32 RAPID PROTOTYPING AND ADDITIVE MANUFACTURING

Review Questions

32.1 Define *rapid prototyping*.

Answer. Rapid prototyping consists of fabrication processes to make engineering prototypes in minimum possible lead times based on a computer-aided design (CAD) model of the item.

32.2 How does *additive manufacturing* differ from rapid prototyping?

Answer. There is no difference in the technologies used for rapid prototyping and additive manufacturing. There is a difference in emphasis, with rapid prototyping being used to make engineering part prototypes, while additive manufacturing emphasizes part production.

32.3 What is the common approach used in all of the material addition technologies to prepare the control instructions for the RP system?

Answer. The text describes the common approach as a three step process: (1) Geometric modeling, which involves creation of a solid model of the component on a CAD system to define its enclosed volume; (2) tessellation of the geometric model, in which the CAD model is converted into a format that approximates its surfaces by facets (triangles or polygons); and (3) slicing of the model into layers that approximate the solid geometry.

32.4 What are the four types of starting materials in rapid prototyping?

Answer. The four types of starting materials in RP are (1) liquid-based, (2) powder-based, (3) molten material, and (4) solid sheets.

32.5 Besides the starting material, what are the layer-forming processes by which each layer is created in rapid prototyping technologies?

Answer. The main processes are based on (1) lasers, (2) printing heads that use inkjet technology, and (3) extruder heads. Other processes are based on electron beams, cutting knives, and ultraviolet light systems.

32.6 In addition to the layer-forming processes, what are the three channel modes used in RP?

Answer. The three channel modes are (1) a moving point or moving spot; for example, a laser spot moving in an *x-y* plane; (2) a moving line consisting of a linear array of spots that sweeps across the entire layer in one translational motion; and (3) a layer mode using a mask projection system in which the entire layer is created all at the same time.

32.7 Describe the stereolithography process.

Answer. Stereolithography (SL) is a process for fabricating a solid plastic part out of a photosensitive liquid polymer using a directed laser beam to solidify the polymer. Part fabrication is accomplished as a series of layers, in which one layer is added onto the previous layer to gradually build the desired three-dimensional geometry.

32.8 Describe mask projection stereolithography.

Answer. In mask projection stereolithography (MPSL), the entire layer of liquid photopolymer is exposed at once to an ultraviolet light source through a mask instead of using a scanning laser beam. The hardening process for each layer in MPSL is therefore much shorter than conventional stereolithography.

32.9 Describe selective laser sintering.

Answer. Selective laser sintering (SLS) uses a moving laser beam to fuse powders in areas corresponding to the CAD geometric model one layer at a time to build the solid part. After each layer is completed, a new layer of loose powders is spread across the surface and leveled using a counter-rotating roller..

32.10 Describe three-dimensional printing.

Answer. Three-dimensional printing builds the part using an inkjet printer to eject adhesive bonding material onto successive layers of powders. The binder is deposited in areas corresponding to the cross sections of the solid part, as determined by slicing the CAD geometric model into layers. The binder holds the powders together to form the solid part, whereas the unbonded powders remain loose to be removed later.

32.11 What is the starting material in fused-deposition modeling?

Answer. The starting material is a long filament of wax or polymer.

32.12 Describe the RP technology called *laminated-object manufacturing*.

Answer. Laminated object manufacturing produces a solid physical model by stacking layers of sheet stock that are each cut to an outline corresponding to the cross-sectional shape of a CAD model that has been sliced into layers. The layers are bonded one on top of the previous prior to cutting. After cutting, the excess material in the layer remains in place to support the part during building. Starting material in LOM can be virtually any material in sheet stock form, such as paper, plastic, cellulose, metals, or fiber-reinforced materials. Stock thickness is 0.05 to 0.50 mm (0.002 to 0.020 in).

Problems

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

32.1 (USCS units) 3D Printing is used to fabricate a prototype part whose total volume = 1.17 in^3, height = 1.22 in, and base area = 1.72 in^2. The printing head is 5 in wide and sweeps across the 7-in worktable in 3 sec for each layer. Repositioning the worktable height, recoating powders, and returning the printing head for the next layer take another 13 sec. Layer thickness = 0.005 in. Compute an estimate for the time required to build the part. Ignore setup time.

Solution: Each sweep of the printing head completes the layer formation process for the part. The area of the base layer and volume of the part are irrelevant.
Layer thickness t = 0.005 in
Number of layers n_i = 1.22 in/(0.005 mm/layer) = 244 layers
Time per layer T_i = 3 + 13 = 16 s
Cycle time T_c = 244(16) = **3904 s = 65.07 min = 1.084 hr**

32.2 **(A)** (SI units) A tube with a rectangular cross section is to be fabricated by stereolithography. Outside dimensions of the rectangle are 38 mm by 60 mm, and the corresponding inside dimensions are 30 mm by 52 mm (wall thickness = 4 mm except at corners). The height of the tube (z-direction) = 40 mm. Layer thickness = 0.10 mm, and laser spot diameter = 0.25 mm. The beam velocity across the surface of the photopolymer = 800 mm/s. Compute an estimate for the cycle time to build the part, if 20 s are lost each layer for repositioning and recoating. Ignore setup time.

Solution: Layer area A_i same for all layers.
A_i = 38(60) – 30(52) = 2280 – 1560 = 720 mm^2
Time to complete one layer T_i same for all layers.
T_i = (720 mm^2)/(0.25 mm × 800 mm/s) + 20 s = 3.6 + 20 = 23.6 s
Number of layers n_l = (40 mm)/(0.10 mm/layer) = 400 layers
T_c = 400(23.6) = **9,440 s = 157.33 min = 2.622 hr**

32.3 (SI units) Solve the previous problem, except that the layer thickness = 0.20 mm.

Solution: Layer area A_i same for all layers.
A_i = 38(60) – 30(52) = 2280 – 1560 = 720 mm^2
Time to complete one layer T_i same for all layers.
T_i = (720 mm^2)/(0.25 mm × 800 mm/s) + 20 s = 3.6 + 20 = 23.6 s
Number of layers n_l = (40 mm)/(0.20 mm/layer) = 200 layers
T_c = 200(23.6) = **4,720 s = 78.67 min = 1.311 hr**

32.4 (SI units) The part in the previous problem is fabricated using fused-deposition modeling instead of stereolithography. Layer thickness = 0.25 mm, and the width of the extrudate deposited on the surface of the part = 0.75 mm. The extruder work head moves in the *x-y* plane at a speed of 200 mm/s. A delay of 10 s is experienced between each layer to reposition the worktable. Compute an estimate for the time required to build the part. Ignore setup time.

Solution: Use same basic approach as in stereolithography.
A_i = 38(60) – 30(52) = 2280 – 1560 = 720 mm^2
Time to complete one layer T_i same for all layers
T_i = (720 mm^2)/(0.75 mm × 200 mm/s) + 10 s = 4.8 + 10 = 14.8 s
Number of layers n_l = (40 mm)/(0.25 mm/layer) = 160 layers
T_c = 160(14.8) = **2,368 s = 39.47 min = 0.658 hr**

32.5 (SI units) Solve the previous problem, except the following additional information is known: The diameter of the filament fed into the FDM extruder work head is 1. 5 mm, and the filament is fed into the work head from its spool at a rate of 21.22 mm of length per second while the work head is depositing material. Between layers, the feed rate from the spool is zero.

Solution: Cross-sectional area of filament = $\pi D^2/4 = 0.25\pi(1.5)^2$ = 1.767 mm^2
Volumetric rate of filament deposition = (1.767 mm^2)(21.22 mm/s) = 37.5 mm^3/s
Layer area A_i same for all layers.
A_i = 38(60) – 30(52) = 2280 – 1560 = 720 mm^2
Time to complete one layer T_i same for all layers
Part volume = part cross sectional area multiplied by height = $A_i h$
Part volume V = 720(40) = 28,800 mm^3
Number of layers n_l = (40 mm)/(0.25 mm/layer) = 160 layers
T_c = (28,800 mm^3)/(37.5 mm^3/s) + (160 layers)(10 s delay/layer) = 768 + 1600
= **2368 s = 39.47 min = 0.658 hr**

This is the same value as the calculated value in the previous problem.

32.6 **(A)** (SI units) The photopolymer used in Problem 32.2 costs \$150/liter. The SL machine cost rate = \$15.00/hr. Assume that all of the liquid photopolymer not used for the part can be reused. Labor rate = \$30.00/hr, but labor utilization during the build cycle is only 10%. Post-processing time = 5.0 min/part. Using the cycle time from Problem 32.2, determine the part cost.

Solution: Material cost = \$150/L (1 L = 1 dm^3 = 1(10^6) mm^3). The part in Problem 32.2 has a volume $V = A_i h$ = 720(40) = 28,800 mm^3
From Problem 32.2, T_c = 2.622 hr
C_m = (\$150 × 10^{-6}/mm^3)(28,800 mm^3) = \$4.32/pc
Cost per piece C_{pc} = 4.32 + (30.00(0.10) + 15.00)(2.622) + 30.00(5/60) = **\$54.02/pc**

32.7 (SI units) A cone-shaped part is to be fabricated using stereolithography. The radius of the cone at its base = 35 mm, and its height = 50 mm. To minimize the staircase effect, layer thickness = 0.05 mm. The diameter of the laser beam = 0.22 mm, and the beam is moved across the surface of the photopolymer at a velocity of 900 mm/s. Compute an estimate for the time required to build the part, if 15 s are lost each layer to lower the height of the platform that holds the part. Neglect post-curing time. Setup time for the job = 25 min.

Solution: Volume of cone $V = \pi R^2 h/3 = \pi(35)^2(50)/3$ = 64,141 mm^3
Layer thickness t = 0.05 mm
Number of layers n_i = 50 mm/(0.05 mm/layer) = 1000 layers
Average volume per layer V_i= (64,141 mm^3)/1000 = 64.14 mm^3
Since thickness t = 0.05 mm, average area/layer = (64.14 mm^3)/(0.05 mm) = 1283 mm^2
Average time per layer T_i = 1283/(0.22 × 900) + 15 = 6.48 + 15 = 21.48 s
Cycle time T_c = 25(60) + 1000(21.48 s) = **22,979 s = 383.0 min = 6.38 hr**

Check using Equation (32.8): T_c = 25(60) + 64,141/(0.05 × 900 × 0.22) + 1000(15) = **22,979 s**

32.8 (SI units) The cone-shaped part in the previous problem is built using laminated-object manufacturing. Layer thickness = 0.20 mm. The laser beam can cut the sheet stock at a velocity of 200 mm/s. Compute an estimate for the time required to build the part, if 20 s are lost each layer to lower the height of the platform that holds the part and advance the sheet stock in preparation for the next layer. Ignore cutting of the cross-hatched areas outside of the part since the cone should readily drop out of the stack owing to its geometry. Setup time for the job = 25 min.

Solution: For LOM, the circumference of each layer, which is the outline to be cut by the laser beam, must be determined. For a cone, the total surface area (not including the base) = $\pi R(R^2 + h^2)^{0.5}$
$A = \pi(35)(35^2 + 50^2)^{0.5}$ = 6711 mm^2
Number of layers n_i = 50 mm/(0.20 mm/layer) = 250 layers
Average outside surface area per layer = (6711 mm^2)/(250 layers) = 26.844 mm^2/layer
Layer thickness t = 0.20 mm, circumference C = (26.844 mm^2)/(0.20 mm) = 134.2 mm
Average time to cut a layer T_i = (134.2 mm)/(200 mm/s) + 20 s = 0.671 + 20 = 20.671 s
T_c = 250(20.671) = **5168 s = 86.13 min = 1.435 hr**

32.9 (SI units) Stereolithography is to be used to build the part in Figure 32.1 in the text. Dimensions of the part are height = 125 mm, outside diameter = 75 mm, inside diameter = 65 mm, handle diameter = 12 mm, handle distance from cup = 70 mm measured from center (axis) of cup to center of handle. The handlebars connecting the cup and handle at the top and bottom of the part have a rectangular cross section and are 10 mm thick and 12 mm wide. The thickness at the base of the cup is 10 mm. The laser-beam diameter = 0.25 mm, and the beam can be moved across the surface of the photopolymer at = 2000 mm/s. Layer thickness = 0.10 mm. Compute an estimate of the time required to build the part, if 30 s are lost each layer to lower the height of the platform that holds the part. Neglect setup time and post-processing time.

Solution: The part can be sliced into cross sections that have one of three basic shapes: (1) base, which is 10 mm thick and includes the handle and handle bar; (2) cup ring and handle; and (3) top of cup, which is 10 mm thick and consists of the cup ring, handle, and handle bar. Let us compute the areas of the three shapes.
Area (1): $A_1 = \pi(75)^2/4 + \pi(12)^2/4 +$ (approximately)$(12 \times 32.5 - 0.5\pi(12)^2/4)$
$A_1 = 4417.9 + 113.1 + (390.0 - 56.5) = 4864.5$ mm^2
Area (2): $A_2 = \pi(75^2 - 65^2)/4 + \pi(12)^2/4 = 1099.6 + 113.1 = 1212.7$ mm^2
Area (3): $A_3 = \pi(75^2 - 65^2)/4 + \pi(12)^2/4 +$ (approximately)$(12 \times 32.5 - 0.5\pi(12)^2/4)$
$A_3 = 1099.6 + 113.1 + (390.0 - 56.5) = 1546.2$ mm^2

Number of layers for each area:
(1) n_{l1} = (10 mm)/(0.1 mm/layer) = 100 layers
(2) n_{l2} = (125 – 10 – 10)/(0.1) = 1050 layers
(3) n_{l3} = (10 mm)/(0.1 mm/layer) = 100 layers

Time to complete one layers for each of the three shapes:
(1) T_{i1} = (4864.5 mm^2)/(0.25 × 2000) + 30 = 9.73 + 30 = 39.73 s
(2) T_{i2} = (1212.7 mm^2)/(0.25 × 2000) + 30 = 2.43 + 30 = 32.43 s
(3) T_{i3} = (1546.2 mm^2)/(0.25 × 2000) + 30 = 3.09 + 30 = 33.09 s

Total time for all layers T_c = 100(39.73) + 1050(32.43) + 100(33.09)
T_c = **41,334 s = 688.9 min = 11.48 hr**

32.10 **(A)** (SI units) A part prototype is to be fabricated using stereolithography. The base of the part is shaped like a right triangle with dimensions 36 mm by 48 mm. In application, the part will stand on this base. The height of the part is 30 mm. In the stereolithography process, the layer thickness = 0.15 mm. Diameter of the laser-beam spot = 0.40 mm, and the beam is moved across the surface of the photopolymer at a velocity of 2200 mm/s. Compute the minimum possible time required to build the part, if 25 s are lost each layer to lower the height of the platform that holds the part. Neglect the time for setup and post-processing.

Solution: The part should be oriented on its side in the stereolithography process; thus, layer area A_i and time to complete are the same for all layers.
A_i = 0.5(36 × 48) = 864 mm^2
T_i = (864 mm^2)/(0.15 mm)(2200 mm/s)+ 25 s = 2.62 + 25 = 27.62 s
Number of layers n_l = (30 mm)/(0.15 mm/layer) = 200 layers
T_c = 200(27.62) = **5524 s = 92.06 min = 1.534 hr**