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Optimization Model of Multi-Procedure Cost of Turning for Shaft Parts

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Abstract. How to choose the turning parameters for shaft part? This paper established an optimization model based on minimum multi-procedure costs. The constraints of the model include machined surface roughness, power of lathe, parameters of lathe, and turning allowance. Different from the existing optimization models, the variables include the cutting speed, the feed rate and the back engagement of the cutting edge. The model was solved by using MATLAB program. Finally, we performed a motor shaft as an experiment case to verify the validity of the optimization model, compared with the choice of parameters using the traditional methods, process costs reduced by more than 30%.

Introduction and Literature Review

In turning how to choose the optimal values of Cutting Speed (v_c), Feed Rate(f) and Back Engagement of the Cutting Edge(a_p)? One of the most important methods at present is to establish a mathematical model by using the metal cutting theory, and use the computer simulation algorithm to find the optimal values. Many scholars have researched this problem. In the reference [1], the influences of cutting parameters on surface roughness and cutting time were preliminarily determined. In the reference [2], the relationships of cutting force, chip macro-sharp and micro-sharp with the cutting parameter and tool wear were experimental demonstrated. In the reference [3], the influencing trends of cutting speed, feed rate and cutting depth on specific cutting energy were analysed. In the reference [4], the multi-pass milling parameters optimization for green and higher efficiency based on service-oriented manufacturing has been researched on perspective. In the reference [5], a practical guide for optimization of machining parameters was provided. Reference [6] according to the most optimization idea, the NC milling mathematical model was built. In the reference [7], a way of optimizing the turning process to achieve the minimum power consumption and best surface quality was outlined. In the reference [8], a method of turning parameters optimization was proposed based on grey system theory. Great achievements have been made in these studies. But most of the cutting optimization models were aimed at one procedure, and the back engagement of the cutting edge (a_p) was invariant. This is quite different with the actual machining works. To make a workpiece, the cutting work is usually divided into rough machining and finish machining. In each procedure, the selection of cutting parameters must meet the requirements of the machining accuracy, the influence of the subsequent procedure must also be considered. Hence, this paper aimed at turning, to establish an optimization model, which is based on the minimum multi-procedure costs. The constraints of the model were analysed. Finally, an experiment case was performed to verify the validity of the optimization model.

Optimization Model of Multi-Procedure Costs

In turning, the costs of each procedure mainly include two parts: the costs of machine tool and the costs of cutting-tool. According to our research, and the existing literature, the costs of each procedure can be calculated as follows:

$$C = M_c t + \frac{t_m}{T} \times (\frac{C_p}{k_1+1} + Gt_a + \frac{Gt_b}{k_2} + \frac{C_0}{k_3} + C_{ms} + Gt_p) \tag{1}$$

where C is the costs of each turning procedure for one workpiece (CNY). M_C is the total cost per unit time (CNY/min), which includes the labor wages, the operational expenses, the depreciation expense of machine tool, the cost of machine tool management. t is the man-hour quota of one workpiece (min). C_p is the price of cutting tool (CNY). C_0 is the price of a blade or an insert blade (CNY). C_{ms} is the grinding wheel's cost for the tool re-sharping (CNY). t_a is the time of the cutting tool re-sharping (min). t_b is the time of welding a blade or refitting and alignment a blade (min). t_p is the time of off-line tool setting (min). G is the labor wages and management expenses for re-sharping or alignment the blade (CNY/min). k_1 is the times of re-sharping before the cutting-tool scrapped. k_2 is the times before the blade re-welding or re-alignment. k_3 is the times before the blade scrapped. t_m is the basic time (or cutting time) (min). T is the life of cutting tool (min).

In batch production, the man-hour quota of one workpiece for turning procedure as follows:

$$t = (t_m + t_f) \times (1 + \frac{\alpha + \beta}{100}) + \frac{t_\varepsilon}{N} \tag{2}$$

where t_f is the non-cutting time (that is the time which consumed by auxiliary actions in order to fulfill the cutting process) (min). $\alpha+\beta$ is the time using to organize the work place, and the workers' time to rest and physiological needs. Generally calculated in accordance with the operating time (%). t_ε is the time of prepare and end the machining (min). N is the production lot sizing.

When turning outer circle of the shaft parts, the basic time is:

$$t_m = \frac{l\pi d_w A}{1000 v_c f a_p} \tag{3}$$

where l is the length of turning (mm). d_w is the outside diameter of workpiece (mm). A is the finishing allowance (mm).

And if you plug formula (3) and (2) into the formula (1), you can get the follow formula:

$$\begin{aligned} C = M_C \times [(\frac{l\pi d_w A}{1000 v_c f a_p} + t_f) \times (1 + \frac{\alpha+\beta}{100}) + \frac{t_\varepsilon}{N}] + \\ \frac{l\pi d_w A}{1000 T v_c f a_p} \times (\frac{C_p}{k_1+1} + Gt_a + \frac{Gt_b}{k_2} + \frac{C_0}{k_3} + C_m + Gt_p) \end{aligned} \tag{4}$$

Since a workpiece needs to be turned in i procedure, the total costs is the summation cost of each procedure, that is:

$$\begin{aligned} \sum C = \sum_{i=1}^{n} \{ M_C \times [(\frac{l_i \pi d_{wi} A_i}{1000 v_{ci} f_i a_{pi}} + t_f) \times (1 + \frac{\alpha+\beta}{100}) + \frac{t_\varepsilon}{N}] \\ + \frac{l_i \pi d_{wi} A_i}{1000 T_i v_{ci} f_i a_{pi}} \times (\frac{C_p}{k_1+1} + Gt_a + \frac{Gt_b}{k_2} + \frac{C_0}{k_3} + C_m + Gt_p) \} \end{aligned} \tag{5}$$

The minimum procedure costs was constrained by:

Surface roughness:

$$Rz \approx \frac{f^2}{8 r_\varepsilon} \le R_{z\max} \tag{6}$$

where r_ε is the corner radius of the tool.

Total machining allowance:

$$A_0 = \sum_{i=1}^{n} A_i \tag{7}$$

where A_i is the allowance of the procedure *No. i*.

Lathe power:

$$P_c = \frac{F_c v_c}{60 \times 1000} \le P_E \eta_E \tag{8}$$

where P_E is the power of lathe's main motor (kW). η_E is the transmission efficiency of lathe.
Performance parameters of the lathe: Which mainly includes spindle speeds, feed rates, etc.
Through the above analyses, the optimization model of turning parameters is:

$$\begin{aligned}
\min\ C = \sum C = \sum_{i=1}^{n} \{ M_C \times [(\frac{l_i \pi d_{wi} A_i}{1000 v_{ci} f_i a_{pi}} + t_f) \times (1 + \frac{\alpha + \beta}{100}) \\
+ \frac{t_\varepsilon}{N}] + \frac{l_i \pi d_{wi} A_i}{1000 T_i v_{ci} f_i a_{p_i}} \times (\frac{C_p}{k_1 + 1} + G t_a + \frac{G t_b}{k_2} + \frac{C_0}{k_3} + C_m \\
+ G t_p) \} \\
s.t.\quad R_z \approx \frac{f^2}{8 r_\varepsilon} \le R_{z\max} \\
P_C = \frac{F_c v_c}{60 \times 1000} \le P_E \eta_E \\
A_0 = \sum_{i=1}^{n} A_i
\end{aligned} \tag{9}$$

Case Study: Turning a Motor Shaft

Figure 1 is an abbreviated drawing of a motor shaft, the material is 45# forged steel, by hardening and tempering, its tensile strength is 637MPa. Total machining allowance of external circular is 6mm. Its annual production program is 384, 32 pieces per batch.

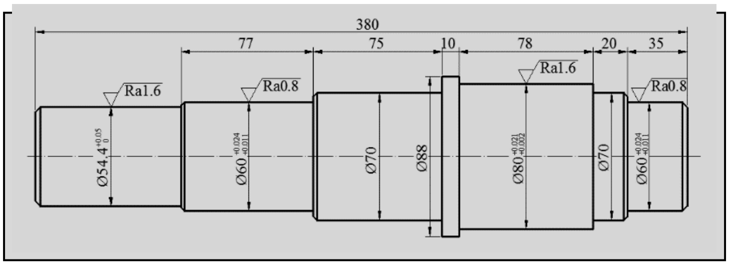

Fig. 1. Motor shaft's abbreviated drawing

Using the lathe type is C620-1, its main performance parameters are shown in Table 1.

Table 1. Main performance parameters of lathe type C620-1

Minimum Spindle speed (r/min)	**MaximumSpindle speed (r/min)**	**Minimum Feed Rate (mm/r)**
12	1200	0.08
Maximum Feed Rate (mm/r)	**Power of Main/Motor (kW)**	**Transmission Efficiency (%)**
1.59	7.5	75

The turning tool adopts the cemented carbide welding blade. The angles of cutting tool are: tool cutting edge angle κ_r=90°, rake angle γ_o=10°, tool cutting edge inclination angle λ_s=5°, corner radius r_ε=1.0mm.

Consulting the machining manual, the empirical formula of turning force calculation is:

$$\begin{cases} F_c = C_{Fc} a_p^{xFc} f^{yFc} v_c^{\eta Fc} K_{Fc} \\ F_p = C_{Fp} a_p^{xFp} f^{yFp} v_c^{\eta Fp} K_{Fp} \\ F_f = C_{Ff} a_p^{xFf} f^{yFf} v_c^{\eta Ff} K_{Ff} \end{cases} \tag{10}$$

where C_{Fc}, C_{Fp}, C_{Ff} are the coefficients which depends on the material and the condition of machining. x_{Fc}, y_{Fc}, η_{Fc}, x_{Fp}, y_{Fp}, η_{Fp}, x_{Ff}, y_{Ff}, η_{Ff} are the exponentials of machine parameters. K_{Fc}, K_{Fp}, K_{Ff} are the products of the correction factors, which can be calculated as:

$$K_F = K_{MF} K_{\gamma OF} K_{\kappa rF} K_{\lambda sF} K_{r\varepsilon F} K_{VBF} \tag{11}$$

where K_{MF} is the correction factor for the mechanical properties of materials. $K_{\gamma oF}$ is the correction factor for the rake angle. $K_{\kappa rF}$ is the correction factor for the tool cutting edge angle. $K_{\lambda sF}$ is the correction factor for the tool cutting edge inclination angle. $K_{r\varepsilon F}$ is the correction factor for the corner radius. K_{VBF} is the correction factor for the cutting tool's flank wear.

Consulting the machining manual, the factors and the exponentials were shown at Table 2.

Table 2. The factors and the exponentials in the calculation formula of turning force

Name	Fators			
Main turning force F_c	C_{Fc}=2650	x_{Fc}=1.00	y_{Fc}=0.75	η_{Fc}=-0.15
Radial thrust force F_p	C_{Fp}=1950	x_{Fp}=0.90	y_{Fp}=0.60	η_{Fp}=-0.30
Axial thrust force F_f	C_{Ff}=2880	x_{Ff}=1.00	y_{Ff}=0.50	η_{Ff}=-0.40

The correction factor of material K_{MF} is:

$$K_{MF} = (\frac{\sigma_b}{650})^{nF} \tag{12}$$

where nF is the exponentials of the main cutting force, the radial thrust force, and the axial thrust force, which is 0.75, 1.35, and 1.0.

The correction factors for geometrical angles of cutting tool is shown in Table 3.

Table 3. The correction factors for geometrical angles of cutting tool

Name	Figure	Coefficient	Cutting force		
			F_c	F_p	F_f
Cutting edge angle κ_r/(°)	90	$K_{\kappa rF}$	0.89	0.50	1.17
Rake angle γ_o/(°)	10	$K_{\gamma oF}$	0.9	0.7	0.7
Cutting edge inclination angle λ_s/(°)	5	$K_{\lambda sF}$	1.0	0.75	0.75
Corner radius r_ε/(mm)	1.0	$K_{r\varepsilon F}$	1.0	0.82	0.93

Now plug the figures in Table 2 and Table 3 into formula 11 and 10, we can get the turning forces:

$$\begin{cases} F_c = 2090.81 a_p f^{0.75} v_c^{-0.15} \\ F_p = 393.34 a_p^{0.9} f^{0.6} v_c^{-0.3} \\ F_f = 1612.30 a_p f^{0.5} v_c^{-0.4} \end{cases} \tag{13}$$

Calculate the turning tool life often use the Taylor formula:

$$T^m = \frac{C_v}{v_c a_p^{x_v} f^{y_v}} \tag{14}$$

where m is exponent. C_v is the coefficient which in connection with the experiment conditions. Consulting the machining manual, we can get that:

$$\begin{cases} T^{0.2} = \dfrac{291}{v_c a_p^{0.15} f^{0.20}} (f < 0.3mm/r) \\ T^{0.2} = \dfrac{242}{v_c a_p^{0.15} f^{0.35}} (0.3 \le f \le 0.7mm/r) \\ T^{0.2} = \dfrac{235}{v_c a_p^{0.15} f^{0.45}} (f > 0.7mm/r) \end{cases} \tag{15}$$

Other parameters of turning are shown in Table 4.

Table 4. Other parameters of turning

M_c	t_f	C_p	C_o	C_{ms}	t_a	t_b
(CNY/MIN)	(MIN)	(CNY)	(CNY)	(CNY)	(MIN)	(MIN)
0.40	1.0	13	11.3	0.5	5	1.5
t_p	G	k_1	k_2	k_3	$\alpha+\beta$	
(min)	(CNY/MIN)				(%)	
0.5	0.5	20	10	10	21.8	

The shaft needs the following cutting procedure: rough turning, semi-finished turning, finish turning. As the allowance of each procedure is small, each procedure has one feed, so the back engagement of the cutting edge is equal to the allowance. Plug all the related parameters into formula (4), we can get the cost of each procedure:

Rough turning:

$$C_1 = 0.675 + \frac{34.516}{v_{c1} f_1} + 5.249 \times 10^{-10} v_{c1}^{\ 4} f_1^{0.75} a_{p1}^{\ 0.75}$$

Semi-finished turning:

$$C_2 = 0.675 + \frac{32.602}{v_{c2} f_2} + 1.972 \times 10^{-10} v_{c2}^{\ 4} f_2^{0.75} a_{p2}^{\ 0.75}$$

Finish turning:

$$C_3 = 0.675 + \frac{22.860}{v_{c3} f_3} + 1.383 \times 10^{-10} v_{c3}^{\ 4} f_3^{0.75} a_{p3}^{\ 0.75}$$

So, the process costs of turning is:

$$\begin{aligned} \sum C = 2.025 &+ \frac{34.516}{v_{c1} f_1} + 5.249 \times 10^{-10} v_{c1}^{\ 4} f_1^{0.75} a_{p1}^{\ 0.75} + \\ &\frac{32.602}{v_{c2} f_2} + 1.972 \times 10^{-10} v_{c2}^{\ 4} f_2^{0.75} a_{p2}^{\ 0.75} + \frac{22.860}{v_{c3} f_3} \\ &+ 1.383 \times 10^{-10} v_{c3}^{\ 4} f_3^{0.75} a_{p3}^{\ 0.75} \end{aligned}$$

Constrained by:

Surface roughness:

$$\begin{cases} f_2 \le 0.32 \\ f_3 \le 0.08 \end{cases}$$

where f_2 refers to semi-finished turning, f_3 refers to finish turning.

Lathe power for only rough turning:

$$a_{p1} f_1^{0.75} v_{c1}^{\ 0.85} \le 150.659$$

Total cutting allowance:

$$a_{p1} + a_{p2} + a_{p3} = 6$$

Spindle speed:

$$\begin{cases} 2.72 \le v_{c1} \le 271.77 \\ 2.57 \le v_{c2} \le 256.69 \\ 2.49 \le v_{c3} \le 249.15 \end{cases}$$

Feed rate of the lathe:

$$\begin{cases} 0.08 \le f_1 \le 1.59 \\ 0.08 \le f_2 \le 1.59 \\ 0.08 \le f_3 \le 1.59 \end{cases}$$

The model was solved with the MATLAB programming. The optimized process costs is: ΣC=4.55CNY. The machining parameters corresponding are:v_{c1}=47.46m/min, f_1=1.59mm/r, a_{p1}=4.0mm, v_{c2}=186.23m/min, f_2=0.32mm/r, a_{p2}=1.5mm, v_{c3}=249.15m/min, f_3=0.08mm/r, a_{p3}=0.50mm.

Consulting the machining manual and practical experience, the cutting parameters are: v_{c1}=40~60m/min, f_1=0.5~0.7mm/r, a_{p1}=3~5mm, v_{c2}=60~80m/min, f_2=0.16~0.25mm/r, a_{p2}=1~2mm, v_{c3}=120~160m/min, f_3=0.10~0.18mm/r, a_{p3}=0.05~0.80mm. If we counted with the intermediate values, the process costs is: $\Sigma C'$=6.57CNY. The optimization process costs dropped by 30.75%.

Summary

In china, turning occupies above 60% of all the mechanical working, so it is the most important machining method. One of the difficulties is how to choose the cutting parameters. In this paper we established a new method to choose the cutting parameters, which has proved to be effective.

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