Problems

Arc Welding

30.1 A SMAW operation is accomplished in a work cell using a fitter and a welder. The fitter takes 5.5 min to place the unwelded components into the welding fixture at the beginning of the work cycle, and 2.5 min to unload the completed weldment at the end of the cycle. The total length of the several weld seams to be made is 2000 mm, and the travel speed used by the welder averages 400 mm/min. Every 750 mm of weld length, the welding stick must be changed, which takes 0.8 min. While the fitter is working, the welder is idle (resting); and while the welder is working, the fitter is idle. (a) Determine the average arc time in this welding cycle. (b) How much improvement in arc time would result if the welder used FCAW (manually operated), given that the spool of flux-cored weld wire must be changed every five 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 + 2000/400 + (2000/750)(0.8) + 2.5
= 5.5 + 5.0 + 2.133 + 2.5 = 15.133 min
Arc time = 5.0/15.133 = **33.0%**

(b) FCAW cycle time T_c = 5.5 + 2000/400 + (1/5)(5.0) + 2.5
= 5.5 + 5.0 + 1.0 + 2.5 = 14.0 min
Arc time = 5.0/14.0 = **35.7%**

(c) SMAW R_p = 60/15.133 = **3.96 pc/hr**
FCAW R_p = 60/14.0 = **4.29 pc/hr**.

30.2 In the previous problem, suppose an industrial robot cell were installed to replace the welder. The cell consists of the robot (using GMAW instead of SMAW or FCAW), two welding fixtures, and the fitter who loads and unloads the parts. With two fixtures, fitter and robot 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 electrode wire spool must be changed every five workparts, which task requires 5.0 minutes and is accomplished by the fitter. Determine (a) arc time and (b) production rate for this work cell.

Solution: (a) Fitter: T_c = 5.5 + 2.5 + (1/5)(5.0) = 9.0 min
Robot: T_c = 2000/400 = 5.0 min
Limiting cycle is the fitter: arc time = 5.0/9.0 = **55.5%**

(b) R_p = 60/9.0 = **6.67 pc/hr.**

30.3 A shielded metal arc-welding operation is performed on steel at a voltage = 30 volts and a current = 225 amps. The heat transfer factor = 0.85 and melting factor = 0.75. The unit melting energy for steel = 10.2 J/mm^3. Determine (a) the rate of heat generation at the weld and (b) the volume rate of metal welded.

Solution: (a) $R_{HW} = f_1 f_2 EI$ = (0.85)(0.75)(30)(225) = **4303.1 W**

(b) R_{WV} = (4303.1 W)/(10.2 J/mm^3) = **421.9 mm^3/sec.**

30.4 A GTAW operation is performed on low carbon steel, whose unit melting energy is 10.3 J/mm^3. The welding voltage is 22 volts and the current is 135 amps. The heat transfer factor is 0.7 and the melting factor is 0.65. If filler metal wire of 3.5 mm diameter is added to the operation, the final weld bead is composed of 60% volume of filler and 40% volume base metal. If the travel speed in the operation is 5 mm/sec, determine (a) cross-sectional area of the weld bead, and (b) the feed rate (mm/sec) at which the filler wire must be supplied.

Solution: (a) $R_{HW} = f_1 f_2 EI = U_m A_w v$
$A_w = f_1 f_2 EI/(U_m v)$ = 0.7(0.65)(22)(135)/(10.3x5.0) = **26.24 mm^2**

(b) Volume of weld = $A_w v$ = 26.24(5.0) = 131.2 mm^3/s
Filler wire $A = \pi D^2/4 = \pi(3.5)^2/4$ = 9.62 mm^2
At 60% filler metal, feed rate of filler wire = 131.2(0.60)/9.62 = **8.18 mm/s**

30.5 A flux-cored arc-welding operation is performed to butt weld two austenitic stainless steel plates together. The welding voltage is 21 volts and the current is 185 amps. The cross-sectional area of the weld seam = 75 mm^2 and the melting factor of the stainless steel is assumed to be 0.60. Using tabular data and equations given in this and the preceding chapter, determine the likely value for travel speed v in the operation.

Solution: From Table 30.1, f_1 = 0.9 for FCAW.
From Table 29.2, T_m = 1670°K for austenitic stainless steel.
$U_m = 3.33 \times 10^{-6} (1670)^2 = 9.29$ J/mm^3
$f_1 f_2 EI = U_m A_w v$
$v = f_1 f_2 EI/U_m A_w$ = 0.9(0.6)(21)(185)/(9.29 x 75) = **3.01 mm/s**

30.6 A flux-cored arc-welding process is used to join two low alloy steel plates at a 90° angle using an outside fillet weld. The steel plates are ½ in thick. The weld bead consists of 55% metal from the electrode and the remaining 45% from the steel plates. The melting factor of the steel is 0.65 and the heat transfer factor is 0.90. The welding current is 75 amps and the voltage is 16 volts. The velocity of the welding head is 40 in/min. The diameter of the electrode is 0.10 in. There is a core of flux running through the center of the electrode that has a diameter of 0.05 in and contains flux (compounds that do not become part of the weld bead). (a) What is the cross-sectional area of the weld bead? (b) How fast must the electrode be fed into the workpiece?

Solution: (a) T_m from Table 29.2 is 3060°R
$U_m = KT_m^2 = 1.467\times10^{-5}(3060^2)$ = 137.4 Btu/in^3
$R_{HW} = f_1 f_2 EI = U_m A_w v$, rearranging, $A_w = f_1 f_2 EI/U_m v$
$f_1 f_2 EI$ = 0.90(0.65)(16)(75) = 702 J/sec
$U_m v$ = (137.4 Btu/in^3)(40 in/min) = 5496 Btu/in^2-min
Conversions: 1 Btu = 1055 J and 1 min = 60 sec
$U_m v$ = 5496 Btu/in^2-min(1055 J/Btu)(min/60 sec) = 96,638 J/in^2-sec
A_w = (702 J/sec) / (96,638 J/in^2-sec) = **0.00726 in^2**

(b) Volume of weld = $A_w v$ = 0.00726(40) = 0.2906 in^3/min
Electrode $A = \pi D^2/4 = \pi(0.10)^2/4 = 78.5\times10^{-4}$ in^2
Flux $A = \pi D^2/4 = \pi(0.05)^2/4 = 19.6\times10^{-4}$ in^2
Metal in electrode $A = 78.5\times10^{-4} - 19.6\times10^{-4}$ in^2 = 58.9×10^{-4} in^2 = 0.00589 in^2
At 55% electrode metal,
feed rate of electrode = 0.2906 in^3/min (0.55) / 0.00589 = **27.13 in/min (0.452 in/sec)**

30.7 A gas metal arc-welding test is performed to determine the value of melting factor f_2 for a certain metal and operation. The welding voltage = 25 volts, current = 125 amps, and heat transfer factor is assumed to be = 0.90, a typical value for GMAW. The rate at which the filler metal is added to the weld is 0.50 in^3 per minute, and measurements indicate that the final weld bead consists of 57% filler metal and 43% base metal. The unit melting energy for the metal is known to be 75 Btu/in^3. (a) Find the melting factor. (b) What is the travel speed if the cross-sectional area of the weld bead = 0.05 in^2?

Solution: (a) $f_1 f_2 EI = U_m A_w v$
$A_w v$ = welding volume rate = R_{WV} = (0.50 in^3/min)/0.57 = 0.877 in^3/min = 0.01462 in^3/sec.
Therefore, $f_1 f_2 EI = U_m(R_{WV})$
1 Btu/sec = 1055 J/s = 1055 W, so 75 Btu/sec = 79,125 W
$f_2 = U_m(R_{WV})/f_1 EI$ = 79,125(0.01462)/(0.9 x 25 x 125) = **0.41**

(b) Given that $A_w = 0.05$ in^2, $v = (R_{WV})/A_w = 0.877/0.05 =$ **17.54 in/min**

30.8 A continuous weld is to be made around the circumference of a round steel tube of diameter = 6.0 ft, using a submerged arc welding operation under automatic control at a voltage of 25 volts and current of 300 amps. The tube is slowly rotated under a stationary welding head. The heat transfer factor for SAW is = 0.95 and the assumed melting factor = 0.7. The cross-sectional area of the weld bead is 0.12 in^2. If the unit melting energy for the steel = 150 Btu/in^3, determine (a) the rotational speed of the tube and (b) the time required to complete the weld.

Solution: (a) $f_1 f_2 EI = U_m A_w v$
$v = f_1 f_2 EI/U_m A_w$
1 Btu/sec = 1055 J/s = 1055 W, so 150 Btu/sec = 158,250 W
$v = 0.95(0.7)(25)(300)/(158{,}250 \times 0.120) = 0.263$ in/sec = 15.76 in/min
Circumference $C = \pi D = 12 \times 6\pi = 226.2$ in/rev.
Rotational speed N = (15.76 in/min)/(226.2 in/rev) = **0.06967 rev/min**

(b) Time to weld around circumference = C/v = (226.2 in/rev)/(15.76 in/min) = **14.35 min**

Resistance Welding

30.9 An RSW operation is used to make a series of spot welds between two pieces of aluminum, each 2.0 mm thick. The unit melting energy for aluminum = 2.90 J/mm^3. Welding current = 6,000 amps, and time duration = 0.15 sec. Assume that the resistance = 75 micro-ohms. The resulting weld nugget measures 5.0 mm in diameter by 2.5 mm thick. How much of the total energy generated is used to form the weld nugget?

Solution: $H = I^2Rt = (6000)^2(75 \times 10^{-6})(0.15) = 405$ W-sec = 405 J
Weld nugget volume $V = \pi D^2 d/4 = \pi(5)^2(2.5)/4 = 49.1$ mm^3
Heat required for melting = $U_m V$ = (2.9 J/mm^3)(49.1 mm^3) = 142.4 J
Proportion of heat for welding =142.4/405 = **0.351 = 35.1%**

30.10 An RSW operation is used to join two pieces of sheet steel having a unit melting energy of 130 Btu/in^3. The sheet steel has a thickness of 1/8 in. The weld duration will be set at 0.25 sec with a current of 11,000 amp. Based on the electrode diameter, the weld nugget will have a diameter of 0.30 in. Experience has shown that 40% of the supplied heat melts the nugget and the rest is dissipated by the metal. If the electrical resistance between the surfaces is 130 micro-ohms, what is the thickness of the weld nugget assuming it has a uniform thickness?

Solution: $H = I^2Rt = 11{,}000^2(0.000130)(0.25) = 3{,}930$ J = 3,930/1055 = 3.727 Btu
$V = H_w/U_m = (0.4)(3.727/130) = 0.0115$ in^3
$V = (d)\pi D^2/4$; $d = V/(\pi D^2/4) = 0.0115/(0.25\pi(0.30^2)) =$ **0.162 in**

30.11 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 5.0 mm thick. The weld duration will be set at 0.3 sec. If it is assumed that the electrical resistance between the surfaces is 140 micro-ohms, and that 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: $H_m = U_m V$
$V = \pi D^2 d/4 = \pi(5.5)^2(5.0)/4 = 118.8$ mm^3
$H_w = 9.5(118.8) = 1129$ J
Required heat for the RSW operation $H = 1129/(1/3) = 3386$ J
$H = I^2Rt = I^2(140 \times 10^{-6})(0.3) = 42 \times 10^{-6}\, I^2 = 3386$ J
$I^2 = 3386/(42 \times 10^{-6}) = 80.6 \times 10^6$ A^2
$I = 8.98 \times 10^3 =$ **8,980 A**

30.12 A resistance spot-welding operation is performed on two pieces of 0.040 in thick sheet steel (low carbon). The unit melting energy for steel = 150 Btu/in^3. Process parameters are: current = 9500 A and time duration = 0.17 sec. This results in a weld nugget of diameter = 0.19 in and thickness = 0.060 in. Assume the resistance = 100 micro-ohms. Determine (a) the average power density in the interface area defined by the weld nugget, and (b) the proportion of energy generated that went into formation of the weld nugget.

Solution: (a) $PD = I^2R/A$
$A = \pi D^2/4 = \pi(0.19)^2/4 = 0.02835$ in^2
$I^2R = (9500)^2\ (100 \times 10^{-6}) = 9025$ W
1 Btu/sec = 1055 W, so 9025 W = 8.554 Btu/sec
$PD = 8.554/0.02835 =$ **302 Btu/sec-in^2**

(b) $H = I^2Rt = (9500)^2\ (100 \times 10^{-6})(0.17) = 1534$ W-sec = 1.454 Btu
Weld nugget volume $V = \pi D^2 d/4 = \pi(0.19)^2(0.060)/4 = 0.0017$ in^3
Heat required for melting = $U_m V$ = (150 Btu/in^3)(0.0017) = 0.255 Btu
Proportion of heat for welding = 0.255/1.454 = **0.175 = 17.5%**

30.13 A resistance seam-welding operation is performed on two pieces of 2.5-mm-thick austenitic stainless steel to fabricate a container. The weld current in the operation is 10,000 amps, the weld duration = 0.3 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 mm and thickness = 3 mm (assume the weld nuggets are disc-shaped). These 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. Given these conditions, determine (a) the unit melting energy of stainless steel using the methods of the previous chapter, (b) the proportion of energy generated that goes into the formation of each weld nugget, and (c) the rotational speed of the electrode wheels.

Solution: (a) From Table 29.2, T_m = 1670°K for austenitic stainless steel.
$U_m = 3.33 \times 10^{-6}\ (1670)^2 =$ **9.29 J/mm^3.**

(b) $H_w = U_m V$
$V = \pi D^2 d/4 = \pi(6.0)^2(3.0)/4 = 84.82$ mm^3
H_w = (9.29 J/mm^3)(84.82 mm^3) = 788 J
$H = I^2Rt = (10{,}000)^2(75 \times 10^{-6})(0.3) = 2225$ J
Proportion of heat for welding =788/2225= **0.354 = 35.4%**

(c) Total cycle time per weld T_c = 0.3 + 1.0 = 1.3 sec.
Distance moved per spot weld in order to have contiguous spot welds for the seam = D = 0.6 mm.
Therefore, surface speed of electrode wheel v = 6.00 mm/1.3 sec = 4.61 mm/s = 276.9 mm/min.
$N = v/\pi D$ = (276.9 mm/min)/(200π mm/rev) = **0.441 rev/min**

30.14 Suppose in the previous problem that a roll spot-welding operation is performed instead of seam welding. The interface resistance increases to 100 micro-ohms, and the center-to-center separation between weld nuggets is 25 mm. Given the conditions from the previous problem, with the changes noted here, determine (a) the proportion of energy generated that goes into the formation of each weld nugget, and (b) the rotational speed of the electrode wheels. (c) At this higher rotational speed, how much does the wheel move during the current on-time, and might this have the effect of elongating the weld nugget (making it elliptical rather than round)?

Solution: (a) $U_m = 3.33 \times 10^{-6}\ (1670)^2 = 9.29$ J/mm^3 from previous problem.
H_w = (9.29 J/mm^3)(84.82 mm^3) = 788 J from previous problem.
$H = I^2Rt = (10{,}000)^2(100 \times 10^{-6})(0.3) = 3000$ J
Proportion of heat for welding =788/3000 = **0.263 = 26.3%**

(b) Total cycle time per spot weld T_c = 1.3 sec as in previous problem.
Distance moved per spot weld = 25 mm as given.
Surface speed of electrode wheel v = 25 mm/1.3 sec = 19.23 mm/s = 1153.8 mm/min
$N = v/\pi D$ = (1153.8 mm/min)/(200π in/rev) = **1.836 rev/min**

(c) Power-on time during cycle = 0.3 sec.
Movement of wheel during 0.3 sec = (0.3 sec)(19.23 mm/s) = **5.77 mm**. This movement is likely to make the weld spot elliptical in shape.

30.15 Resistance projection welding is used to simultaneously weld two thin, steel plates together at four locations. One of the pieces of steel plate is preformed with projections that have a diameter of 0.25 in and a height of 0.20 in. The duration of current flow during the weld is 0.30 sec and all four projections are welded simultaneously. The plate steel has a unit melting energy of 140 Btu/in^3 and a resistance between plates of 90.0 micro-ohms. Experience has shown that 55% of the heat is dissipated by the metal and 45% melts the weld nugget. Assume the volume of the nuggets will be twice the volume of the projections because metal from both plates is melted. How much current is required for the process?

Solution: Volume single projection = $d\pi D^2/4$ = 0.00982 in^3
Volume of one nugget V = 2*0.00982 = 0.01964 in^3
Volume of 4 nuggets = 4(0.01964) = 0.07854 in^3
$H_m = U_m V$ = 140(0.07854) = 11.00 Btu
Total H required = H_w/(% used to melt plate) = 11.00/0.45 = 24.43 Btu
Total H in Joules = 24.43(1055) = 25,780 J
$I^2 = H/(Rt)$ = 25,780/(90x10^{-6}*0.3) = 9.55x10^8 amp^2
I = (9.55x10^8)$^{0.5}$ = **30,900 amp**

30.16 An experimental power source for spot welding is designed to deliver current as a ramp function of time: I = 100,000 t, where I = amp and t = sec. At the end of the power-on time, the current is stopped abruptly. The sheet metal being spot welded is low carbon steel whose unit melting energy = 10 J/mm^3. The resistance R = 85 micro-ohms. The desired weld nugget diameter = 4 mm and thickness = 2 mm (assume a disc-shaped nugget). It is assumed that 1/4 of the energy generated from the power source will be used to form the weld nugget. Determine the power-on time the current must be applied in order to perform this spot-welding operation.

Solution: $H_w = U_m V$
$V = \pi D^2 d/4 = \pi(4)^2(2)/4$ = 25.14 mm^3
H_w = (10 J/mm^3)(25.14 mm^3) = 251.4 J
H = 251.4/0.25 = 1005.6 J
Power $P = \int I^2 R\, dt = \int (100{,}000t)^2 R\, dt = 100{,}000\mathrm{R} \int t^2\, dt = (10^5)^2(85 \times 10^{-6})t^3/3$ evaluated between 0 and t.
$H = 850{,}000t^3/3 = 31481.5\, t^3$ = 1005.6
t^3 = 1005.6/31481.5 = 0.031943
t = (0.031943)$^{1/3}$ = **0.317 s.**

Oxyfuel Welding

30.17 Suppose in Example 30.3 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 is 60% instead of 75 %. Compute (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 x 10^6 J/m^3)
= 27.5 x 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/mm²**

30.18 An oxyacetylene torch supplies 8.5 ft^3 of acetylene per hour and an equal volume rate of oxygen for an OAW operation on 1/4 in steel. Heat generated by combustion is transferred to the work surface with a heat transfer factor of 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, find: (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 = $f_1 R_H = 0.30(3.47$ 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-in²**

Electron Beam Welding

30.19 The voltage in an EBW operation is 45 kV. The beam current is 60 milliamp. The electron beam is focused on a circular area that is 0.25 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 $PD = f_1 EI/A$
Power $P = f_1 EI = 0.87(45 \times 10^3)(60 \times 10^{-3}) = 2349$ W
Area $A = \pi D^2/4 = \pi(0.25)^2/4 = 0.0491$ mm^3
$PD = 2349/0.0491 =$ **47,853 W/mm²**

30.20 An electron-beam welding operation is to be accomplished to butt weld two sheet-metal parts that are 3.0 mm thick. The unit melting energy = 5.0 J/mm^3. The weld joint is to be 0.35 mm wide, so that the cross section of the fused metal is 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 can be made along the seam.

Solution: Available heat for welding $R_{HW} = f_1 f_2 EI = U_m A_w v$
Travel velocity $v = f_1 f_2 EI/U_m A_w$
Cross sectional area of weld seam $A_w = (0.35)(3.0) = 1.05$ mm^2
$v = 0.85(0.75)(25 \times 10^3)(30 \times 10^{-3})/(5.0 \times 1.05) =$ **91.05 mm/s**

30.21 An electron-beam welding operation will join two pieces of steel plate together. The plates are 1.00 in thick. The unit melting energy is 125 Btu/in^3. The diameter of the work area focus of the beam is 0.060 in, hence the width of the weld will be 0.060 in. The accelerating voltage is 30 kV and the beam current is 35 milliamp. The heat transfer factor is 0.70 and the melting factor is 0.55. If the beam moves at a speed of 50 in/min, will the beam penetrate the full thickness of the plates?

Solution: Assume the melted portion of the weld bead has a rectangular cross-section with a width of 0.060 in and a depth, d. Therefore $A_w = 0.060$d or $d = A_w/0.060$
$A_w = f_1 f_2 EI/U_m v = (0.70)(0.55)(30000)(0.035)/(125(50)) = 0.065$ in^2
$d = A_w/D = (0.065)/(0.060) =$ **1.08 in**
The electron beam should penetrate the full thickness of the material.

30.22 An electron-beam welding operation uses the following process parameters: accelerating voltage = 25 kV, beam current = 100 milliamp, and the circular area on which the beam is focused has a diameter = 0.020 in. If the heat transfer factor = 90%, determine the average power density in the area in Btu/sec in^2.

Solution: Power density $PD = f_1 EI/A$
Area in which beam is focused $A = \pi D^2/4 = \pi(0.020)^2/4 = 0.000314$ in^3

Power $P = 0.90(25 \times 10^3)(100 \times 10^{-3})/1055 = 2.133$ Btu/sec

$PD = 2.133/0.000314 =$ **6792 Btu/sec-in^2**