A TAYLOR TOOL LIFE CONSTANT-BASED METHOD FOR THE ANALYSIS OF THE EFFECT OF COOLANT/ LUBRICANT SELECTION ON MACHINING OPERATIONS

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Abstract

The calculation of the cutting conditions, which result in the optimization of parameters such as unit cost of production and maximum production rate, has traditionally been performed under the assumptions that each factor considered is deterministic and that the major determining factor in these calculations is cutting speed. Many factors incorporated in these calculations, however, exhibit stochastic variation rather than deterministic behavior. Recently, it has become evident that the properties of the coolants/lubricants employed in machining operations, for example, exhibit stochastic variation.

One result of the stochastic variation observed in coolant/ lubricant properties and performance is a variation in tool life and, specifically, a variation in the values of the constants appearing in the Taylor Tool Life equation. In this paper, a method is detailed capturing and accounting for this variation and assessing its effect on the unit cost of production of machined work parts. A test case was also formulated and analyzed and the results of coolant/lubricant property variation were shown to be potentially much larger than the effects associated with variations in cutting speed.

Introduction

The use of cutting fluids (either coolants or lubricants) in machining operations provides benefits including [1]:

- Increased cutting-tool life;
- Reduced temperatures at the tool/work/chip interface;
- Improved surface finish and integrity;
- Reduction or elimination of residual stresses in the machined work part;
- Reduction or elimination of built-up-edge chip formation; and,
- Increased rate of production.

The use of coolants/lubricants in machining may, therefore, result in lower unit costs of production and improved work part quality. However, costs are incurred through the use of coolants/lubricants as well. As Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) regulations have become more stringent, increased costs have become associated with the use of these fluids [2]. For a particular work material, the selection of cutting-tool material can also have a significant effect on many of these parameters. In particular, the selection of cutting-tool material has an effect on tool life, production rate, and unit cost. Often, the use of a more expensive cutting-tool material results in a lower unit cost and/or a greater production rate [3].

The determination of the cutting conditions, which result in maximum production rate or those which result in minimum unit cost, was derived in 1950 [4] and is relatively straightforward. This traditional derivation, however, assumed deterministic rather than stochastic work material, tool material, and coolant/lubricant properties. A variation in cutting-tool material results in changes in the constants employed in Taylor's Tool Life equation. In addition, coolant/lubricant selections have an effect on Taylor Tool Life constants [5]. These constants appear in the relationships that describe material removal rate, production rate, and the unit cost of machined work parts. As Taylor constants vary, optimum cutting conditions, including spindle speed, cutting speed, feed, and feed rate, also vary [6]. As a result, changes in either the cutting-tool material employed and/or the coolant/lubricant used may have a significant effect on production rate and the unit cost of production.

In addition to these considerations, stochastic variations in work material properties, tool material properties, and coolant/lubricant properties each may have an effect on material removal rate, production rate, and the unit cost of production [7]. To compound these effects, changes in cutting conditions deliberately induced by shop floor personnel as well as inadvertent changes in coolant/lubricant mixture ratios may compound these effects. As a result of these factor changes, some amount of uncertainty exists in the selection of optimum cutting conditions for any given work part/ cutting-tool/cutting-fluid scenario. Extensive analyses have been performed to document the effect of changes in cutting speed and cutting-tool material on tool life and, ultimately, on the unit cost of production. Very little attention, however, has been focused on the effect of the stochastic changes in coolant/lubricant properties and their effect on unit cost. In this study, the authors examined these effects.

Current Methodologies

The calculation of cutting speed, which maximizes production rate and minimizes the unit cost of production of machined work parts, is well documented [8] and given in Equation (1):

$$T_c = T_h + T_m + \frac{T_t}{n_p} \quad (1)$$

where,

- T_c = cycle time
- T_h = handling time
- T_m = machining time
- T_t = tool change time, when the tool change is attributed to a depleted cutting tool
- n_p = the number of parts that may be machined before the cutting tool is depleted

Note that the term T_t/n_p is the tool change time on a per-work part basis. Also:

$$T_m = \frac{\pi DL}{Vf} \quad (2)$$

where,

- D = cutting-tool diameter (for operations with rotating tools such as end milling and drilling)
- L = length of cut
- V = cutting speed
- f = feed

The simplest form of the Taylor Tool Life equation is shown in Equation (3):

$$C = VT^n \quad (3)$$

where,

- T = the life of the cutting tool, as predicted by the Taylor Tool Life equation (in minutes)
- C = a Taylor Tool Life equation constant that is numerically equal to the cutting speed (expressed in surface feet per minute, sfpm), which results in one minute of tool life
- n = a Taylor Tool Life equation constant that expresses the sensitivity of tool life with regard to changes in cutting speed

The number of parts that may be machined before the cutting tool is depleted, due to gradual wear is given by Equation (4):

$$n_p = \frac{T}{T_m} = \frac{fC^{1/n}}{\pi DLV^{\left(1/n - 1\right)}} \quad (4)$$

In expanded form, then, Equation (1) becomes Equation (5):

$$T_c = T_h + \frac{\pi DL}{Vf} + \frac{T_t \pi DLV^{\left(1/n - 1\right)}}{fC^{1/n}} \quad (5)$$

The cutting speed that results in minimum cycle time (and therefore maximum production rate) may be found by setting the derivative of Equation (5) to zero, as shown in Equation (6):

$$V_{max\,Rp} = \frac{C}{\left[T_t\left(\frac{1}{n} - 1\right)\right]^n} \quad (6)$$

where,

- V_{maxRp} = the cutting speed, which results in maximum rate of production.

The derivation for the cutting speed, which results in minimum unit cost, is similar and its result is presented in Equation (7):

$$V_{minCpc} = C\left[\frac{n}{1 - n}\left(\frac{C_o}{C_o T_t + C_t}\right)\right]^n \quad (7)$$

where,

- V_{minCpc} = the cutting speed, which results in minimum unit cost
- C_o = the shop rate (cost per time to operate the production operation)
- C_t = the cost of disposable tooling on a per-tool life (for re-grindable tooling) or on a per-cutting edge (for disposable insert tooling) basis

The C_t term may be expanded, as shown in Equation (8):

$$C_t = \frac{C_{pt}}{1 + n_{rs} - a} + (1 - a)C_{otr}T_{rs} \quad (8)$$

where,

- C_{pt} = the cost to purchase one cutting tool
- n_{rs} = the number of allowable tool re-conditionings (for re-grindable tooling) or cutting edges (for disposable insert tooling)
- a = a factor equal to zero (for re-grindable tooling) or one (for disposable insert tooling)

Traditionally, the cutting speed, which results in minimum unit cost, has served as the lower bound for the cutting speed, which is actually employed in a given operation, while the cutting speed, which results in maximum production rate, has served as the upper bound, as depicted in Figure 1.

The values employed in the generation of the graph of Figure 1 are:

C = 809.3
n = 0.125

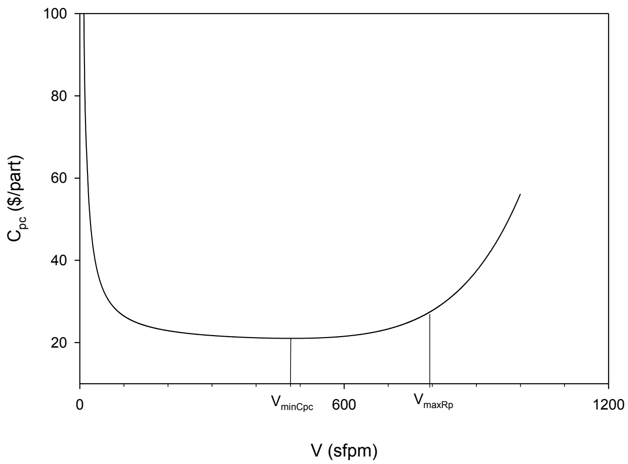

Figure 1. Unit Cost as a Function of Cutting Speed

These values are representative of the case where the work part is comprised of AISI 4140 steel with a hardness of approximately R_C25; the cutting tool is an uncoated carbide end mill, and the coolant/lubricant is a soluble oil (10% concentration by volume in water).

The Tool Life Constant Uncertainty Model

Figure 2 depicts the cutting speed versus unit cost curves for the production of a particular work part using two different coolant/lubricants.

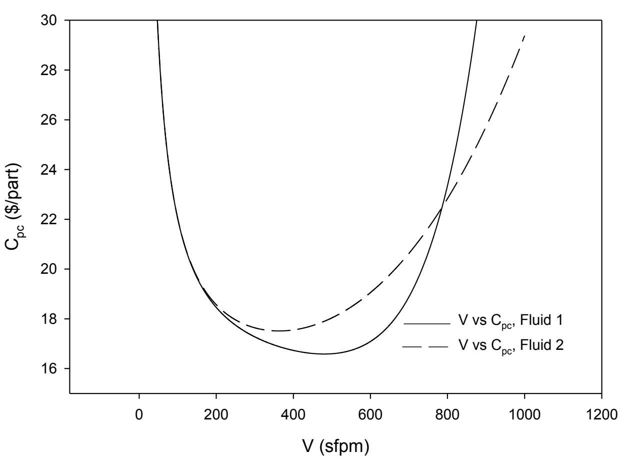

Figure 2. Cutting Speed versus Unit Cost Using Two Coolant/Lubricants

The data from which the curves of Figure 2 were generated are detailed in Table 1.

Table 1. Work part and Manufacturing Process Summary

Characteristic	Parameter
Work part Material	AISI 4140 Steel
Work part Material Hardness	R_c 24 to R_c 26
Operation	End Milling
Volume Removed	4.3 in^3
Material Removal Rate	0.459 in^3/min.
Cutting Speed	400 sfpm
Chip Load	0.005 ipt
Number of Teeth	2
Machining Time	9.37 min.
Tool Material	Uncoated Carbide
Coolant/Lubricant 1	Soluble Oil, 10% Concentration in Water
Coolant/Lubricant 2	Soluble Oil with Extreme Pressure Additives, 10% Concentration in Water

Table 2 details the Taylor Tool Life equation constants for these work part material/cutting-tool/cutting fluid combinations (derived from data from the work done by McClure et al. [2] and Groover [8]).

Table 2. Taylor Tool Life Constant Values

Cutting Fluid	C	n
Coolant/Lubricant 1	809.3	0.125
Coolant/Lubricant 2	833.5	0.150

The unit cost of production may be calculated using a modified version of one commonly accepted machined work part unit cost equation [6]. This equation—shown in Equation (9)—accounts for three major factors: the costs associated with raw material, time spent by the work part in the machine tool, and disposable tooling.

$$C_{pc} = C_m + C_{MT} + C_{DT} \tag{9}$$

where,

C_{pc} = the work part unit cost of production
C_m = raw material cost for one work part
C_{MT} = the cost associated with the time spent by the work part in the machine tool
C_{DT} = the cost, on a per-work part basis, associated with disposable tooling wear

Expanding Equation (9) yields Equation (10):

$$C_{pc} = C_m + C_o\left(\left(\sum_{i=1}^{n_t} T_{m_i}\right) + \frac{R}{r} + n_{tc}T_{tc}\right) + \sum_{i=1}^{n_t}\left[\frac{T_m}{T}\left(\frac{C_{pt}}{1+n_{rs}-a} + (1-a)C_{otr}T_{rs}\right)\right]_i \quad (10)$$

where,

C_o = shop rate: the cost per time to operate the production system on a per-machine basis
T_m = machining time per part
R = rapid travel distance/work part required
r = rapid travel rate
n_{tc} = number of tool changes/work part required
T_{tc} = time required to perform one tool change
n_t = number of different cutting tools required to produce the work part
T = cutting-tool life
C_{pt} = cost to purchase disposable tool type i
n_{rs} = number of allowable tool re-conditionings (for re-grindable tooling) or cutting edges (for disposable insert tooling) for tool type i
a = a factor equal to zero (for re-grindable tooling) or one (for disposable insert tooling)
C_{otr} = tool room rate: cost/time to operate tool room
T_{rs} = time required to re-sharpen tool type i

The Taylor Tool Life equation constants C and n are influenced by numerous factors, which may vary stochastically [9]. The concentration and composition of the coolant/lubricant may vary as a result of variability in the initial mixture, particularly in the case of water-soluble oils, where the dilution ratio is typically in the range of 5:1 to 30:1 (water to soluble oil, by volume) [10]; variability in the mixture ratio, due to water evaporation over time; variability in the mixture, due to make-up fluid mixing inconsistencies; variability in the properties of soluble oil attributed to age and time-in-service; and the presence of tramp oil in the fluid. Other factor variations, which have an effect on tool life, include deliberately induced changes in spindle speed (resulting in changes in cutting speed) as well as stochastic variations in work part and cutting-tool material properties. Figure 3 depicts the effect of changes in the Taylor constant C on the unit cost of production.

The type of fluid employed, changes in soluble oil water-to-fluid ratio, and changes in application method each may have an effect on the Taylor Tool Life constant C [8]. As the value of C increases, the unit cost as a function of cutting speed curve becomes slightly elongated along the horizontal (cutting speed) axis. Coolant/lubricant type, concentration, condition, and application method may have a significant effect on the Taylor Tool Life constant n, as well [11]. A five percent change in cutting fluid concentration alone may result in a change in the value of n of approximately 10.5% or more [12]. Figure 4 depicts the effect of changes in the value of the Taylor constant n on the unit cost of production as a function of cutting speed.

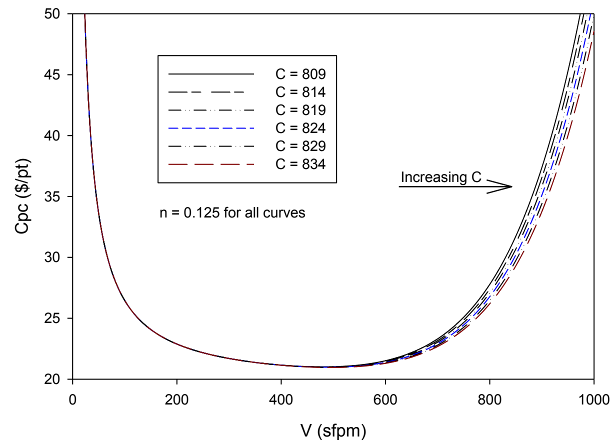

Figure 3. Effect of Increases in the Taylor Tool Life Constant C on Unit Cost as a Function of Cutting Speed (n = 0.125)

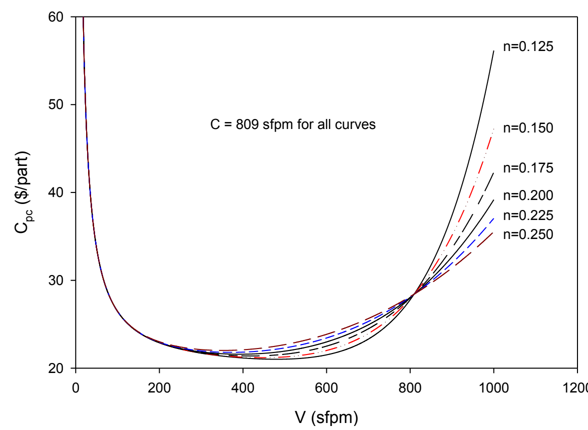

Figure 4. Effect of Increases in the Taylor Tool Life Constant n on Unit Cost as a Function of Cutting Speed (C = 809 sfpm)

As the value of the constant n increases, the curve becomes markedly shallower, or more flat. Increases in the value of the constant n have an effect that is similar to decreasing the degrees-of-freedom parameter in a statistical t distribution or increasing the eccentricity of an ellipse. For the purposes of this discussion, the eccentricity analogy will be employed. Since stochastic variations in the coolant/lubricant are inevitable, and since it is also extremely common for machine operators to make adjustments to machining parameters "on the fly", curves with a larger (wider) region in which the slope of the curve is small are preferable to those exhibiting narrower near-zero-slope regions. In practical terms, curves with larger near-zero-slope regions (i.e., larger values of "eccentricity") depict unit cost functions which are more forgiving with regard to deliberately induced and/or stochastic process variable changes.

Through the appropriate choice of cutting fluid, the effects of fluid and process variability on unit cost may be minimized. Differing combinations of cutting fluid, cutting-tool material, and work material result in differing values of the Taylor constants C and n. Changes in the value of the constant n, in particular, have the potential to minimize the effects of stochastic variation on the unit cost of production of machined work parts. Note that in Figure 4, a point of singularity exists where all curves intersect. This point of singularity occurs where the cutting speed, V, is equal to the Taylor Tool Life constant C. Equation (9) states that the unit cost of production for a machined work part is made up of three elements: the cost of raw material, the cost associated with time spent in the machine tool, and the cost associated with disposable tooling. The cost of raw material, obviously, is not dependent either on cutting speed or on the Taylor constants. The cost of machine time is, then, is given in Equation (11):

$$C_{MT} = C_o\left(\left(\sum_{i=1}^{n_t} T_{m_i}\right) + \frac{R}{r} + n_{tc}T_{tc}\right) \quad (11)$$

where, C_{MT} term is dependent on cutting speed, since machining time is a function of cutting speed but is not dependent on the Taylor constants C and n. The cost associated with disposable tooling is given in Equation (12):

$$C_{DT} = \sum_{i=1}^{n_t}\left[\frac{T_m}{T}\left(\frac{C_{pt}}{1+n_{rs}-a} + (1-a)C_{otr}T_{rs}\right)\right]_i \quad (12)$$

where, T_m is a function of cutting speed, while the tool life (T) is dependent on cutting speed as well as the Taylor constants C and n. From Equation (13), the fraction T_m/T, in practical terms, is the proportion of the cutting tool expended to make one work part. When the cutting speed, V, is equal to the Taylor constant C, tool life, T, is equal to one minute.

$$\left.\frac{T_m}{T}\right|_{V=C} = T_m \quad (13)$$

When cutting speed is less than the Taylor constant C, tool life, T, is greater than one minute, as shown Equation (14):

$$\left.\frac{T_m}{T}\right|_{V<C} < T_m \quad (14)$$

When cutting speed is greater than the Taylor constant C, tool life, T, is less than one minute, as shown in Equation (15):

$$\left.\frac{T_m}{T}\right|_{V>C} > T_m \quad (15)$$

At cutting speeds less than C, lower values of n result in somewhat smaller unit costs. At cutting speeds greater than C, larger values of n result in markedly lower unit costs. From a practical perspective, however, the choice of a cutting speed lying to the right of the point of singularity exhibited in Figure 4 is unlikely. In addition, it is worth noting that traditional practice has been to select cutting speeds that lie in the region bounded by the cutting speed, which results in the maximum production rate (V_{maxRp}) and minimum unit cost (V_{minCpc}). Figure 5 depicts these boundaries calculated using the average of the two values of the Taylor constant n (n = 0.125 and n=0.250) considered previously.

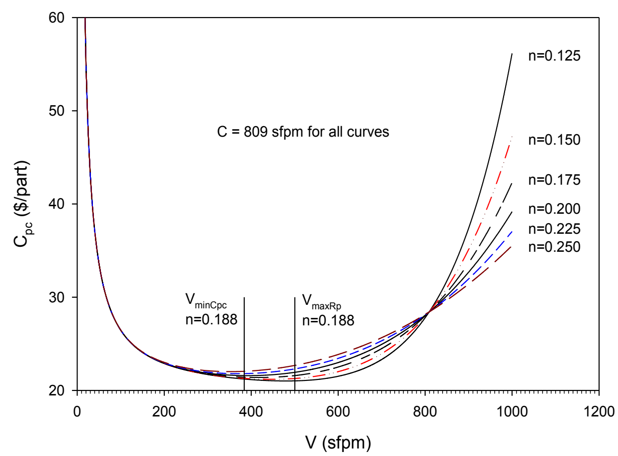

Figure 5. V_{minCpc} and $V_{max\ Rp}$ with n = 0.188

Table 3 details the unit cost incurred at the cutting speed, which results in minimum unit cost (C_{pcVmin}); the unit cost incurred at the cutting speed, which results in maximum production rate (C_{pcVmax}); and the change in unit cost, as cutting speed is increased from V_{minCpc} to V_{maxRp}. Note that as n increases, the change in unit cost, as cutting speed is increased, results in minimum unit cost and maximum production rate (i.e., as n increases, ΔC_{pc} increases). The largest percentage increase in Table 3 is 2.2%, corresponding to a Taylor constant n = 0.250. Figure 6 graphically depicts ΔC_{pc} for n=0.125. Over the range of n values considered here, the relationship between n and ΔC_{pc} (as well as n and $\%\Delta C_{pc}$) is essentially linear, as depicted in Figure 7.

Table 3. Change in Unit Cost due to Changes in Cutting Speed at Various Values of the Taylor Constant n

n	V_{minCpc} (sfpm)	V_{maxRp} (sfpm)	$C_{pc\ Vmin}$ ($/part)	$C_{pc\ Vmax}$ ($/part)	DC_{pc} ($/part)	$\%DC_{pc}$ ($/part)
0.125	463	553	16.59	16.74	0.15	0.9%
0.150	428	529	16.77	16.97	0.20	1.2%
0.175	398	509	16.97	17.21	0.24	1.4%
0.188	383	500	17.07	17.34	0.27	1.6%
0.200	371	492	17.17	17.45	0.28	1.7%
0.225	348	478	17.38	17.72	0.34	2.0%
0.250	328	467	17.61	17.99	0.38	2.2%

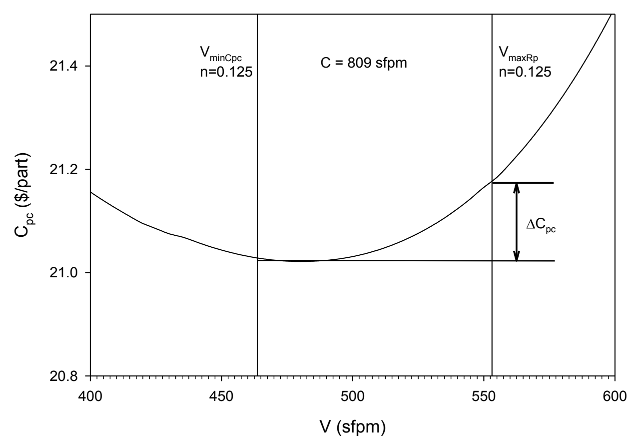

Figure 6. ΔC_{pc} for n = 0.125

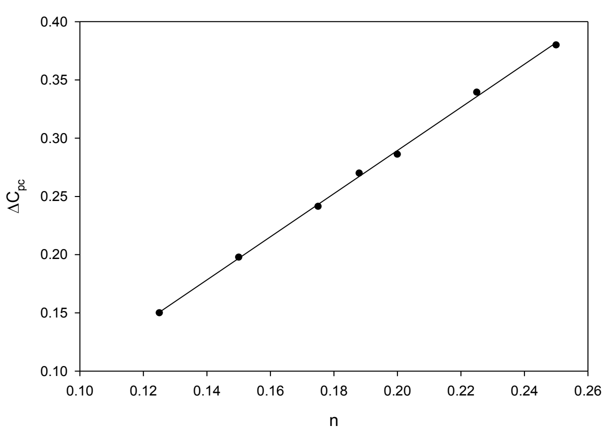

Figure 7. ΔC_{pc} as a Function of the Taylor Constant n

The variation in unit cost due to changes in cutting conditions (specifically, cutting speed) has been of traditional concern [13]. Stochastic changes resulting in differing values of the Taylor constant n, however, may have an effect on unit cost that is more than twice as large as that resulting from changes in cutting conditions. If there is reason to believe that the Taylor constant n has a value that lies between 0.125 and 0.250, then there may be reason to assign a value for n of 0.188 as "most likely". If the process is operated at a cutting speed of 383 sfpm (V_{minCpc} for n=0.188), and if the "true" value of n is 0.125, then the unit cost of production is evaluated as $16.79. If, on the other hand, the actual value of n is 0.250, then the unit cost of production is evaluated to $17.62. This variation represents a ΔC_{pc} = $0.83 per part, and a $\%\Delta C_{pc}$ = 4.9%. Figure 8 depicts this situation graphically.

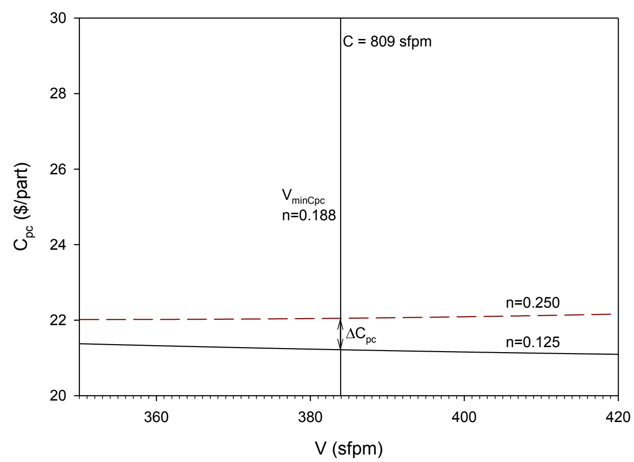

Figure 8. ΔC_{pc}, n V = 383 sfpm, n Varying from 0.125 to 0.250

At a cutting speed of 500 sfpm (V_{maxRp} for n=0.188), as n varies from 0.125 to 0.250, ΔC_{pc} = $1.66 per part and $\%\Delta C_{pc}$ = 10%. This variation in unit cost is approximately 4.5 times greater than that associated with a cutting speed variation from V_{minCpc} to V_{maxRp} with n held constant at 0.250.

Conclusions

The properties of coolants/lubricants, and specifically those of water-based soluble oil solutions employed in machining operations, vary stochastically due to variability in the initial mixture ratio, variability in the mixture ratio as a result of water evaporation over time, variability in the mixture due to make-up fluid mixing inconsistencies, variability in the properties of soluble oil attributed to age and time-in-service, and the presence of tramp oil in the fluid. These stochastic variations result in variability in the values of the Taylor Tool Life equation constants C and n.

The effect of variations in the Taylor constant C on the unit cost of production of machined work parts is relatively small, particularly if cutting speeds are maintained in the range $V_{minCpc} \leq V \leq V_{maxRp}$. The effect of variations in the value of the Taylor constant n, however, may be relatively large. Traditionally, analyses of unit cost variation have been focused on the effect of variations in the cutting speed. For the work part, cutting tool, and cutting conditions analyzed in this paper, the effect of stochastic variations in coolant/lubricant properties may result in an increase in unit cost between 2 and 4.5 times greater than that associated with variations in cutting speed. As a result, it is permissible to conclude that stochastic coolant/lubricant property variations have significantly larger effects on unit cost than cutting speed variations.

In summary:

- The properties of the coolants/lubricants employed in machining operations vary stochastically.
- These stochastic variations result in varying values of the constants C and n, which appear in the Taylor Tool Life equation.
- The effect of variations in the Taylor constant C on unit cost is relatively small.
- The effect of variations in the Taylor constant n on unit cost may be large.

In this paper, the authors quantified the variation in unit cost due to variations in fluid properties for a sample workpart/process combination. The results of this analysis showed that cutting fluid condition may have a much larger effect on unit cost than cutting speed, which has been the traditional parameter of concern. Future work will investigate the applicability of this current approach on different materials, tools, and coolants.

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