47,355 mm^3
The length of wire consumed in each weldment = 47,355/7.07 = 6698 mm = 6.698 m
Cost of weld wire per cycle = ($0.90/m)(6.698 m) = $6.03/pc
Total additional cost of 9.5-mm fillet = 2.80 + 2.00 + 0.06 + (6.03 – 2.74) = **$8.15/pc**