Prediction Model for Net Cutting Specific Energy in CNC Turning

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Abstract: A prediction model for net cutting specific energy in computer numerical control (CNC) turning based on turning parameters and tool wear is developed. The model can predict the net cutting energy consumption before turning. The prediction accuracy of the model is verified in AISI 1045 steel turning. The comparative experimental results show that the prediction accuracy of the model is significantly improved because the influence of tool wear is taken into account. Finally, the influences of turning parameters and tool wear on net cutting specific energy are studied. With the increase of cutting depth, the net cutting specific energy decreases. With the increase of spindle speed, the additional load loss power of spindle drive system increases, so the net cutting specific energy increases. The net cutting specific energy increases approximately linearly with tool wear. The results are helpful to formulate efficient and energy-saving CNC turning schemes and realize low-carbon manufacturing.

Key words: net cutting specific energy; turning parameters; tool wear; processing scheme; low-carbon manufacturing

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0 Introduction

Manufacturing consumes electricity to convert raw materials into parts, while generating wastes and CO_2 emissions. The industrial sector accounts for about 31% of the total energy consumption in the USA, and the manufacturing accounts for about 60% of the energy consumption in the industrial sector. The CO_2 emission per unit gross domestic product (GDP) in China is much higher than that of developed countries in Europe and America. As the world's largest producer and consumer of machine tools, the total energy consumption of machine tools is very high in China. How to reduce energy consumption and environmental pollution in machining to achieve low-carbon manufacturing is an urgent problem to solve[1-2].

Gutowski et al. pointed out that the actual energy consumption for cutting in computer numerical control (CNC) milling, turning and grinding is less than 15% of the total energy consumption of machine tools[3]. And reasonable processing parameters are helpful to achieve energy-saving manufacturing[4]. The efficient prediction models for machine tools energy consumption are of great significance for optimizing processing parameters to reduce energy consumption[5-6]. Zhang et al. divided the energy consumption of machine tools during the whole processing into the cutting energy consumption, the air-cutting energy consumption and the tool change energy consumption in the non-cutting stage, and established the energy consumption model in each processing stage to find processing scheme with the lowest energy consumption[7]. Specific energy is the

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energy consumption when removing unit volume material. Yan et al. proposed a prediction model for machine tool specific energy, which can be regarded as a function of material removal rate and spindle speed[8]. Under various constraints of lathe processing, Zhou et al. developed an energy efficiency model based on multi-objective teaching and learning algorithm to optimize cutting parameters[9]. Zhou et al. established an energy consumption prediction model of surface grinder based on back propagation (BP) neural network, with the grinding wheel speed, the table feed speed, and the grinding depth as input signals[10]. Liu et al. divided the input power of spindle drive system into no-load power, cutting power, and additional load loss power[11]. Jia et al. defined 15 manufacturing characteristics and energy attributes for machine tool functional components, and proposed a method for estimating energy consumption in processing[12]. Aiming at the characteristics of dynamic changes of processing tasks and processing parameters, He et al. proposed a dynamic energy consumption modeling method for multi-energy sources of CNC machine tools[13].

In summary, various energy consumption prediction models of machine tool were established, and in-depth research on optimization processing parameters is conducted. However, most of the prediction models do not consider the influence of tool wear on energy consumption.

The energy consumption used only to form chips and surface in cutting is called net cutting energy consumption. In hard milling, Liu et al. calculated the net cutting energy consumption based on spindle power, air-cutting power, material removal rate and removal material volume[14]. Diaz et al. proposed a calculation model for net cutting energy consumption in milling based on cutting depth, side cutting depth, feedrate, spindle speed, and removal material volume[15].

The objectives of the paper are triple fold: (1) to establish the power and energy consumption model of CNC lathe in cutting process; (2) to develop a prediction model for net cutting specific energy in CNC turning, which is only related to turning parameters and tool wear; and (3) to reveal the influences of turning parameters and tool wear on net cutting specific energy.

1 Power and Energy Consumption of CNC Lathe in Cutting

In the turning of inner and outer cylindrical surface, conical surface and complex revolving surface of parts, CNC lathe consumes electric energy and converts the blank parts into products with required shape and characteristics, as shown in Fig.1. CNC lathe has many energy-consuming functional components, including spindle system, feed axis system, cooling system, lubrication system, CNC device, lighting device, fan, tool change and other auxiliary systems[16]. The complete working process of CNC lathe includes start-up, standby, spindle start, no-load operation, cutting materials, no-load operation, spindle stop, standby, and shutdown, as shown in Fig.2. In the cutting process, the power of CNC lathe includes standby power P_{idle}, spindle no-load power P_{sno}, net cutting power P_{tooltip}, cutting fluid pump power P_{cool} and feed axis no-load power. Compared with the spindle no-load power, the feed axis no-load power is very small and can be neglected[17]. So the power of CNC lathe in cutting process can be obtained, namely

$$P_{\mathrm{cutting}}=P_{\mathrm{idle}}+P_{\mathrm{tooltip}}+P_{\mathrm{sno}}+P_{\mathrm{cool}} \tag{1}$$

The energy consumption of CNC lathe in cutting process mainly includes standby energy E_{idle}, spindle no-load energy E_{sno}, net cutting energy E_{tooltip} and cutting fluid pump energy E_{cool}. We have

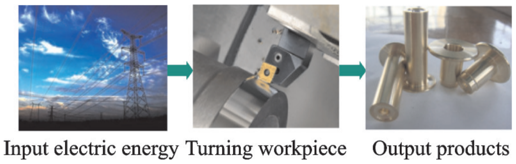


Fig.1 Energy conversion in turning

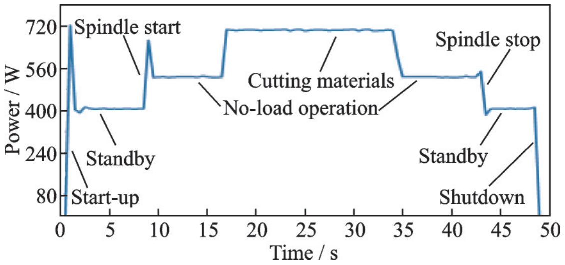


Fig.2 Complete turning process

$$E_{\text{cutting}} = E_{\text{idle}} + E_{\text{tooltip}} + E_{\text{sno}} + E_{\text{cool}} \tag{2}$$

where E_{idle} mainly includes the energy consumption of lubrication system, numerical control device, lighting device and fan, which is related to the working time of machine tool from start to close; E_{sno} is related to the structure of spindle drive system and the power characteristics of spindle motor, depending on the spindle speed and movement time; E_{cool} depends on the power of cutting fluid pump; E_{tooltip} refers to the net cutting energy consumption used only for chip formation and surface generation.

2 Prediction Model for Net Cutting Specific Energy in Turning

2.1 Tool wear in cutting

The machined surface contacts and rubs with the tool flank in turning, resulting in tool flank wear[18], as shown in Fig.3. Tool wear process can be divided into three stages: Initial wear, normal wear and sharp wear. Generally speaking, the tool wear rate is very high in the initial wear stage. In the normal wear stage, the tool wear rate is relatively low and uniform, and the wear amount increases approximately proportional to the cutting time. In the sharp wear stage, tool wear accelerates because the cutting force and the cutting temperature increase rapidly.

2.2 Prediction model for net cutting specific energy in turning

A method of measuring net cutting specific energy in turning by power analyzer is established in this paper. Net cutting specific energy U_{tooltip} is defined as the net cutting energy consumption when removing unit volume material , that is

$$U_{\text{tooltip}} = \frac{E_{\text{tooltip}}}{Q} \tag{3}$$

where Q is the removal material volume.

Further, convert the net cutting specific energy into the function of the net cutting power P_{tooltip} and the material removal rate(MRR). We have

$$U_{\text{tooltip}} = \frac{E_{\text{tooltip}}}{Q} = \frac{E_{\text{tooltip}}/t}{Q/t} = \frac{P_{\text{tooltip}}}{\text{MRR}} \tag{4}$$

According to Eq.(1), separate the standby power, spindle no-load power and cutting fluid pump power from the CNC lathe power in cutting process, then obtain the net cutting power

$$P_{\text{tooltip}} = P_{\text{cutting}} - P_{\text{idle}} - P_{\text{sno}} - P_{\text{cool}} \tag{5}$$

Substitute Eq.(5) into Eq.(4), and obtain the method of measuring U_{tooltip} shown in Eq.(6).

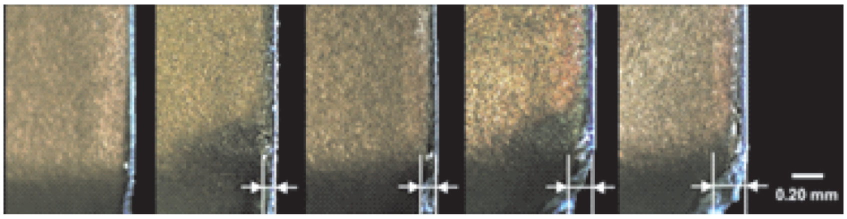
$$U_{\text{tooltip}} = \frac{P_{\text{tooltip}}}{\text{MRR}} = \frac{P_{\text{cutting}} - P_{\text{idle}} - P_{\text{sno}} - P_{\text{cool}}}{\text{MRR}} \tag{6}$$

That is to say, the net cutting specific energy can be measured according to the lathe power in cutting process, standby power, spindle no-load power and cutting fluid pump power. The inconvenience of this method is that the net cutting specific energy can only be measured and calculated by means of power analyzer. Establishing a simple and effective prediction model for net cutting specific energy, is of great significance for optimizing processing parameters and realizing energy-saving manufacturing.

According to metal cutting theory, the cutting power is closely related to cutting force and turning parameters. The index prediction model for net cutting specific energy based on turning parameters is established

$$U_{\text{tooltip}} = b \cdot a_{\text{p}}^{c} \cdot f^{x} \cdot n^{y} \tag{7}$$

where a_{p} is the cutting depth(unit: mm); f the feedrate(unit: mm/r); and n the spindle speed(unit: r/mm). b, c, x and y are the undetermined coeffi-



(a) VB=0 (b) VB=0.08 mm (c) VB=0.10 mm (d) VB=0.15 mm (e) VB=0.20 mm

Fig.3 Wear detection of tool flank VB in cutting cients.

Turning experiments are carried out with the same workpiece material and processing parameters. It is found that the net cutting specific energy varies greatly with the tool wear. This shows that the net cutting specific energy in turning is related to both turning parameters and tool wear.

On the basis of Eq.(7), an index prediction model for net cutting specific energy based on turning parameters (a_p, f, n) and tool flank wear (VB) is developed in the paper

$$U_{\text{tooltip}} = b \cdot a_p^c \cdot f^x \cdot n^y \cdot (1 + VB)^z \tag{8}$$

where z is the undetermined coefficients. Then the net cutting energy consumption can be calculated according to the removal material volume in turning

$$E_{\text{tooltip}} = U_{\text{tooltip}} \cdot Q \tag{9}$$

3 Experimental Verification

3.1 CNC turning experiments and power measurement

The proposed prediction model for net cutting specific energy is proved in AISI 1045 steel turning, as shown in Fig.4. The CKJ6163 CNC lathe is used, with positioning accuracy of 0.020 mm and spindle speed range of 10—1 000 r/min.

Fig.4 Turning and power measurement

The workpiece is AISI 1045 steel rod with diameter of 50 mm and length of 200 mm. The CNMG120408 4025 carbide turning tool is used with cutting fluid in turning. The power and energy consumption are measured by power analyzer WT1800. The standby power of the CNC lathe is 423 W, and the curve of spindle no-load power and spindle speed is shown in Fig.5.

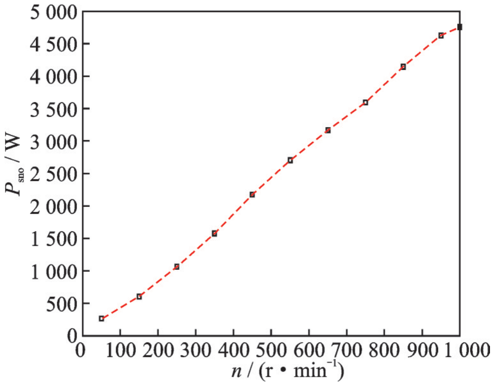


Fig.5 Curve of spindle no-load power and spindle speed

Sixteen groups orthogonal experiments of AISI 1045 steel cylindrical turning are carried out, and the turning parameter levels are shown in Table 1. The tool flank wear is measured twice before and after processing, and the average value is taken as the tool wear in this group of turning experiment. The turning parameters, tool wear and net cutting specific energy measured with Eq.(6) are shown in Table 2.

Table 1 Turning parameter levels

Level	a_p / mm	f / (mm•r^{-1})	n / (r•min^{-1})
1	0.3	0.15	450
2	0.6	0.2	600
3	1.1	0.25	700
4	1.5	0.3	800

3.2 Verification of prediction model for net cutting specific energy in turning

Firstly, the prediction model for net cutting specific energy shown in Eq.(7) is adopted, which is based on turning parameters only and regardless of the influence of tool wear. Substitute the sixteen groups of data in Table 2 into Eq.(7) to obtain an overdetermined equation group. The undetermined coefficients are calculated based on least square method: b=0.105 7, c=−0.140 6, x=0.052 3, y=0.508 0, correlation coefficient R^2=0.814 3 and MSE(mean square error)=0.032 16. Then the prediction model for net cutting specific energy based on turning parameters only can be obtained

$$U_{\text{tooltip}} = 0.105\,7 \cdot a_p^{-0.140\,6} \cdot f^{0.052\,3} \cdot n^{0.508\,0} \tag{10}$$

Secondly, the prediction model for net cutting specific energy shown in Eq.(8) is adopted, which

Table 2 Turning experiment results

Group number	a_p / mm	f / (mm•r^{-1})	n / (r•min^{-1})	VB / mm	U_tooltip / (J•mm^{-3})
1	0.3	0.15	450	0.083 0	2.473 6
2	0.3	0.20	600	0.102 5	3.127 2
3	0.3	0.25	700	0.113 5	3.346 2
4	0.3	0.30	800	0.128 5	3.777 0
5	0.6	0.15	600	0.139 0	2.510 3
6	0.6	0.20	450	0.140 0	2.123 7
7	0.6	0.25	800	0.141 0	2.983 2
8	0.6	0.30	700	0.144 5	2.786 3
9	1.1	0.15	700	0.249 5	3.021 7
10	1.1	0.20	800	0.160 5	2.820 6
11	1.1	0.25	450	0.170 0	2.219 2
12	1.1	0.30	600	0.196 0	2.352 6
13	1.5	0.15	800	0.203 5	2.711 0
14	1.5	0.20	700	0.206 5	2.431 8
15	1.5	0.25	600	0.209 5	2.333 5
16	1.5	0.30	450	0.215 5	2.360 1

is based on turning parameters and tool wear. Substitute the sixteen groups of data in Table 2 into Eq.(8) to obtain an overdetermined equation group. The undetermined coefficients are calculated based on least square method: b=0.095 0, c=−0.289 4, x=0.042 4, y=0.454 3, z=2.614 4, R^2=0.889 0 and MSE =0.016 71. Then the prediction model for net cutting specific energy based on turning parameters and tool wear can be obtained

$$U_\mathrm{tooltip}=0.0950\cdot a_\mathrm{p}^{-0.2894}\cdot f^{0.0424}\cdot n^{0.4543}\cdot(1+VB)^{2.6144} \tag{11}$$

Thirdly, a new group of processing parameters shown in Table 3 is used to verify the accuracy of prediction model for net cutting specific energy in turning. As shown in Table 4, the net cutting specific energy measured is 2.463 7 J/mm^3, the net cutting specific energy predicted is 2.809 2 J/mm^3 with Eq.(10), and the prediction accuracy is 86.0%. While the net cutting specific energy predicted is 2.586 0 J/mm^3 with Eq.(11), and the prediction accuracy is 95.0%.

In conclusion, the prediction accuracy of the model shown in Eq.(11) is higher than that shown in Eq.(10). Therefore, the influence of tool wear must be considered in the calculation and prediction of net cutting specific energy in turning.

Table 3 Processing parameters in verification experiment

a_p / mm	f /(mm•r^{-1})	n /(r•min^{-1})	VB / mm
0.9	0.23	720	0.142 0

Table 4 Comparison of prediction results

Model adopted	U_tooltip measured / (J•mm^{-3})	U_tooltip predicted / (J•mm^{-3})	Prediction accuracy / %
Eq.(10)	2.463 7	2.809 2	86.0
Eq.(11)	2.463 7	2.586 0	95.0

According to the predicted net cutting specific energy and the removal material volume during the turning, the net cutting energy consumption can be calculated with Eq.(9). For example, in the verification experiment shown in Table 4, the removal material volume is 20 278 mm^3, the net cutting specific energy predicted with Eq.(11) is 2.586 0 J/mm^3, the net cutting energy consumption predicted is 52.44 kJ while the actual net cutting energy consumption is 49.96 kJ, and the predicted accuracy is

95.0%.

3.3 Influences of turning parameters and tool wear on net cutting specific energy

Turning parameters and tool wear have important effects on cutting force and cutting temperature. Based on the prediction model for net cutting specific energy shown in Eq.(11), the influences of a_p, f, n and VB on the net cutting specific energy $U_{tooltip}$ in AISI 1045 steel turning are studied.

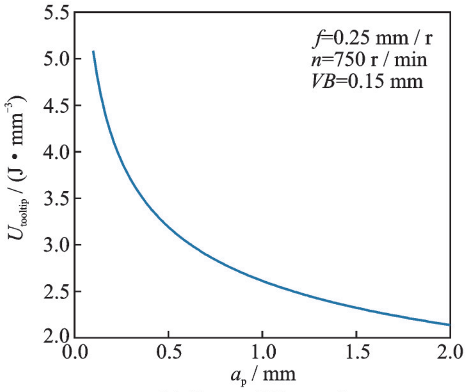
As shown in Fig.6, a_p, n and VB have a greater influence on $U_{tooltip}$. The increase of a_p leads to the increase of material removal rate, so $U_{tooltip}$ decreases. The increase of n results in that the additional load loss power of spindle drive system increases, so $U_{tooltip}$ increases. $U_{tooltip}$ increases approximately linearly with VB. The reason is that the small edge with zero back angle is formed on the tool flank when the tool wears. As the tool wears gradually, the contact area between the tool flank and the workpiece increases, so the cutting force and $U_{tooltip}$ both increase.

In addition, f has less influence on $U_{tooltip}$. When f increases, the additional load loss power of the z-axis motor of CNC lathe increases slightly. The speed and power of the z-axis motor are much smaller than that of the spindle motor, so $U_{tooltip}$ grows very slowly with the increase of f. For example, the $U_{tooltip}$ increases less than 0.3 J/mm^3 when f increases from 0.1 mm/r to 0.9 mm/r.

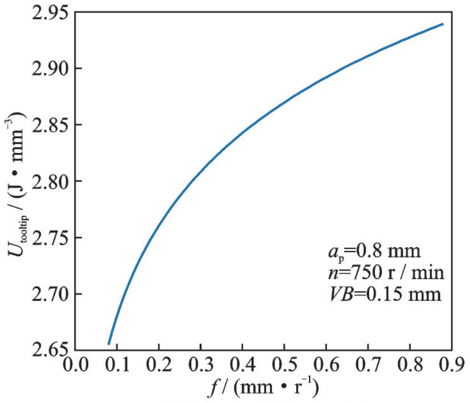
4 Conclusions

The prediction model for net cutting specific energy based on turning parameters and tool wear is developed. The prediction model is proved in AISI 1045 steel turning, and the influences of turning parameters and tool wear on the net cutting specific energy are studied. The results have been used in Shandong Yishui Machine Tool Factory Limited Company, to optimize the processing parameters and improve the energy efficiency of turning scheme. The main conclusions are as follows:

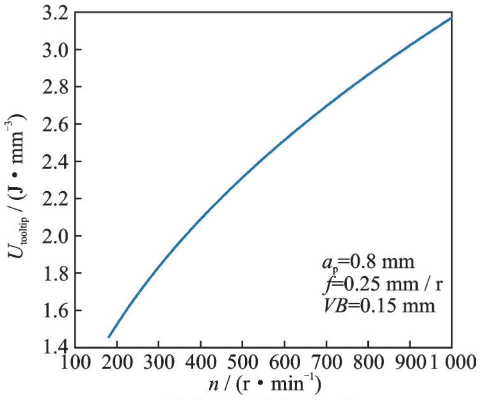
(1) Tool wear has an important influence on the net cutting specific energy and the net cutting energy consumption in turning. The developed predic-



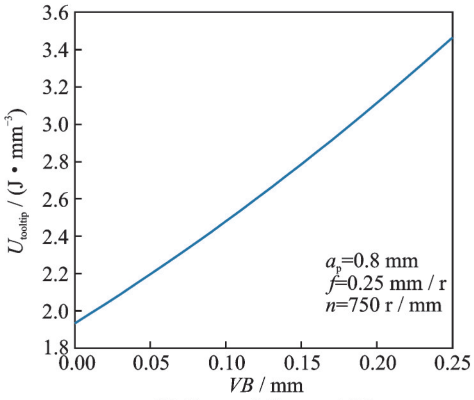
(a) Curve of $U_{tooltip}$ and a_p



(b) Curve of $U_{tooltip}$ and f



(c) Curve of $U_{tooltip}$ and n



(d) Curve of $U_{tooltip}$ and VB

Fig.6 Influences of turning parameters and tool wear on $U_{tooltip}$

tion model for net cutting specific energy based on turning parameters and tool wear is simple, and can be used to optimize the processing parameters.

(2) In CNC turning, the increase of cutting depth leads to the increase of material removal rate, so the net cutting specific energy decreases. With the increase of the spindle speed, the additional load loss power of the spindle drive system increases, so the net cutting specific energy increases. The net cutting specific energy increases approximately linearly with tool wear.

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Author contributions Prof. **ZHAO Guoyong** developed the prediction model, Mr. **LI Chunxiao** analyzed the experimental data, Mr. **TIAN Yingzhou** established the machine power monitoring platform, Dr. **ZHAO Guangxi** analyzed the tool wear mechanism, and Mr. **ZHANG Junfeng** carried out the turning process experiment. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

数控车削中净去除材料比能预测模型

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摘要:建立了基于车削参数和刀具磨损的数控车削中净去除材料比能预测模型,可在车削加工前预测计算净去除材料能耗。在AISI 1045钢车削试验中验证了该模型的预测精度。对比试验表明,该模型因为考虑了刀具磨损的影响,所以预测精度显著提高。最后研究了车削参数和刀具磨损对净去除材料比能的影响。随着背吃刀量增加,净去除材料比能降低。主轴转速增加,使得数控车床主传动系统附加载荷损耗功率增加,所以净去除材料比能增加。净去除材料比能随着刀具逐渐磨损近似呈线性增大。研究结果有助于制定高效节能的数控车削加工方案,实现低碳制造。

关键词:净去除材料比能;车削参数;刀具磨损;加工方案;低碳制造