Int J Adv Manuf Technol (2001) 17:861–869

The International Journal of Advanced Manufacturing Technology

Integration of Cutting Parameter Selection and Tool Adjustment Decisions for Multipass Turning

M. Liang[1], M. Mgwatu[2], and M. Zuo[3]

[1]Department of Mechanical Engineering, University of Ottawa, Ottawa, Canada K1N 6N5; [2]Department of Materials Processing, Royal Institute of Technology, Stockholm, Sweden; and [3]Department of Manufacturing Engineering and Engineering Management, City University of Hong Kong, Hong Kong

This paper presents an integrated approach to simultaneous optimisation of machining parameters, including machining speed, feedrate and depth of cut, number of passes, tool adjustment interval, and the amount of adjustment. Associated models have been developed for both small parts, where each tool can be used to machine several parts, and large parts, where several tools may be required for a single workpiece. Examples are given to demonstrate the application of the proposed models. The impact of machining parameters and tool cost on tool adjustment and the effect of rapid reverse on the final solution are also discussed.

Keywords: Integration; Machining parameter selection; Multipass turning; Tool adjustment

1. Introduction

The selection of efficient machining parameters such as machining speed, feedrate, and depth of cut has a direct impact on production economics in the metal cutting processes. Dimensional accuracy is a major concern in machining processes. It has been recognised that dimensional accuracy is significantly affected by tool wear [1–3]. Therefore, to improve the dimensional accuracy, one or more tool adjustments may be desirable before a tool is replaced [3].

Machining parameter selection has been investigated extensively, chiefly for single-pass turning. However, if a large amount of material is to be removed, it may not be feasible to remove the material in a single pass owing to the force and power restrictions, and to the surface finish requirement. In some cases, multipass cutting may be more economical than single-pass machining [4,5]. This gives rise to studies of the multipass problem which involves not only the selection of machining parameters, but also the economical number of passes. As Tan and Creese [6] pointed out, because of the lack of an efficient optimisation tool, early work in this direction was limited to small problems with mostly two or three passes, and a few variables and constraints [7,8]. The latest developments show that larger problems with more passes or more constraints have been solved using various approximation methods (e.g. [6,9–14]). As the total depth of cut increases (e.g. a total depth of cut of 38.1 mm has been used in the experimental study by Kee [11]), the accumulated dimensional error caused by tool wear can be quite significant. Tool adjustment is hence important for the multipass turning processes. Related work has not been reported in the accessible literature.

In previous research pertinent to machining parameter selection, it has often been assumed that a tool can be used up to its life limit specified by the allowable wear. The tool cost, so calculated, is then distributed to each workpiece. However, it is not uncommon to replace a tool before its allowable wear limit is reached, since the residual tool life may not be sufficient to complete the next cutting pass, noting that it is impractical to replace a tool in the middle of a cutting process. To obtain a more realistic result for shop floor decision making, such tool replacement practice has to be taken into account.

Owing to its economic significance, tool adjustment has attracted much attention in the past few years [1,3,15,16]. Quesenberry [3] proposed a two-part compensator to minimise the mean square error of the deviation from the target value. The purpose is to reduce quality loss, but the cost required for tool adjustment was not considered. Sanjanwala et al. [1] developed a compensating system for tool wear. The system consists of an on-line pneumatic sensor and an actuating mechanism to adjust the tool position. A control device involving initial investment are required for implementing the system. As indicated by Wang et al. [16], an expensive control and adjustment mechanism can be justified if the tool wear is substantial during each cutting pass and when continuous in-process adjustment is necessary. If the tool wear during each pass is not substantial, it is preferable to adjust tools between passes. Wang and Zuo [15] reported a tool adjustment method based on the Taguchi quality loss concept. The main purpose

Correspondence and offprint requests to: Dr Ming Liang, Department of Mechanical Engineering, University of Ottawa, 770 King Edward Avenue, Ottawa, Ontario, Canada, K1N 6N5. E-mail: mliang@uottawa.ca

was to minimise the expected cost per unit of time during the life of a single tool. The cost components are tool replacement and adjustment costs, and quality loss. This work was later extended to developing a tool adjustment approach based on available but inaccurate tool wear information [16]. Though the studies reported in [15,16] have advanced the research in this direction, some important factors, such as machining speed, feedrate and depth of cut, were not considered. It is, however, well known that tool wear depends not only on the amount of removed material, but also on the specified machining parameters. Therefore, the machining parameters should be incorporated in the analysis of tool adjustment.

The above clearly reveals a need to investigate the machining parameter selection and tool adjustment problems together. To this end, we present an integrated approach for simultaneously solving the two problems for the multipass turning processes.

2. Problem Formulation

2.1 Cost Components

The cost components to be considered include machining cost, tool cost, tool replacement and adjustment costs, and quality loss. To facilitate later discussions, they are explained as follows.

Machining Cost

The machining cost for pass i is a function of machining speed and feedrate and is given by

$$C_{mi} = C_0 t_{mi} = \frac{\pi D_{i-1} L\, C_o}{1000 v_i f_i} \tag{1}$$

where machining time $t_{mi} = \dfrac{\pi D_{i-1} L}{1000 v_i f_i}$

Tool and Tool Replacement Costs

The two cost components are modelled differently for small and large parts. The small parts are specified as parts for which a tool can be used to complete several parts and many passes. In this case, the remaining tool life before tool replacement is negligible. It is reasonable to assume, as commonly adopted in the literature, that a tool can be used up to its life limit. The large parts, on the other hand, are defined as those for which a tool can be used for only a few passes. A tool has to be replaced if its expected residual life is not enough to complete the next pass, even if the residual life is a significant portion of the tool life.

For small parts, the tool and tool replacement costs can be distributed to each pass based on the amount of tool life used for actual machining. According to Lambert and Walvekar [8], the extended tool-life Eq. for pass i can be expressed as

$$T_i = \frac{B_{Ti}}{v_i^{\alpha_T} f_i^{\beta_T} d_i^{\gamma_T}} \tag{2}$$

The tool cost for pass i is then

$$C_{ti} = \frac{t_{mi}}{T_i} C_t = \frac{\pi D_{i-1} L}{1000\, B_T} v_i^{\alpha_T - 1} f_i^{\beta_T - 1} d_i^{\gamma_T} C_t \tag{3}$$

The tool replacement cost distributed to each pass is

$$C_{ri} = \frac{t_{mi}}{T_i} C_r t_r = \frac{\pi D_{i-1} L}{1000\, B_T} v_i^{\alpha_T - 1} f_i^{\beta_T - 1} d_i^{\gamma_T} C_r t_r \tag{4}$$

For large parts, Eqs (3) and (4) are no longer valid. The tool and tool replacement costs should be calculated according to the accumulated discrete number of tools that have been used/replaced, rather than the accumulative tool life used for actual machining. The details will be shown in the associated models.

Tool Adjustment Cost

The dimensions of a part at the end of each pass may deviate from their target values owing to tool wear (Fig. 1). To maintain the part dimensions within tolerance limits, it may be desirable to adjust the tool position between passes. The cost associated with a tool adjustment is $C_a t_a$. However, the tool may or may not be adjusted for every pass, since each adjustment involves additional machine downtime and labour cost. An adjustment is justified only when the reduced quality loss can offset the increased cost.

Quality Loss

Quality loss is specified as the cost incurred when the quality characteristic of the part deviates from its target value. The quality loss due to the deviation from the target dimension is assumed to be contributed mainly by the tool wear and is related only to the finish pass. According to Taguchi et al. [17], the quality loss function can be expressed as a quadratic function of the quality deviation from the target dimension, i.e.

$$L(x) = \frac{A}{\delta^2}(x - m_o)^2 \tag{5}$$

where A is the rework or scrap cost, δ the tolerance limit, x the quality characteristic of the product, and m_o the quality target value. In the metal cutting context, the quality loss function can be written as

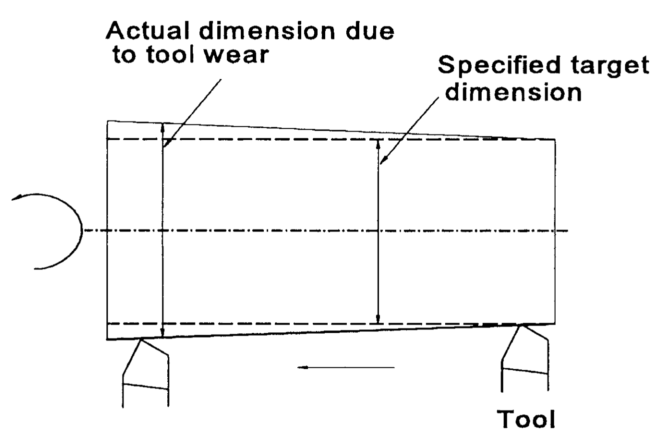

Fig. 1. Dimensional error caused by tool wear.

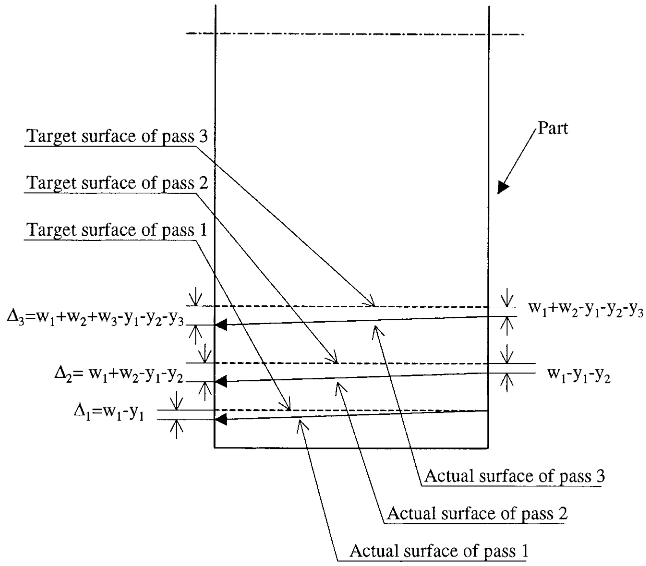

Fig. 2. Single-direction turning (a 3-pass example).

$$L\,(\Delta_I) = \frac{A}{\delta^2}\,\Delta_I^2 \tag{6}$$

Rapid Reverse Cost

For completeness of the analysis, we consider both bidirectional and single-directional turning (Figs 2 and 3). Cutting operations can be performed in both forward and back directions, thus eliminating traversal tool movements [18]. In single-directional turning, the operations always start from one end of the workpiece. After each pass, the tool traverses back to the same end, and resumes the next cutting pass. The rapid reverse cost occurs only in single-directional operations.

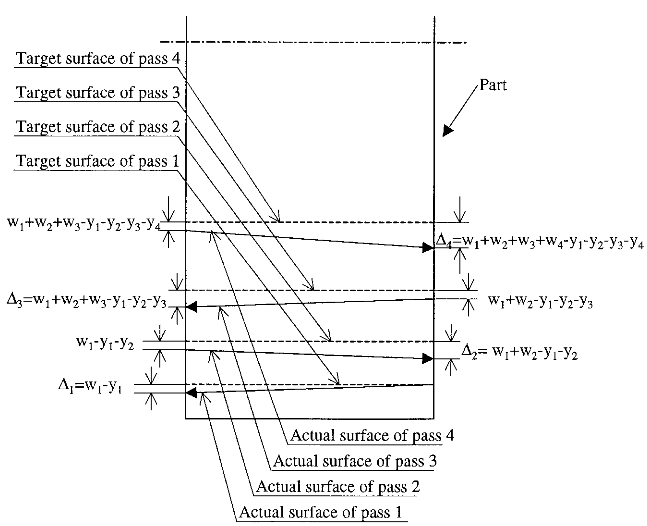

Fig. 3. Bidirection turning (a 4-pass example).

2.2 Model Development

2.2.1 Models for Small Parts

Our purpose is to minimise the unit production cost consisting of machining cost, tool and tool replacement costs, tool adjustment cost, and quality loss. For small parts, several parts can be machined within a tool life span. As stated earlier, the tool and tool replacement costs can be distributed to each pass according to the consumed tool life for actual machining. To simplify the analysis, we further assume that the machining parameters of the same pass are identical for every workpiece and hence the machining cost, and the distributed tool and tool replacement costs are the same for all parts. The tool adjustment cost and quality loss, on the other hand, may vary from part to part as the amount of adjustment may be different and adjustment may not be made for some parts. For this reason, the unit production cost may be different for different parts within a tool life span. Therefore, the average tool adjustment cost and the quality loss are used in the model and the objective is to minimise the average unit cost. The models are presented below.

Model 1.1 (Bidirectional turning)

$$\text{Min} \sum_{i=1}^{I} \frac{\pi D_{i-1} L}{1000\, B_T}\left[\frac{B_T C_o}{v_i f_i} + v_i^{\alpha_T - 1} f_i^{\beta_T - 1} d_i^{\gamma_T}\,(C_t + C_r t_r)\right]$$

$$p_i + \frac{1}{N}\sum_{n=1}^{N}\left[\sum_{i=1}^{I} C_a t_a x_{ni} + A\left(\frac{\Delta_{nI}}{\delta}\right)^2\right] \tag{7}$$

where $D_{i-1} = D_o - 2\sum_{q=1}^{i-1} d_q$

subject to:

1. Restriction of machining parameters

$$v_i^l \leqslant v_i \leqslant v_i^u \qquad \forall i \tag{8}$$

$$f_t^l \leqslant f_t \leqslant f_i^u \qquad \forall i \tag{9}$$

$$d_i \leqslant d_i^u \qquad \forall i \tag{10}$$

2. Constraints of cutting force, power, and surface roughness

$$B_F\, v_i^{\alpha_F} f_i^{\beta_F} d_i^{\gamma_F} \leqslant F_{\max} \qquad \forall \mathrm{i} \tag{11}$$

$$B_P v_i^{\alpha_P} f_i^{\beta_P} d_i^{\gamma_P} \leqslant P_{\max} \qquad \forall \mathrm{i} \tag{12}$$

$$B_R\, r^{\eta} \mathrm{BHN}^{\theta}\, v_i^{\alpha_R} f_i^{\beta_R} \leqslant R_{\max} \qquad \forall \mathrm{i} \tag{13}$$

3. Pass selection constraints

$$\sum_{i=1}^{I} d_i = d_T \tag{14}$$

$$\sum_{i=1}^{I} d_i p_i = d_T \tag{15}$$

$$0 \leqslant p_i \leqslant 1 \qquad \forall i \tag{16}$$

$$d_i \leqslant d_i^l p_i \qquad \forall i \tag{17}$$

$$p_I = 1 \tag{18}$$

4. Tool adjustment constraints

$$y_{1,1} = 0 \tag{19a}$$

$$y_{n,i} \leq \Delta_{n,i-1} \qquad \forall n,i > 1 \tag{19b}$$

$$y_{n,1} \leq \Delta_{n-1,I} \qquad \forall n > 1 \tag{19c}$$

$$y_{n,i} \leq w_T x_{n,i} \qquad \forall n,\ i \tag{20a}$$

$$\Delta_{n,i} \leq w_T \qquad \forall n,\ i \tag{20b}$$

$$\Delta_{1,1} = w_1 \tag{21a}$$

$$\Delta_{n,i} = \Delta_{n,i-1} + w_i - y_{n,i} \qquad \forall n,\ i>1 \tag{21b}$$

$$\Delta_{n,1} = \Delta_{n-1,I} + w_i - y_{n,1} \qquad \forall n>1,\ i \tag{21c}$$

$$\Delta_{n,I} \leq \delta \qquad \forall\ n \tag{22}$$

$$x_{n,i} \leq p_i \qquad \forall n,\ i \tag{23}$$

Solving this model will provide simultaneous solutions for machining parameter selection, pass selection, and tool adjustment. Constraint set (1), i.e. constraints (8), (9), and (10), specifies upper and lower limits to cutting speed, feedrate and depth of cut. The permissible cutting force, power consumption, and surface roughness are given by constraints (11), (12), and (13). Constraint (14) states that the sum of depths of cut of all passes should be equal to the total material to be removed. An auxiliary constraint (15) is added, which in conjunction with constraints (14) and (16) will guarantee the value of p_i to be binary, i.e. either 0 or 1, thus reducing the computational burden introduced by integer variables. Constraint (17) is used to avoid the scenario where $d_i = 0$ even when $p_i = 1$. Constraint (18) simply says that at least one pass has to be performed which is the final pass.

In constraint set (4), Eq. (19*a*) reflects the fact that tool adjustment is unnecessary at the beginning of the first pass of the first part after a tool replacement. Constraint (19*b*) states that the amount of tool adjustment should be no more than the currently accumulated error, and constraint (19*c*) ensures the continuity of constraint (19*b*) between two adjacent parts. Constraints (20*a*) and (20*b*) specify that an adjustment has to be made before the tool is worn out, and a tool adjustment should not be performed if it is not justified economically. The relation between the accumulated error, tool wear and the amount of adjustment is given by Eq. (21). The tolerance limit is imposed by constraint (22). Finally, constraint (23) states that tool adjustment is possible only if a pass is selected but it may not be performed for every pass.

Model 1.2 (Single-directional turning)
The only difference between Model 1.2 and Model 1.1 is the rapid reverse cost in the objective function. Model 1.2 is as follows.

$$Min \sum_{i=1}^{L} \frac{\pi D_{i-1} L}{1000 B_T}$$

$$\left[\frac{B_T C_o}{v_i f_i} + v_i^{\alpha_T - 1} f_i^{\beta_T - 1} d_i^{\gamma_T} (C_T + C_r t_r) + C_{rp} t_{rp} \right]$$

$$p_i + \frac{1}{N} \sum_{n=1}^{N} \left[\sum_{i=1}^{I} C_a t_a x_{ni} + A \left(\frac{\Delta_{nI}}{\delta} \right)^2 \right] \tag{24}$$

subject to constraint sets 1 to 4.

2.2.2 Models for Large Parts

As mentioned earlier, a cutting edge may not be sufficiently unworn to complete all the passes for a large part. In reality, it is impossible to replace a tool during cutting or in the middle of a pass. Therefore, if the residual tool life is not sufficient for the next pass, the tool has to be replaced even if it is not completely worn out. As a result, the tool and tool replacement cost term used in Models 1.1 and 1.2 is no longer valid since it was implicitly assumed that a tool can be continuously used until it is completely worn out, i.e. the allowable wear limit is reached. The models are accordingly formulated as follows.

Model 2.1 (Bidirectional turning)

$$\text{Min} \sum_{i=1}^{I} \left\{ \frac{\pi C_o D_{i-1} L}{1000\ v_i f_i} p_i + x_i \right.$$

$$\left. [(C_t + C_r t_r) z_i + C_a t_a (1 - z_i)] \right\} + A \left(\frac{\Delta_I}{\delta} \right)^2 \tag{25}$$

subject to constraint sets 1 to 2 and

$$y_1 = 0 \tag{19a'}$$

$$y_i \leq \Delta_{i-1} \qquad \forall i \tag{19b'}$$

$$y_i \leq w_T x_i \qquad \forall i \tag{20a'}$$

$$\Delta_i \leq w_T \qquad \forall i \tag{20b'}$$

$$\Delta_1 = w_1 \tag{21a'}$$

$$\Delta_i = \Delta_{i-1} + w_i - y_i \qquad \forall i \tag{21b'}$$

$$\Delta_I \leq \delta \tag{22'}$$

$$x_i \leq p_i \qquad \forall i \tag{23'}$$

$$\Delta_{i-1} + w_i - w_T \leq z_i \qquad \forall i - 1 \tag{26a}$$

$$w_1 - w_T \leq z_1 \tag{26b}$$

In this model, constraints (19*a*′) to (23′) map the same relationships as stated in Model 1.1. Constraint (26) and the associated term in the objective function together specify that if the residual tool life is less than that required for the next pass, then the tool should be replaced. In this case, the tool adjustment and replacement are carried out in one set-up. Both tool cost and replacement cost have to be taken into account, but tool adjustment is not considered since a separate tool adjustment is unnecessary. Otherwise, tool adjustment should suffice and there will be no tool cost.

Model 2.2 (Single-directional turning)

$$\text{Min} = \sum_{i=1}^{I} \left\{ \left(\frac{\pi C_o D_{i-1} L}{1000 v_i f_i} + C_{rp} t_{rp} \right) \right.$$

$$\left. p_i + x_i [(C_t + C_r t_r) z_i + C_a t_a (1 - z_i)] \right\}$$

$$+A\left(\frac{\Delta_L}{\delta}\right)^2 \tag{27}$$

subject to the same constraints as used in Model 2.1.

3. Examples

Since the rapid reverse time is very short, usually less than 0.1 min depending on the part length [19], inclusion of this cost component has little effect on the final solution. We, therefore, focus here on the bidirectional turning models and leave the single-directional turning models for the discussion.

Example for Model 1.1

Consider a batch of mild steel bars to be machined using carbide tools. The dimensions of the steel block are D_o=200 mm and L=225 mm. The total depth of cut d_T=5 mm. The tool-life equation and cutting-force equation are obtained from [19]. The parameters in the tool-life and cutting-force equations are given in Table 1. The power consumption equation is obtained according to the following relationship [20]:

$$P = \frac{Fv}{60E}\,(\text{kW}) \tag{28}$$

The surface roughness Eq. are from [21]:

$$\begin{aligned} R_a &= 122r^{-0.714}\,\text{BHN}^{-0.323}\,v^{-1.52}\,f^{1.004}\,(\text{mm}) \\ &\quad \text{for } 25 \le v \le 250 \text{ m min}^{-1}, f \le 0.75 \text{ mm rev}^{-1} \\ \text{R}_a &= 0.071057r^{-0.714}\,\text{BHN}^{-0.323}v^{-1.52}\,f^{1.54}\,(\text{mm}) \\ &\quad \text{for } v > 250 \text{ m min}^{-1}, f \le 0.75 \text{ mm rev}^{-1} \\ \text{R}_a &= 0.3013r^{-0.714}\,\text{BHN}^{-0.323}v^{-1.52}\,f^{4.54}\,(\text{mm}) \\ &\quad \text{for } f > 0.75 \text{ mm rev}^{-1} \end{aligned} \tag{29}$$

All of the above tool-life, cutting-force, and surface-roughness equations are for the combination of a mild steel workpiece and carbide tool. The tolerance level is specified as δ = 0.1 mm and the maximum quality loss, i.e. rework cost is A = \$2. The maximum number of passes is set to three. Other input data are common for both Models 1 and 2 and are listed in Table 1.

Note that the summation limit N in the objective function of Model 1.1 is a variable, which makes the model a "nested" problem. To solve the nested problem, special software is needed. Fortunately, since the problem is small, the best N can be determined by enumeration. Model 1.1 with the above input data was solved using a software package, Lingo [22], on a Pentium PC. In the computation process, the tool usage is updated by accumulating the total tool wear. The computation was carried out for different values of N until the specified tool nose wear limit is reached. In this example, the tool wear limit is reached after 6 parts. The results are summarised in Table 2.

As shown in Table 2, a total of two passes are selected. The optimal feedrates and depths of cut are achieved at their upper limits for all passes. The optimal machining speeds fall within the specified feasible ranges and are different when different values of N are used. By enumerating up to 6 parts, it is found that, starting from the 2-part case, the average unit cost increases monotonously with the number of parts used for calculation. The best tool adjustment policy is achieved at N = 2 with an average cost of \$5.0974 per part and a cyclical adjustment of 0.0501 mm for the second pass of every second part. The tool is replaced after every 6 parts.

If the best N is less than or equal to 3, the cycle will be the same as N. For example, if N = 3, then the adjustment pattern repeats itself after every 3 parts. If the best N is greater than 3, say 4, the adjustment will be arranged in a 2, 4, 2, 4, …, pattern since the tool has to be replaced after every 6 parts. Then, the tool adjustment will be performed following the pattern associated to N = 2 for the first two parts and N = 4 for the next four parts. The average unit cost is now: (2×*COST*(2)+4×*COST*(4))/6, where *COST*(2), or *COST*(4), represents the unit cost when the pattern associated to N = 2, or 4, is strictly followed.

Table 1. Common input data for both Models 1 and 2.

Symbol	Value
C_o, C_t, C_r, C_a	\$1 min^{-1}, \$3 edge^{-1}, \$1 min^{-1}, \$1 min^{-1}
t_r, t_a, t_{rp}	1 min, 0.5 min, 1 min
w_T	0.2 mm
r	1 mm
BHN	195
y_i^l, v_i^u	60, 150 m min^{-1} for non-finish passes, 160, 200 m min^{-1} for finish pass
f_i^l, f_i^u	0.2, 0.7 mm rev^{-1} for non-finish passes, 0.1, 0.3 for finish pass
d_i^l, d_i^u	1.0, 4.0 mm for non-finish passes, 0.1, 1.0 mm for finish pass
$F_{\max}$, $P_{\max}$	6 kN, 15 kW
$R_{\max}$	0.003 mm
α_F, β_F, γ_F, B_F	−0.15, 0.75, 1, 2.65
α_P, β_P, γ_P, B_P	0.85, 0.75, 1, 0.059
α_R, β_R, η, θ, B_R	−1.52, 1.004, −0.714, −0.323, 122
α_T, β_T, γ_T, B_T	1.41, 0.35, 0.25, 17795
E	0.75

Example for Model 2.1

Now we consider large workpieces. Again, we use the combination of a mild steel workpiece and a carbide cutter to illustrate the model application. The dimensions of the raw material block are L = 600 mm and D_o = 380 mm. The tool-life, force, power, and surface-roughness equations are all the same as those used in the example for Model 1. The quality loss, i.e. rework cost is now A = \$10, and the tolerance specification for the final part is δ = 0.3 mm. Other input data are listed in Table 1. The maximum number of passes is set at 9. The computations are also extended to different total depths of cut for comparison purposes. The results are summarised in Table 3.

Table 3 shows that all the concerned parameters including cutting speed, feedrate, depth of cut, number of cutting passes, tool adjustment interval, and the amount of adjustment have been optimised simultaneously. It is also shown that the optimal

Table 2. Results of the example for Model 1.

N	1	2	3	4	5	6
Cost ($)	5.2890	5.0974	5.1323	5.1716	5.1727	5.1939
Tool adjustment (mm)	$y_{1,2} = 0.0134$	$y_{2,2} = 0.0501$	$y_{2,2} = 0.0443$	$y_{2,2} = 0.0468$ $y_{4,2} = 0.0634$	$y_{2,2} = 0.0443$ $y_{4,2} = 0.0598$	$y_{2,2} = 0.0459$ $y_{4,2} = 0.0310$ $y_{5,2} = 0.0620$
Machining parameters	Number of passes selected = 2					
v_1 (m min^{-1})	116.02	120.54	117.84	119.59	118.21	119.29
v_2 (m min^{-1})	192.15	194.44	185.96	188.19	184.96	186.50
f_1 (mm rev^{-1})	0.7	0.7	0.7	0.7	0.7	0.7
f_2 (mm rev^{-1})	0.3	0.3	0.3	0.3	0.3	0.3
d_1 (mm)	4.0	4.0	4.0	4.0	4.0	4.0
d_2 (mm)	1.0	1.0	1.0	1.0	1.0	1.0

Note: For presentation purpose, we list only the selected passes.

Table 3. Results of the example for Model 2.1.

d_T (mm)	Number of passes	Case[a]	Cost ($)	Machining parameters[b]	Tool adjustment (mm)
10	4	1	37.33	v_1=114.26, v_2=127.76, v_3=114.26, v_4=200.00, f_1=0.7, f_2=0.7, f_3=0.7, f_4=0.3, d_1=4.0, d_2=1.9, d_2=4.0, d_4=0.1	y_4=0.1811
		2	37.55 ϵ^c=0.59%	$v_1=v_2=v_3$=117.40, $f_1=f_2=f_3$=0.7 $d_1=d_2=d_3$=3.3, v_4=200.00, f_4=0.3, d_4=0.1	y_4=0.1811
15	5	1	46.20	$v_1=v_2$=128.25, v_3=127.31, v_4=133.61, v_5=200.00, $f_1=f_2=f_3=f_4$=0.7, f_5=0.3, $d_1=d_2=d_3$=4.0, d_4=2.9, d_5=0.1	y_3=0.2000 y_5=0.1816
		2	46.54 ϵ=0.74%	$v_1=v_2=v_3=v_4$=128.15, $f_1=f_2=f_3=f_4$=0.7 $d_1=d_2=d_3=d_4$=3.725, v_5=200.00, f_5=0.3, d_5=0.1	y_3=0.1891 y_5=0.1816
20	6	1	55.93	v_1=116.19, $v_2=v_3$=116.20, v_4=127.43, v_5=127.91, v_6=200.00, $f_1=f_2=f_3=f_4=f_5$=0.7, f_6=0.3, $d_1=d_2=d_3=d_4$=4.0, d_5=3.9, d_6=0.1	y_4=0.2000 y_6=0.1822
		2	57.37 ϵ=2.57%	$v_1=v_2=v_3=v_4=v_5$=116.30, v_6=200.00, $f_1=f_2=f_3=f_4=f_5$=0.7, f_6=0.3, $d_1=d_2=d_3=d_4=d_5$=3.98, d_6=0.1	y_4=0.1440 y_6=0.1822
25	7	1	66.85	$v_1=v_2$=128.25, $v_3=v_4$=129.65, $v_5=v_6$=118.67, v_7=181.16, $f_1=f_2=f_3=f_4=f_5=f_6$=0.7, f_7=0.3, $d_1=d_2=d_3=d_4=d_5=d_6$=4.0, d_7=1.0	y_3=0.2000 y_5=0.2000 y_7=0.1342
		2	68.62 ϵ=2.65%	$v_1=v_2=v_3=v_4=v_5=v_6$=109.63, v_7=200.00, $f_1=f_2=f_3=f_4=f_5=f_6$=0.7, f_7=0.3, $d_1=d_2=d_3=d_4=d_5=d_6$=4.0, d_7=1.0	y_3=0.1068 y_7=0.2000
30	9	1	80.53	$v_1=v_2$=128.25, v_3=131.40, v_4=146.93, $v_5=v_6$=130.73, $v_7=v_8$=129.41, v_9=200.00, $f_1=f_2=f_3=f_4=f_5=f_6=f_7=f_8$=0.7, f_9=0.3, $d_1=d_2=d_3$=4.0, d_4=1.9, $d_5=d_6=d_7=d_8$=4.0, d_9=0.1	y_3=0.2000 y_5=0.2000 y_7=0.2000 y_9=0.1832
		2	81.29 ϵ = 0.93%	$v_1=v_2=v_3=v_4=v_5=v_6=v_7=v_8$=129.88, v_9=200.00, $f_1=f_2=f_3=f_4=f_5=f_6=f_7=f_8$=0.7, f_9=0.3, $d_1=d_2=d_3=d_4=d_5=d_6=d_7=d_8$=3.7375, d_7=1.0	y_3=0.1959 y_5=0.1961 y^7=0.1801 y_9=0.1802

[a] Case 1 = machining parameters are completely determined by the software;
Case 2 = identical machining parameters are used for all rough passes.
[b] For presentation purpose, we list only the selected passes.
[c] ϵ=[(case 1 cost − case 2 cost)/case 1 cost]×100%

Table 4. Results of the example for Model 2.2.

d_T (mm)	Number of passes	Cost ($)	Machining parameters	Tool adjustment (mm)
10	4	37.63	$v_1=v_2=114.35$, $v_3=127.86$, $v_4=200.00$, $f_1=f_2=f_3=0.7$, $f_4=0.3$, $d_1=d_2=4.0$, $d_3=1.9$, $d_4=0.1$	$y_4=0.1811$
15	5	46.75	$v_1=v_2=128.25$, $v_3=133.52$, $v_4=127.23$, $v_5=200.00$, $f_1=f_2=f_3=f_4=0.7$, $f_5=0.3$, $d_1=d_2=d_4=4.0$, $d_3=2.9$, $d_5=0.1$	$y_3=0.2000$ $y_5=0.1816$
20	6	56.53	$v_1=v_2=v_3=116.20$, $v_4=127.43$, $v_5=127.92$, $v_6=200.00$, $f_1=f_2=f_3=f_4=f_5=0.7$, $f_6=0.3$, $d_1=d_2=d_3=d_4=4.0$, $d_5=3.9$, $d_6=0.1$	$y_4=0.2000$ $y_6=0.1822$
25	7	67.55	$v_1=v_2=128.25$, $v_3=v_4=129.65$, $v_5=v_6=118.67$, $v_7=181.16$, $f_1=f_2=f_3=f_4=f_5=f_6=0.7$, $f_7=0.3$, $d_1=d_2=d_3=d_4=d_5=d_6=4.0$, $d_7=1.0$	$y_3=0.2000$ $y_5=0.2000$ $y_7=0.1342$
30	9	81.27	$v_1=v_2=128.25$, $v_3=v_4=129.65$, $v_5=132.90$, $v_6=148.60$, $v_7=v_8=129.41$, $v_9=200.00$, $f_1=f_2=f_3=f_4=f_5=f_6=f_7=f_8=0.7$, $f_9=0.3$, $d_1=d_2=d_3=d_4=d_5=4.0$, $d_6=1.9$, $d_7=d_8=4.0$, $d_9=0.1$	$y_3=0.2000$ $y_5=0.2000$ $y_7=0.2000$ $y_9=0.1832$

Note: For presentation purpose, we list only the selected passes.

Table 5. Results of Model 2.1 with tool cost = $1 edge^{-1}.

d_T (mm)	Number of passes	Cost ($)	Machining parameters	Tool adjustment (mm)
10	4	35.25	$v_1=129.98$, $v_2=145.33$, $v_3=149.56$, $v_4=200.00$, $f_1=f_2=f_3=0.7$, $f_4=0.3$, $d_1=4.0$, $d_2=1.9$, $d_3=4.0$, $d_4=0.1$	$y_3=0.2000$ $y_4=0.1811$
15	5	43.72	$v_1=150.00$, $v_2=129.70$, $v_3=136.11$, $v_4=150.00$, $v_5=200.00$, $f_1=f_2=f_3=f_4=0.7$, $f_5=0.3$, $d_1=d_2=4.0$, $d_3=2.9$, $d_4=4.0$, $d_5=0.1$	$y_2=0.1891$ $y_4=0.2000$ $y_5=0.1783$
20	6	51.89	$v_1=v_2=150.00$, $v_3=129.71$, $v_4=130.20$, $v_5=150.00$, $v_6=200.00$, $f_1=f_2=f_3=f_4=f_5=0.7$, $f_6=0.3$, $d_1=d_2=d_3=4.0$, $d_4=3.9$, $d_5=4.0$, $d_6=0.1$	$y_2=0.1891$ $y_3=0.1852$ $y_5=0.1956$ $y_6=0.1777$
25	7	61.40	$v_1=v_2=v_3=150.00$, $v_4=v_5=130.38$, $v_6=136.78$, $v_7=191.95$, $f_1=f_2=f_3=f_4=f_5=f_6=0.7$, $f_7=0.3$, $d_1=d_2=d_3=d_4=d_5=d_6=4.0$, $d_7=1.0$	$y_2=0.1743$ $y_3=0.2000$ $y_4=0.1812$ $y_6=0.2000$ $y_7=0.1170$
30	9	73.86	$v_1=v_2=v_3=v_4=150.00$, $v_5=v_6=131.13$, $v_7=131.58$, $v_8=147.12$, $v_9=200.00$, $f_1=f_2=f_3=f_4=f_5=f_6=f_7=f_8=0.7$, $f_9=0.3$, $d_1=d_2=d_3=d_4=d_5=d_6=d_7=4.0$, $d_8=1.9$, $d_9=0.1$	$y_2=0.1884$ $y_3=0.1670$ $y_4=0.2000$ $y_5=0.1772$ $y_7=0.2000$ $y_9=0.1832$

Note: For presentation purpose, we list only the selected passes.

cutting parameters for different roughing passes tend to be different. This is in agreement with several recent studies in the literature [6,11]. In reality, identical machining parameters may be used for different passes to simplify the process planning. To examine this practice, additional computations are carried out by setting machining parameters identical for all roughing passes. The outputs are listed as Case 2 in Table 3. It is found that the cost increase by setting all the parameters equal is in the range of 0.59%–2.65% for this example problem. This may suggest that, to simplify process planning, equal machining parameters should be used for roughing passes in practice.

4. Discussions

4.1 Tool Adjustment Interval

It is observed from Table 3 that the tool adjustment intervals vary significantly. The reason is that the adjustment interval and the amount of adjustment depend not only on the amount of material being removed, but also on the cutting speed, feed, and depth of cut. Removing the same amount of material with different machining parameters could lead to a quite different tool wear and thus different adjustment intervals. This can be illustrated by examining the cases of $d_T = 10$ mm and $d_T = 30$ mm in Table 3. When the total depth of cut is 10 mm, only one adjustment is required for all 4 passes, whereas 4 adjustments are needed for 9 passes in the case of $d_T = 30$ mm.

The difference can also be illustrated by comparing the amount of material removed and the amount of tool adjustment in the two cases. The materials removed are 6 974 336 mm^3 and 19 792 033 mm^3, respectively. The latter is 2.84 times of the former. However, the amount of tool adjustment for the latter case is 4.32 times as much as the former ($0.2 \times 3 + 0.1832$ mm vs. 0.1811 mm). The variations in the adjustment interval and in the amount of adjustment are caused by the difference in machining speeds. Table 3 shows that much higher roughing cutting speeds are used for the latter. This again indicates that the machining parameter selection and tool adjustment decisions should be made simultaneously.

4.2 Single-Direction Turning

As the rapid reverse time is relatively short, the effect of rapid reverse cost on the final decision is minor. This can be shown by additional computations using the same data as used in the example for Model 2.1 with a rapid reverse time of 0.1 min and a cost of \$1.0 min^{-1}.

The results for various total depths of cut are summarised in Table 4. As compared to the results in Table 3, it clearly shows that the effect of rapid reverse can be neglected in reality. The example for Model 1.2 is not provided since the number of reverses is even less and its effect on the final solution is negligible.

4.3 Effect of Tool Cost

Table 3 shows that the tool adjustments for roughing passes under Case 1 are mostly 0.2000 mm, i.e. the maximum allowable tool wear. This is chiefly caused by high tool cost. To offset the high tool cost, the adjustment tends to be large and adjustments tend to be less frequent. The opposite is true if the tool cost is relatively low. This can be illustrated by solving Model 2.1 with a lower tool cost, \$1.00 $edge^{-1}$ instead of \$3.00 $edge^{-1}$, as used previously. The results are summarised in Table 5. It is seen from Table 5 that most tool adjustments are made before the maximum allowable tool wear limit is reached. It can also be seen, by comparing Table 3 (Case 1) and 5, that lower tool cost is preferable for more frequent tool adjustment and higher cutting speeds. This is expected since higher cutting speed generally leads to lower machining cost but consumes more tools.

5. Conclusions

Optimisation models have been developed to provide various parameters simultaneously including machining speed, feedrate, depth of cut, number of passes, tool adjustment interval and amount of adjustment for multipass turning operations. To address the difference in machining small and large parts, separate models have been proposed. For small parts, the tool adjustment is scheduled cyclically based on both cutting passes and number of parts being completed. For large parts, tool adjustment is scheduled according to number of passes, and unequal tool adjustment intervals are often recommended owing to different machining parameters used for different passes. In both cases, the optimal machining parameters and optimal number of cutting passes can be obtained simultaneously. The applications of the models have been illustrated using example problems. The discussion examined the effects of machining parameters and tool cost on tool adjustment and the effect of rapid tool reverse on the final solution for single-direction turning.

References

1. A. Sanjanwala, S. K. Choudhury and V. K. Jain. "On-line tool wear sensing and compensation during turning operation". Transactions ASME Journal of Engineering for Industry, 114, pp. 494–499, 1992.
2. S. Kalpakjian, Manufacturing Engineering and Technology, 2nd edn, Addison-Wesley, Reading, Massachusetts, 1992.
3. C. P. Quesenberry, "An SPC approach to compensating a tool-wear process", Journal of Quality Control, 20, pp. 220–229, 1988.
4. D. Ermer and S. Kromodihardjo, "Optimization of multipass turning with constraints", Transactions ASME Journal of Engineering for Industry, 103, pp. 462–468, 1981.
5. P. Tsai, "An optimization algorithm and economic analysis for a constrained machining model", PhD thesis, West Virginia University, 1986.
6. F. P. Tan and R. C. Creese, "A generalized multi-pass machining model for machining parameter selection in turning", International Journal of Production Research, 33(5), pp. 1467–1487, 1995.
7. P. G. Petropoulos, "Optimal selection of machining rate variables by geometric programming", International Journal of Production Research, 11, pp. 305–314, 1973.
8. B. K. Lambert and A. G. Walvekar, "Optimization of multi-pass machining operations", International Journal of Production Research, 16(4), pp. 259–265, 1978.
9. M. S. Chua, M. Rahman, Y. S. Wong and H. T. Loh, "Determination of optimal cutting conditions using design of experiments and optimization techniques", International Journal of Machine Tools and Manufacture, 33(2), pp. 297–305, 1993.
10. P. Kee, "Alternative optimization strategies and CAM software for multipass rough turning operations", International Journal of Advanced Manufacturing Technology, 10(5), pp. 287–298, 1995.
11. P. Kee, "Development of constrained optimization analyses and strategies for multi-pass rough turning operations", International Journal of Machine Tools and Manufacture, 36(1), pp. 115–127, 1996.
12. R. Gupta, J. L. Batra and G. K. Lal, "Determination of optimal subdivision of depth of cut in multipass turning with constraints", International Journal of Production Research, 33(9), pp. 1555–2565, 1995.

13. Y. C. Shin and Y. S. Joo, "Optimization of machining conditions with practical constraints", International Journal of Production Research, 30, pp. 2907–2919, 1992.
14. J. S. Agapiou, "The optimization of machining operations based on a combined criterion, part 2: multipass operations", Transactions ASME Journal of Engineering for Industry, 114, pp. 508–513, 1992.
15. D. X. Wang and M. J. Zuo, "Analysis of machining tool adjustment and replacement", Proceedings of the 3rd Industrial Engineering Research Conference, pp. 350–354, 1994.
16. D. X. Wang, M. J. Zuo, K. Z. Qi and M. Liang, "On-line tool adjustment with adaptive tool wear function identification", International Journal of Production Research, 34(9), pp. 2499–2515, 1996.
17. G. Taguchi, E. Elsayed and T. Hsiang, Quality Engineering in Production Systems, McGraw-Hill, New York, 1989.
18. Carboloy Seco Tools Company, Manufacturing Engineering, p. 27, November 1996.
19. S. Meng (ed.), Handbook of Metal Cutting Processes, Machinery Industry Press, Beijing, 1996.
20. Machinability Data Center, Machining Data Handbook, 3rd edn, vol. 2, Cincinnati, 1980.
21. A. Bhattacharyya, R. Faría-González and I. Ham, "Regression analysis for predicting surface finish and its application in the determination of optimum machining conditions", Transactions ASME Journal of Engineering for Industry, 92, pp. 711–714, 1970.
22. Lindo Systems Inc., Lingo User's Guide, 1995.

Nomenclature

Parameters

i	cutting pass, i=1, … , I
I	assumed maximum number of passes
n	part, n=1, …, N
A	scrap or rework cost ($)
D_0	initial stock diameter of workpiece (mm)
D_i	workpiece diameter after pass i (mm)
L	cutting length of workpiece (mm)
C_o	operating cost ($ min^{-1})
C_t	tool cost ($ edge^{-1})
C_r, C_a, C_{rp}	tool replacement cost ($ min^{-1}), tool adjustment cost ($ min^{-1}), and rapid reverse cost $ min^{-1})
t_r, t_a, t_{rp}	tool replacement time (min), tool adjustment time (min), and rapid traversing time (min)
w_T	allowable tool nose wear (mm)
w_i	tool wear caused by pass i
δ	tolerance limit for the finished part (mm)
r	tool nose radius (mm)
BHN	workpiece hardness (Brinell hardness number)
v_i^l, v_i^u	cutting speed limits for pass i (m min^{-1})
f_i^l, f_i^u	feed rate limits for pass i (mm rev^{-1})
d_i^l, d_l^u	limit of depth of cut for pass i (mm)
d_T	total depth of cut (mm)
$F_{\max}$, $P_{\max}$	maximum cutting force (kN), and maximum power of the motor (kW)
F, P	cutting force (kN) and power consumption (kW)
$R_{\max}$	maximum allowable surface roughness (mm)
R_a	surface roughness (mm)
α_F, β_F, γ_F, B_F	empirical parameters in the cutting force equation
α_P, β_P, γ_P, B_P	empirical parameters in the power consumption equation
α_R, β_R, η, θ, B_R	empirical parameters in the surface roughness equation
α_T, β_T, γ_T, B_T	empirical parameters in the tool life equation
E	machine tool efficiency
t_m	machining time (min)
T	tool life (min)

Variables

N	tool adjustment cycle
v_i, f_i, d_i	cutting speed (m min^{-1}), feed (mm rev^{-1}), and depth of cut (mm) of pass i
p_i	pass selection indicator, $p_i = 1$, if pass i is selected; $p_i = 0$, otherwise
x_{ni}	tool adjustment indicator used in Models 1.1 and 1.2, $x_{ni} = 1$, if a tool adjustment is performed for pass i of part n, $x_{ni} = 0$, otherwise
x_i	tool adjustment indicator used in Models 2.1 and 2.2, $x_i = 1$, if a tool adjustment is performed for pass i, $x_i = 0$, otherwise
y_{ni}	amount of tool adjustment performed after pass i-1 and before pass i of part n (used in Models 1.1 and 1.2)
y_i	amount of tool adjustment performed after pass i-1 and before pass i (used in Models 2.1 and 2.2)
Δ_{ni}	accumulated dimension deviation after pass i of part n (used in Models 1.1 and 1.2)
Δ_i	accumulated dimension deviation after pass i (used in Models 2.1 and 2.2)
z_i	indicator of a tool replacement, $z_i = 1$, if a tool replacement is justified for pass i, $z_i = 0$, otherwise.