OPTIMIZATION OF STEPPED PART TURNING

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ABSTRACT

The determination of the optimal cutting conditions for a stepped part is still one of the most difficult problems facing the production engineer. A computer program has been constructed to find the optimal cutting variables to minimize the production cost and to increase the rate of production and consequently the profit. The computer program is used to determine the optimum cutting variables for any number of steps and dimensions. These determined cutting variables can be applied for each step without changing the setting of the machine tool used.

KEYWORDS

Optimization, turning operation, stepped part, minimum cost, maximum production rate, objective function.

INTRODUCTION

The optimization of the production process aims to produce any part with minimum manufacturing cost and maximum production rate to gain maximum profit. This optimization means the selection of the optimum cutting variables (cutting speed, cutting feed and cutting depth) taking into consideration such constraints as tool life, maximum power of machine tool, maximum cutting speed, maximum and minimum feed.

The determination of optimal cutting conditions for a single stage cylindrical part has been investigated [1-6]. However, in practice mechanical parts consist of different steps with differing lengths and diameters.

For parts with large diameter ratios, the spindle speed should be changed at each step to achieve the optimal conditions [7], and for parts with relatively small diameter ratios $R (R = 2)$ a computer program must be constructed to find a single spindle rotational speed which incorporates all the steps without interrupting the machine setting.

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PROBLEM FORMULATION

The workpiece shown in Fig.1 is to be turned from a bar stock its diameter \( d_1 \). The number of steps is \( n \), the diameter of the \( i \)th step is \( d_i \), the length of the \( i \)th step is \( k_i \). The dimensions of the workpiece can be expressed as follows:

- Raw material diameter : \( d_1 \)
- First step diameter : \( d_2 \)
- Second step diameter : \( d_3 \)
- \( i \)th step diameter : \( d_{i+1} \)
- nth step diameter : \( d_{n+1} \)

If the total length of the workpiece is \( L_1 \) and the length of the first step \( K_1 \) referring to Fig.1, the following relations can be written:

\[
\begin{align*}
L_1 &= \frac{n}{1} - K_1 \\
L_2 &= L_1 - K_1 \\
L_3 &= L_2 - K_2 \\
L_i &= L_{i-1} - K_{i-1} \\
L_n &= L_{n-1} - K_{n-1} \\
\Delta 1 &= \frac{(d_1 - d_2)}{2} \\
\Delta 2 &= \frac{(d_2 - d_3)}{2} \\
\Delta i &= \frac{(d_i - d_{i+1})}{2} \\
\Delta n &= \frac{(d_n - d_{n+1})}{2}
\end{align*}
\]

Objective Functions

The production time \( (t_p) \) can be calculated from the following statement:

\[
t_p = t_h + t_m + t_c \cdot \frac{t_m}{T} \tag{1}
\]

where,

- \( t_h \): handling time in min., 
- \( t_m \): machining time in min. and 
- \( T \): tool lift in min.

The tool life can be calculated by applying Taylor's equation

\[
T = C_1 \cdot V \cdot f \cdot A \tag{2}
\]
where, \( T \): tool life in min., \( V \): cutting speed in m/min., \( f \): feed rate in mm/rev., \( A \): cutting depth in mm, \( C_1, C_2, C_3, C_4 \) are constants depending upon cutting tool and workpiece materials.

\[ C_2 > 1, C_3 \geq 1 \text{ and } C_4 < 1 \]  \([2]\)

The machining time for a single pass for one stage can be calculated from the following equation:

\[
\frac{L}{f \times N} = \frac{L}{f \times N} \tag{3}
\]

where, \( t_m \): machining time in min., \( L \): cutting tool travel which includes the length to be turned, tool approach and tool overtravel, \( f \): feed rate in mm/rev. & \( N \): rotational speed of the main spindle in rpm.

In the present case only the length of the step itself is taken into account and the others are neglected. For a stepped part as previously mentioned, the total machining time for \( n \) steps can be calculated as follows:

\[
\frac{L}{f \times N} + \frac{L}{f \times N} + \ldots + \frac{L}{f \times N} = \frac{1}{f \times N} \sum_{i=1}^{n} \frac{L_i \cdot A_i}{A_i} \tag{4}
\]

where, \( A \): cutting depth in mm

The cutting speed can be calculated from the following equation:

\[
V = \frac{\pi \times d \times N}{1000} \text{ m/min} \tag{5}
\]

Substituting the values of \( V, T \) and \( t_m \) in the production time equation we get:

\[
\frac{\sum_n {L_i \cdot A_i}}{A_i} + \frac{1}{f \times N} \sum_{i=1}^{n} \frac{L_i \cdot A_i}{A_i} + \frac{1}{f \times N} \cdot \frac{C_2 \cdot N}{C_1 (\pi \times d \times N)} + \frac{C_3 \cdot C_4}{C_1 \times 1000} \tag{6}
\]
where, mean cutting depth.
\[ A_m = \frac{\sum_{i=1}^{n} A_i}{n} \]

mean diameter
\[ d_m = \frac{\sum_{i=1}^{n} d_i}{n} \]

The total manufacturing cost per piece is calculated from the following equation:

\[ C_t = C_0 \cdot t_h + C_0 \cdot t_m + \left( C_0 \cdot t_c + C_{th} / e \right) \cdot \frac{t_m}{T} \]  \hspace{1cm} (7)

where, \( C_0 \): labour cost rate L.E./hr, \( C_{th} \): cost of throwaway tip L.E., \( e \): number of cutting edges and \( t_c \): tool change time in min.

Referring to Fig.1, the total manufacturing cost is written as follows:

\[ C_t = C_0 \cdot t_h + C_0 \cdot \frac{1}{f \cdot N} \sum_{i=1}^{n} \left( \frac{L_i \cdot \Delta_i}{A_i} \right) + \left( C_0 \cdot t_c + C_{th} / e \right) \cdot \frac{t_m}{T} \]

\[ \sum_{i=1}^{n} \left( \frac{L_i \cdot \Delta_i}{A_i} \right) \]

\[ f \cdot N \cdot C_1 \left( \frac{\pi \cdot d_m \cdot N}{1000} \right) \cdot f \cdot A_m \] \hspace{1cm} (8)

The constraints are:
\[ N_{\text{min}} \leq N \leq N_{\text{max}} \]
\[ f_{\text{min}} \leq f \leq f_{\text{max}} \]
\[ A_{\text{min}} \leq A \leq A_{\text{max}} \]

The lower and upper limits of the above mentioned constraints can be determined from the machine tool specification and surface finish required, the range of spindle speed will be:

\[ N_{\text{min}} = 1000 \times V_{\text{min}} \]
\[ N_{\text{max}} = 1000 \times V_{\text{max}} \]

\[ \frac{\pi \cdot d_{\text{max}}}{d_{\text{min}}} \]

where, \( d_{\text{min}} \) and \( d_{\text{max}} \) are the minimum and maximum diameters to be turned.
Equations 1&7 are the objective functions. In the present work a computer program has been constructed to determine the optimum rotational speed giving minimum production time and minimum cost per piece for all steps, without changing the setting of the machine tool used. This program has been written in BASIC.

RESULTS AND DISCUSSIONS

The obtained results from the computer program show that the feed rate has a very small effect on the objective functions and the larger value of the rate is recommended. The rotational spindle speed leading to minimum cost is usually smaller than that required for minimum production time. The optimum rotational speed varies from machine tool to another according to the machine tool specification for machining the same workpiece. The spindle speed is the most important decision factor for minimizing the objective function. The machine tools having smaller values of the common ratio of its gearbox-steps, are preferred in case of minimum cost. On other hand larger values of the common ratio of gearbox-steps are recommended in case of minimum manufacturing time.

The computer program can be used to determine the machine tool which gives minimum cost or minimum time when there are different types of machine tools capable to machine the same workpiece.

REFERENCES

A computer program for determining the optimum rotational speed in case of stepped part turning.

10 REM OPTIMIZATION OF CUTTING CONDS
20 REM ENTER DATA
50 INPUT "NUMBER OF SPEEDS" ; NN
55 INPUT "NUMBER OF STAGES" ; ND
60 INPUT "AVG DIAMETER" ; DM
65 INPUT "LABOR&M/C COST" ; CO
70 INPUT "HANDLING&SETTING TIME" ; TH
75 INPUT "TIP COST" ; CTH
80 INPUT "NUMBER OF EDGES" ; E
90 INPUT "CHANGE TIME" ; TC
95 INPUT "TAYLOR CONST 1" ; C1
100 INPUT "TAYLOR CONST 2" ; C2
105 INPUT "TAYLOR CONST 3" ; C3
110 INPUT "TAYLOR CONST 4" ; C4
115 INPUT "FEED" ; F
120 FOR I = 1 TO ND : PRINT "DEPTH OF CUT IN STAGE" ; I ; INPUT A(I) ; AM = AM + A(I)
125 PRINT "REDUCTION IN RADIUS STAGE" ; I ; INPUT D(I)
130 PRINT "LENGTH TO BE TURNED STAGE" ; I ; INPUT L(I) ; NEXTI
140 AM = AM / ND
150 FOR I = 1 TO ND : S = S + D(I) * L(I) / A(I) ; NEXTI
155 S = S / F
160 VV = F * DM / 1000
170 PRINT " 	 N 	 	 TP 	 TC" ; PRINT
200 FOR I = 1 TO NN : PRINT "SPEED" ; I ; INPUT N
210 TP = TH + S / N + TC * S / N / (C1 * (VV * N)^1 + C2 * F + C3 * AM + C4)
214 IF I = 1 THEN MTP = TP ; N1 = N
215 IF TP < MTP THEN MTP = TP ; N1 = N
220 PRINTTP,
225 CT = CO * TH + CO * S / N + (CO * TC + CTH / E) * S / N / (C1 * (VV * N)^1 + C2 * F + C3 * AM + C4)
230 IF I = 1 THEN MCT = CT ; N2 = N
235 IF CT < MCT THEN MCT = CT ; N2 = N
240 PRINTCT
275 NEXTI : PRINT " 	 MINIMUM TIME IS " ; MTP ; " AT SPEED" ; N1
290 PRINT " 	 MINIMUM COST IS " ; MCT ; " AT SPEED" ; N2
300 END

READY.
The results which are obtained by using the computer program in case of turning the workpiece on two machines having different spindle speeds.

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MINIMUM TIME IS 12.2162761 AT SPEED 355
MINIMUM COST IS 1.98678236 AT SPEED 250

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MINIMUM TIME IS 12.2437258 AT SPEED 400
MINIMUM COST IS 1.81908151 AT SPEED 200