23 ECONOMIC AND PRODUCT DESIGN CONSIDERATIONS IN MACHINING

Review Questions

23.1 Define *machinability*.

Answer. Machinability can be defined as the relative ease with which a material can be machined using an appropriate cutting tool under appropriate cutting conditions.

23.2 What are the criteria by which machinability is commonly assessed in a production machining operation?

Answer. The machinability criteria include (1) tool life, (2) forces and power, (3) surface finish, and (4) ease of chip disposal.

23.3 Name some of the important mechanical and physical properties that affect the machinability of a work material.

Answer. The properties mentioned in the text include hardness, strength, and ductility.

23.4 Why do costs tend to increase when better surface finish is required on a machined part?

Answer. Costs tend to increase when better surface finish is required because additional operations such as grinding, lapping, or similar finishing processes must be included in the manufacturing sequence.

23.5 What are the basic factors that affect surface finish in machining?

Answer. The factors that affect surface finish are (1) geometric factors such as type of operation, feed, and tool shape (nose radius in particular); (2) work material factors such as built-up edge effects, and tearing of the work surface when machining ductile materials, which are affected by cutting speed; and (3) vibration and machine tool factors such as setup and work part rigidity, and backlash in the feed mechanism.

23.6 What are the parameters that have the greatest influence in determining the ideal surface roughness R_i in a turning operation?

Answer. The ideal surface roughness is determined by the following geometric parameters of the machining operation: (1) tool nose radius and (2) feed. In some cases, the end cutting edge and end cutting edge angle of the single-point tool affects the feed mark pattern on the work surface.

23.7 Name some of the steps that can be taken to reduce or eliminate vibrations in machining.

Answer. Steps to reduce vibration in machining include (1) increase stiffness or damping in the setup; (2) operate at speeds away from the natural frequency of the machine tool system; (3) reduce forces in machining by changing feed or depth, and (4) change the cutter design to reduce forces (e.g., reduce rake angle).

23.8 What are the factors on which the selection of feed in a machining operation should be based?

Answer. The factors are (1) type of tooling (e.g., a cemented carbide tool should be used at a lower feed than a high-speed steel tool), (2) whether the operation is roughing or finishing (e.g., higher feeds are used in roughing operations), (3) cutting forces limitations that would require lower feeds, and (4) surface roughness requirements.

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23.9 The unit cost in a machining operation is the sum of four cost terms. The first three terms are: (1) cost of time the tool is actually cutting the work, (2) part load/unload cost, and (3) cost of the time to change the tool. What is the fourth term?

Answer. The fourth term is the cost of the tool itself (purchasing the tool and grinding it, if applicable).

23.10 Which cutting speed is always lower for a given machining operation, cutting speed for minimum cost or cutting speed for maximum production rate? Why?

Answer. Cutting speed for minimum cost is always lower because of the fourth term in the unit cost equation, which deals with the actual cost of the cutting edge. This term tends to push the U-shaped function toward a lower value in the case of cutting speed for minimum cost.

Problems

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

Machinability

23.1 (SI units) Machinability ratings are to be determined for a new work material using the cutting speed for a specified tool life as the basis of comparison. For the base material (B1112 steel), test data resulted in Taylor equation parameter values of $n = 0.24$ and $C = 450$, where speed is m/min and tool life is min. For the new material, the parameter values were $n = 0.28$ and $C = 490$. Cemented carbide tools were used. Compute machinability ratings for the new material using as the tool life criterion (a) 60 min, (b) 10 min, and (c) 1.0 min. (d) What do the results show about the difficulties in machinability measurement?

Solution: (a) Base material: $v_{60} = 450/60^{0.24} = 168.4$ m/min
New material: $v_{60} = 490/60^{0.28} = 155.7$ m/min
$MR = 155.7/168.4 =$ **0.925 = 92.5%**

(b) Base material: $v_{10} = 450/10^{0.24} = 259.0$ m/min
New material: $v_{10} = 490/10^{0.28} = 257.2$ m/min
$MR = 257.2/259.0 =$ **0.993 = 93.3%**

(c) Base material: $v_1 = 450/1^{0.24} = 450$ m/min
New material: $v_1 = 490/1^{0.28} = 490$ m/min
$MR = 490/450 =$ **1.089 = 108.9%**

(d) Different test conditions often result in different machinability results.

23.2 **(A)** (SI units) Machinability ratings are to be determined for a new steel. For the base material (B1112), test data resulted in Taylor equation parameters $n = 0.28$ and $C = 500$. For the new material, the Taylor parameters were $n = 0.25$ and $C = 430$. Cutting speed units are m/min, and tool life units are min. The tooling was cemented carbide. (a) Compute machinability ratings for the new material using the following criteria: (a) cutting speed for a 30-min tool life and (b) tool life for a cutting speed of 150 m/min.

Solution: (a) Base material: $v_{30} = 500/30^{.28} = 192.9$ m/min
New material: $v_{30} = 430/30^{.25} = 183.7$ m/min
$MR = 183.7/182.8 =$ **0.95 = 95%**

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(b) Base material: $T_{150} = (500/150)^{1/.28} = (3.33)^{3.571} = 73.7$ min
New material: $v_{10} = (430/150)^{1/.25} = (2.87)^{4.0} = 67.8$ min
$MR = 67.8/73.7 =$ **0.92 = 92%**

23.3 (USCS units) Tool life tests were conducted on B1112 steel using high-speed steel tooling. Feed = 0.010 in/rev and depth of cut = 0.100 in. The resulting Taylor equation parameters were $n = 0.15$ and $C = 225$ (ft/min). Using this as the base metal (machinability rating = 1.00) and the machinability values in Table 23.1, determine the cutting speed you would recommend for the following work materials, if the tool life desired in each operation is 30 min (the same feed and depth of cut will be used): (a) annealed aluminum alloy with 40 Brinell hardness, (b) 4140 alloy steel with 200 HB, and (c) Inconel X superalloy with 350 HB.

Solution: Determine v_{30} for the base material: $v_{30} = 225/30^{.15} = 225/1.6656 = 135.1$ ft/min

(a) From Table 23.1, MR for the Al alloy = 2.0. Recommended $v_{30} = 2(135.1) =$ **270 ft/min**

(b) MR for 4140 = 0.55. Recommended $v_{30} = 0.55(135.1) =$ **74 ft/min**

(c) MR for Inconel X = 0.15. Recommended $v_{30} = 0.15(135.1) =$ **20 ft/min**

Surface Roughness

23.4 **(A)** (SI units) In a turning operation on cast iron, the nose radius on the cutting tool = 1.2 mm, feed = 0.22 mm/rev, and speed = 100 m/min. Compute an estimate of the surface roughness for this cut.

Solution: $R_i = f^2/32NR = (0.22)^2/(32 \times 1.2) = 0.00126$ mm = 1.26 μm
From Fig. 23.2, $r_{ai} = 1.3$
$R_a = 1.3 \times 1.26 =$ **1.64 μm**

23.5 (USCS units) A turning operation uses a 2/64-in nose radius cutting tool on a free machining steel. Feed = 0.015 in/rev, and cutting speed = 300 ft/min. Determine the surface roughness for this cut.

Solution: $R_i = f^2/32NR = (0.015)^2/(32 \times 2/64) = 0.000225$ in = 225 μ-in
From Fig. 23.2, $r_{ai} = 1.00$
$R_a = 1.0 \times 225 =$ **225 μ-in**

23.6 (USCS units) A single-point HSS tool with a 4/64-in nose radius is used in a shaping operation on a ductile steel work part. Cutting speed = 75 ft/min, feed = 0.020 in/pass, and depth of cut = 0.135 in. Determine the surface roughness for this operation.

Solution: $R_i = f^2/32NR = (0.020)^2/(32 \times 4/64) = 0.0002$ in = 200 μ-in
From Fig. 23.2, $r_{ai} = 2.0$ $R_a = 2.0 \times 200 =$ **400 μ-in**

23.7 **(A)** (SI units) A part turned in an engine lathe must have a surface finish of 1.6 μm. The part is made of a free-machining aluminum. Cutting speed = 200 m/min, and depth of cut = 4.0 mm. The nose radius on the tool = 1.5 mm. Determine the feed that will achieve the specified surface finish.

Solution: For free-machining aluminum, even though the speed scale does not show 200 m/min, it can be assumed that the ratio $r_{ai} = 1.0$ in Figure 23.2 so $R_a = R_i$.
$R_a = R_i = f^2/32NR$

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Rearranging, $f^2 = R_i(32NR) = 1.6(10^{-6})(32)(1.5)(10^{-3}) = 76.8(10^{-9}) = 7.68(10^{-8})$ m^2
$f = (7.68(10^{-8})$ m$^2)^{0.5} = 2.77(10^{-4})$ m = **0.277 mm** (mm is interpreted mm/rev)

23.8 (SI units) Solve the previous problem except that the part is made of cast iron instead of aluminum and the cutting speed is reduced to 100 m/min.

Solution: For cast iron at 100 m/min, the ratio $r_{ai} = 1.3$ in Figure 23.2 so $R_a = 1.3R_i$.
$R_a = 1.3f^2/32NR$
Rearranging, $f^2 = R_i(32NR)/1.3 = 1.6(10^{-6})(32)(1.5)(10^{-3})/1.3 = 59.08(10^{-9}) = 5.908(10^{-8})$ m^2
$f = 5.908(10^{-8})$ m$^2)^{0.5} = 2.43(10^{-4})$ m = **0.243 mm** (mm is interpreted mm/rev)

23.9 (SI units) The surface finish specification on a cast iron part in a turning job is 0.8 μm. Cutting speed = 75 m/min, feed = 0.5 mm/rev, and depth of cut = 4.0 mm. Determine the minimum nose radius that will obtain the specified finish in this operation.

Solution: For cast iron at 75 m/min, the ratio $r_{ai} = 1.35$ in Figure 23.2.
so $R_a = 1.35R_i = 1.35f^2/32NR$
Rearranging, $NR = 1.35f^2/(32R_a)$
$NR = 1.35(0.5 \times 10^{-3})^2/(32)(0.8)(10^{-6}) = 0.0132$ m = **13.2 mm**

Comment: This is a very large nose radius, suggesting that the specified surface roughness would be readily achieved. However, cast iron tends to produce discontinuous chips which cause problems with surface finish.

23.10 **(A)** (USCS units) A face milling operation will be performed on a cast iron part to finish the surface to 32 μ-in. The cutter uses six inserts, and its diameter is 3.0 in. The cutter rotates at 500 rev/min. A carbide insert with a 4/64-in nose radius will be used. Determine the required feed rate (in/min) that will achieve the 32 μ-in finish.

Solution: $v = \pi DN = \pi(3/12)(500) = 393$ ft/min
For cast iron at 393 ft/min, the ratio $r_{ai} = 1.25$ in Figure 23.2, so $R_a = 1.25\ R_i$
$R_i = R_a/1.25 = 32/1.25 = 25.6\ \mu$-in
$R_i = f^2/32\ NR$
Rearranging, $f^2 = 32R_a(NR) = 32(25.6 \times 10^{-6})(4/64) = 51.2 \times 10^{-6}$ in^2
$f = (51.2 \times 10^{-6})^{.5} = 7.16 \times 10^{-3} = 0.00716$ in/tooth
$f_r = Nn_tf = 500(6)(0.00716) =$ **21.5 in/min**

23.11 A face milling operation is not yielding the required surface finish on the work. The cutter is a four-tooth insert-type face milling cutter. The machine shop foreman thinks the problem is that the work material is too ductile for the job, but this property tests well within the ductility range for the material specified by the designer. Without knowing any more about the job, what changes in (a) cutting conditions and (b) tooling would you suggest to improve the surface finish?

Solution: (a) Changes in cutting conditions: (1) decrease chip load *f*, (2) increase cutting speed *v*, (3) use cutting fluid.

(b) Changes in tooling: (1) increase nose radius *NR*, (2) increase rake angle, and (3) increase relief angle. Items (2) and (3) will have a marginal effect.

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23.12 (USCS units) A turning operation is to be performed on C1010 steel, which is a ductile grade. It is desired to achieve a surface finish of 64 μ-in, while at the same time maximizing the metal removal rate. It has been decided that the speed should be in the range 200 ft/min to 400 ft/min, and that the depth of cut will be 0.080 in. The tool nose radius = 3/64 in. Determine the speed and feed combination that meets these criteria.

Solution: Increasing feed will increase both R_{MR} and R_a. Increasing speed will increase R_{MR} and reduce R_a. Therefore, it stands to reason that the highest possible v should be used.

Try v = 400 ft/min. From Fig. 25.45, r_{ai} = 1.15
$R_a = 1.15\ R_i$
$R_i = R_a/1.15 = 64/1.15 = 55.6\ \mu$-in
$R_i = f^2/32NR$
$f^2 = 32R_a(NR) = 32(55.6 \times 10^{-6})(3/64) = 83.4 \times 10^{-6}\ \text{in}^2$
$f = (83.4 \times 10^{-6})^{.5} = 0.0091$ in/rev
$R_{MR} = 3.51\ \text{in}^3/\text{min}$

Compare at v = 300 ft/min. From Fig. 25.45, r_{ai} = 1.26.
$R_a = 1.26\ R_i$
$R_i = R_a/1.26 = 64/1.26 = 50.8\ \mu$-in
$R_i = f^2/32NR$
$f^2 = 32R_a(NR) = 32(50.8)(10^{-6})(3/64) = 76.2(10^{-6})\text{in}^2$
$f = (76.2 \times 10^{-6})^{.5} = 0.0087$ in/rev
$R_{MR} = 2.51\ \text{in}^3/\text{min}$

Optimum cutting conditions are: ***v* = 400 ft/min** and ***f* = 0.0091 in/rev**, which maximizes R_{MR} = $\mathbf{3.51\ in^3/min}$

Machining Economics

23.13 **(A)** (SI units) A high-speed steel tool is used to turn a steel work part with length = 350 mm and diameter = 75 mm. The parameters in the Taylor equation are n = 0.13 and C = 75 (m/min) for a feed of 0.4 mm/rev. The operator and machine tool rate = \$36.00/hr, and the tooling cost per cutting edge = \$4.25. It takes 3.0 min to load and unload the work part and 4.0 min to change tools. Determine the (a) cutting speed for maximum production rate, (b) tool life, and (c) cycle time and cost per unit of product.

Solution: (a) C_o = \$36/hr = \$0.60/min
$v_{max} = 75/[(1/0.13 - 1)(4.0)]^{.13} = 75/[6.692 \times 4.0]^{.13} = \mathbf{48.9\ m/min}$

(b) $T_{max} = (75/48.9)^{1/.13} = (1.534)^{7.692} = \mathbf{26.85\ min}$

(c) $T_m = \pi DL/fv = \pi(75)(350)/(.4 \times 48.9 \times 10^3) = 4.216$ min
$n_p = 26.85/4.216 = 6.37$ pc/tool life Use $n_p = 6$ pc/tool life
$T_c = T_m + T_h + T_t/n_p = 4.216 + 3.0 + 4.0/6 = \mathbf{7.88\ min/pc}$
$C_c = 0.60(7.88) + 4.25/6 = \mathbf{\$5.44/pc}$

23.14 (SI units) Solve the previous problem except that in part (a), determine the cutting speed for minimum cost.

Solution: (a) C_o = \$36/hr = \$0.60/min
$v_{min} = 75[0.60/((1/0.13 - 1)(.60 \times 4 + 4.25))]^{.13} = 75[.60/(6.692 \times 6.65)]^{.13} = \mathbf{42.8\ m/min}$

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(b) $T_{min} = (75/42.8)^{1/.13} = (1.75)^{7.692} =$ **74.8 min**

(c) $T_m = \pi DL/fv = \pi(75)(350)/(0.4 \times 42.8 \times 10^3) = 4.817$ min/pc
$n_p = 74.8/4.817 = 15.5$ pc/tool life Use $n_p = 15$ pc/tool life
$T_c = T_m + T_h + T_t/n_p = 4.817 + 3.0 + 4/15 =$ **8.08 min/pc**
$C_c = 0.60(8.08) + 4.25/15 =$ **\$5.13/pc**

23.15 (USCS units) Cemented carbide inserts are used to turn a part with length = 21.0 in and diameter = 4.0 in. Feed = 0.015 in/rev. The parameters in the Taylor equation are $n = 0.25$ and $C = 800$ (ft/min). The operator and machine tool rate = \$45.00/hr, and the tooling cost per cutting edge = \$2.00. It takes 2.5 min to load and unload the work part and 1.50 min to change inserts. Determine the (a) cutting speed for maximum production rate, (b) tool life, and (c) cycle time and cost per unit of product.

Solution: (a) $v_{max} = C/((1/n-1)T_t)^n = 800/[(1/0.25-1)(1.5)]^{.25}$
$= 800/[(4-1) \times 1.5]^{.25} =$ **549 ft/min**

(b) $T_{max} = (800/549)^{1/.25} = (1.457)^{4.0} =$ **4.5 min** or $(1/n - 1)\ T_t = (4-1)1.5 =$ **4.5 min**

(c) $T_m = \pi DL/fv = \pi(4)(21)/(.015 \times 549 \times 12) = 2.67$ min
$n_p = 4.5/2.67 = 1.69$ pc/tool Use $n_p = 1$ pc/tool life
$T_c = T_m + T_h + T_t/n_p = 2.67 + 2.5 + 1.5/1 =$ **6.67 min/pc**
$C_o = \$45/\text{hr} = \$0.75/\text{min}$
$C_c = C_o\,(T_m + T_h + T_t/n_p) + C_t/n_p = 0.75(6.67\ ) + 2.5/1 =$ **\$7.00/pc**

23.16 **(A)** (USCS units) Solve the previous problem except that in part (a), determine the cutting speed for minimum cost.

Solution: (a) $C_o = \$45/\text{hr} = \$0.75/\text{min}$
$v_{min} = C[(n/(1-n))(C_o/(C_oT_t + C_t))]^n = 800[(0.25/(1-0.25))(0.75/(0.75(1.5) + 2.0))]^{0.25}$
$v_{min} = 800[0.3333{\times}0.75/(1.125{+}2.0)]^{.25} = 1000[0.3333{\times}0.75/3.125]^{0.25} = 800\ [\ 0.08]^{0.25}$
$v_{min} =$ **425 ft/min**

(b) $T_{min} = (800/425)^{1/.25} = (1.88)^{4.0} =$ **12.50 min**

(c) $T_m = \pi DL/fv = \pi(4)(21)/(0.015 \times 425 \times 12) = 3.45$ min
$n_p = 12.5/3.45 = 3.62$ pc/tool Use $n_p = 3$ pc/tool life
$T_c = T_m + T_h + T_t/n_p = 3.45 + 2.5 + 1.5/3 =$ **6.45 min/pc**
$C_c = C_o\,(T_m + T_h + T_t/n_p) + C_t/n_p = 0.75(6.45) + 2.5/3 =$ **\$5.50/pc**

23.17 (SI units) The same grade of cemented carbide tooling is available in two forms for turning operations in the machine shop: disposable inserts and brazed inserts. Feed = 0.30 mm/rev. The Taylor equation parameters for this grade are $n = 0.25$ and $C = 300$ (m/min). For the disposable inserts, the price of each insert = \$6.00, there are four cutting edges per insert, and the average tool change time = 1.0 min. For the brazed insert, the price of the tool = \$30.00, and it can be used a total of 15 times before it must be scrapped. The tool change time for the regrindable tooling = 3.0 min. The standard time to grind or regrind the cutting edge is 5.0 min, and the cost rate to grind = \$20.00/hr. Machine time on the lathe costs \$24.00/hr. The work part to be used in the comparison is 375 mm long and 62.5 mm in diameter, and it takes 2.0 min to load and unload the work. For the two cases, compare the

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(a) cutting speeds for minimum cost, (b) tool lives, and (c) cycle times and costs per unit of production. (d) Which tool would you recommend?

Solution: Disposable inserts: (a) C_o = \$24/hr = \$0.40/min, C_t = \$6/4 = \$1.50/edge
$v_{min} = 300[0.40/((1/0.25 - 1)(0.40 \times 1.0 + 1.50))]^{.25} = 300[0.40/(3 \times 1.9)]^{.25} =$ **154.4 m/min**

(b) $T_{min} = (1/0.25 - 1)(0.4 + 1.5)/0.4 = 3(1.9/0.4) =$ **14.25 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(154.4) = 1.59$ min/pc
$n_p = 14.25/1.59 = 8.96$ pc/tool life   Use $n_p = 8$ pc/tool
$T_c = 1.59 + 2.0 + 1.0/8 =$ **3.72 min/pc**
$C_c = 0.40(3.72) + 1.50/8 =$ **\$1.674/pc**

Regrindable tooling: (a) C_o = \$24/hr = \$0.40/min, C_t = \$30/15 + 5(\$20/60) = \$3.67/edge
$v_{min} = 300[0.40/((1/0.25-1)(0.40 \times 3.0 + 3.67))]^{.25} = 300[0.40/(3 \times 4.87)]^{.25} =$ **122.0 m/min**

(b) $T_{min} = (1/0.25 - 1)(0.4 \times 3 + 3.67)/0.4 = 3(4.87/0.4) =$ **36.5 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(122) = 2.01$ min/pc
$n_p = 36.5/2.01 = 18.16$ pc/tool life   Use $n_p = 18$ pc/tool
$T_c = 2.01 + 2.0 + 3.0/18 =$ **4.18 min/pc**
$C_c = 0.40(4.18) + 3.67/18 =$ **\$1.876/pc**

(d) Disposable inserts are recommended. Cycle time and cost per piece are less.

23.18 (SI units) Solve the previous problem except that in part (a), determine the cutting speeds for maximum production rate.

Solution: Disposable inserts: (a) C_o = \$24/hr = \$0.40/min, C_t = \$6/4 = \$1.50/edge
$v_{max} = 300[1.0/((1/0.25 - 1)(1.0)]^{.25} = 300[1.0/(3 \times 1.0)]^{.25} =$ **228.0 m/min**

(b) $T_{max} = (1/0.25 - 1)(1.0) = 3(1.0) =$ **3.0 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(228) = 1.08$ min/pc
$n_p = 3.0/1.08 = 2.78$ pc/tool life   Use $n_p = 2$ pc/tool
$T_c = 1.08 + 2.0 + 1.0/2 =$ **3.58 min/pc**
$C_c = 0.40(3.58) + 1.50/2 =$ **\$2.182/pc**

Regrindable tooling: (a) C_o = \$24/hr = \$0.40/min, C_t = \$30/15 + 5(\$20/60) = \$3.67/edge
$v_{max} = 300[1.0/((1/0.25 - 1)(3.0))]^{.25} = 300[1.0/(3 \times 3.0)]^{.25} =$ **173.2 m/min**

(b) $T_{max} = (1/0.25 - 1)(3) = 3(3.0) =$ **9.0 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(173.2) = 1.42$ min/pc
$n_p = 9.0/1.42 = 6.34$ pc/tool life   Use $n_p = 6$ pc/tool
$T_c = 1.42 + 2.0 + 3.0/6 =$ **3.92 min/pc**
$C_c = 0.40(3.92) + 3.67/6 =$ **\$2.180/pc**

(d) Disposable inserts are recommended. Cycle time and cost per piece are less. Comparing the results in this problem with those of the previous problem, note that with the maximum production rate objective in the current problem, cycle times are less, but that unit costs are less in the previous problem where the objective is minimum cost per piece.

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23.19 (USCS units) A vertical boring mill is used to bore the inside diameter of a large batch of tube-shaped parts. The diameter = 28.0 in, and the length of the bore = 14.0 in. Cutting speed = 150 ft/min, feed = 0.015 in/rev, and depth of cut = 0.125 in. The parameters of the Taylor equation for the cutting tool in the operation are n = 0.25 and C = 1100 (ft/min). Tool change time = 3.0 min and tooling cost = $3.50 per cutting edge. Time to load and unload the parts = 14.0 min, and the cost of machine time = $42.00/hr. Management wants to increase production rate by 50%. Is that possible? Assume that feed is unchanged to achieve the required surface finish. What are the current production rate and maximum possible production rate for this job?

Solution: At the current operating speed v = 150 ft/min:
$T = (1100/150)^{1/.25} = 2892$ min
$T_m = \pi(28)(14)/(150 \times 12 \times 0.015) = 45.6$ min/pc
$n_p = 2892/45.6 = 63.4$ pc/tool life Use $n_p = 63$ pc/tool
$T_c = 45.6 + 14 + 3/63 = 59.6$ min
$R_c = 60/59.6 =$ **1.006 pc/hr**

Find v_{max} to compare with current operating speed.
$v_{max} = 1100/[(1/.25 - 1)(3.0)]^{.25} = 850/[(3 \times 3.0)]^{.25} = 491$ ft/min
$T_{max} = (1/.25 - 1)(3.0) = 3(3.0) = 9.0$ min
$T_m = \pi(28)(14)/(491 \times 12 \times 0.015) = 13.93$ min/pc
$n_p = 9/13.93 = 0.65$ pc/tool life
This would mean that the tool would have to be changed during the machining of the workpiece, which is undesirable. A reasonable decision would be to operate at a cutting speed slightly lower than v_{max} so that the tool would last for at least one workpiece. However, we will complete the calculations using the value of $n_p = 0.65$.
$T_c = 13.93 + 14 + 3/.65 = 32.5$ min
$R_c = 60/32.5 =$ **1.84 pc/hr**

Comment: This is an 83% increase in production rate relative to the current 150 ft/min cutting speed. It should be possible to increase production rate by at least 50% and still use a cutting speed that will last at least one workpiece.

23.20 **(A)** (USCS units) A CNC lathe cuts two passes on a cylindrical workpiece under automatic cycle. The operator loads and unloads the machine. The starting diameter of the work = 3.00 in and length = 10 in. The work cycle consists of the following steps (with element times given in parentheses where applicable): 1. Operator loads part into machine, starts cycle (1.00 min); 2. lathe positions tool for first pass (0.10 min); 3. lathe turns first pass (time depends on cutting speed); 4. lathe repositions tool for second pass (0.4 min); 5. lathe turns second pass (time depends on cutting speed); 6. operator unloads part and places in tote pan (1.00 min). In addition, the cutting tool must be changed periodically. Tool change time = 1.00 min. Feed rate = 0.007 in/rev and depth of cut for each pass = 0.100 in. The cost of the operator and machine = $48/hr and the tool cost = $2.00/cutting edge. The applicable Taylor tool life parameters are n = 0.26 and C = 900 (ft/min). Determine the (a) cutting speed for minimum cost per piece, (b) time to complete one production cycle, and (c) cost of the production cycle. (d) If the setup time for this job is 3.0 hours and the batch size = 125 parts, how long will it take to complete the batch?

Solution: (a) C_o = $48/hr = $0.80/min

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v_{min} = 900[.80/((1/.26 – 1)(.80 × 1.0 + 2.00))]$^{.26}$ = 900[0.80/(2.846 × 2.80)]$^{.26}$ = **495 ft/min**

(b) T_{min} = (1/.26 – 1)(.65 × 1 + 2.0)/.80 = 2.846(2.80/.80) = 9.96 min
First pass: T_m = π(3)(10)/(495 × 12 × 0.007) = 2.27 min/pc
Second pass: T_m = π(3.0 – 2×0.100)(10)/(495 × 12 × 0.007) = 2.12 min/pc
n_p = 9.96/0.5(2.27+2.12) = 4.5 passes/tool life
Since there are two passes/workpiece, n_p = 2.25 pc/tool life. Use n_p = 2 pc/tool
T_c = 1.0 + 0.1 + 2.27 + 0.4 + 2.12 + 1.0 + 1.0/2 = **7.39 min/pc**

(c) C_c = 0.80(7.39) + 2.00/2 = **$6.91/pc**

(d) Time to complete batch T_b = 3.0(60) + 125(7.39) = **1103.75 min = 18.40 hr**

23.21 Verify that the derivative of Equation (23.6) is Equation (23.7).

Solution: Start with Equation (23.6): $T_c = \pi DL/fv + T_h + T_t(\pi DLv^{1/n-1})/fC^{1/n}$
$T_c = (\pi DL/f)v^{-1} + T_h + (T_t\pi DL/fC^{1/n})v^{1/n-1}$
$dT_c/dv = -(\pi DL/f)v^{-2} + 0 + (1/n - 1)(T_t\pi DL/fC^{1/n})v^{1/n-2} = 0$
$(\pi DL/f)v^{-2} = (1/n - 1)(T_t\pi DL/fC^{1/n})v^{1/n-2} = 0$
$(\pi DL/f) = (1/n - 1)(T_t\,\pi DL/fC^{1/n})v^{1/n}$
$1 = (1/n - 1)(T_t/C^{1/n})v^{1/n}$
$v^{1/n} = C^{1/n}/[(1/n-1)T_t]$

$v = v_{\max} = C/[(n/(1-n))(1/T_t)]^{n}$ Q.E.D

23.22 Verify that the derivative of Equation (23.12) is Equation (23.13).

Solution: Start with Equation (23.12): $C_c = C_o\pi DL/fv + C_oT_h + (C_oT_t + C_t)(\pi DLv^{1/n-1})/fC^{1/n}$
$C_c = C_o(\pi DL/f)v^{-1} + C_oT_h + (C_oT_t + C_t)(\pi DL/fC^{1/n})v^{1/n-1}$
$dC_c/dv = -C_o(\pi DL/f)v^{-2} + 0 + (1/n - 1)(C_oT_t + C_t)(\pi DL/fC^{1/n})v^{1/n-2} = 0$
$C_o(\pi DL/f)v^{-2} = (1/n - 1)(C_oT_t + C_t)(\pi DL/fC^{1/n})v^{1/n-2} = 0$
$C_o(\pi DL/f) = (1/n - 1)(C_oT_t + C_t)\pi DL/fC^{1/n})v^{1/n}$
$C_o = (1/n - 1)((C_oT_t + C_t)/C^{1/n})v^{1/n}$
$v^{1/n} = C^{1/n}/[(1/n - 1)(C_oT_t + C_t)/C_o]$

$v = v_{\min} = C/[(1/n - 1)(C_oT_t + C_t)/C_o]^n = C[(n/(1-n))(C_o/(C_oT_t + C_t)]^n$ Q.E.D

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