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Modeling and analysis of specific cutting energy of whirling milling process based on cutting parameters

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Abstract

Specific cutting energy (SCE) is significant to manufacturing sustainability and directly relevant to energy efficient machining and quality of surface generation of machining processes. Whirling milling process has been widely used to produce precision transmission lead screw thread parts, however, the prediction and characteristics of SCE remain unknown. This paper presents an SCE model of whirling milling as a function of cutting parameters to predict SCE and analyze its relationship with cutting parameters. This study can provide valuable information and guidance for evaluating operation parameters, process plans and optimal selection of cutting parameters to minimize SCE for manufacturing sustainability.

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Keywords: Whirling milling process; Specific cutting energy; Cutting parameters; Energy model; Cutting forces

1. Introduction

The rapidly increasing global energy demand has caused severe energy crisis and environment impacts. Manufacturing processes and activities play an indispensable role in industrial energy consumption, responsible for approximately 90% of the total [1]. Due to the wide distribution and large energy consumption in low efficiency, manufacturing systems have considerable energy-saving potential [2]. Machining processes used to remove the materials of workpieces are a major part of manufacturing industry, a colossal waste of energy and inefficiency [3]. In particular, traditional machining processes using cutting machine tools consume more energy compared with other types of machining processes (e.g., laser and welding) [4]. Thus, manufacturing enterprises have urgent needs to reduce energy consumption of machining processes which impel process planners and operators to improve their understanding of energy consumption while carrying out production. As a consequence, research efforts have been undertaken to model energy consumption in machining.

A fundamental energy model in machining processes reported that cutting energy represents the energy for actual material removal range from 15% to 70% [5,6]. Thus, cutting energy should be taken into account in the energy modeling of machining processes. Specific cutting energy, defined as the energy consumed in per unit material removal volume (e.g. 1 cm^3) according to Bayoumi et al. [7], is a key indicator of cutting energy. Moreover, specific cutting energy as an important parameter has a great impact on chip formation, cutting forces, tool wear and machined surface integrity [8]. To achieve high energy efficiency and high-quality surface generation of machining processes, it is paramount to predict specific cutting energy and understand its characteristics.

The specific cutting energy in machining processes has been investigated by researchers. An original energy model was proposed to estimate energy consumption using specific

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cutting energy as a constant parameter by Gutowski et al. [9]. Li et al. [10] developed an improved energy model with spindle speed as the added main factor. They also assumed specific cutting energy as a constant parameter. The above researchers assumed specific cutting energy as the constant value to calculate energy consumption. Actually, the specific cutting energy in machining could not be constant due to the great effects of cutting parameters on it.

Several studies (e.g. employing experimental data analysis methods) on specific cutting energy and cutting parameters in machining have been done to predict it and to improve the understanding of its characteristics with cutting parameters. Nandy et al. [11] investigated the effects of cutting parameters on specific cutting energy in turning under different environments via experiments. Sealy et al. [12] developed a predictive model of specific cutting energy in hard milling with cutting parameters by experimental data to quantify the relationship between specific cutting energy and cutting parameters. Cui and Guo [13] studied the optimum cutting parameters via experiments in intermittent hard turning considered specific cutting energy, damage equivalent stress and surface roughness. Other researchers developed analytical specific cutting energy model as functions of cutting parameters to explore directly the relationship between energy and cutting parameters for traditional machining, e.g. milling. The cutting parameters were employed by Bayoumi [7] to analyze the effects of feed rate, spindle speed, the width of flank wear on specific cutting energy in end milling. Pawade et al. [8] presented an analytical model in high-speed turning to predict specific cutting energy and to investigate the influence of cutting parameters. Recently, Liu et al. [14] proposed an analytical model using cutting parameters to predict specific cutting energy in slot milling, and then the relationship between the specific cutting energy and surface roughness was characterized under different cutting parameters. The aforementioned studies mainly focused on traditional machining processes, e.g. turning and milling.

In recent years, whirling milling as a promising cutting machining process has been wildly used to produce precision transmission lead screw thread parts (e.g., worm, ball screw shaft) made of hard-to-machine material for modern advanced equipment. Whirling milling is a variant of milling, which the cutting tools are installed on the tool holder that encompasses the workpiece [15]. It has many advantages such as high cutting rate, e.g. about nine times of that for traditional milling, high surface integrity of machined surface and low cost [16,17]. Different from the machining processes of conventional turning or milling, whirling milling process has a special material removal mechanism led from the combination of workpiece rotation, cutting tools rotation and cutting tools axial feed motion, the interrupted cut by multiple cutting tools, and time variant characteristics of un-deformed chips. The characteristics of specific cutting energy are quite different from that for conventional machining. However, few researchers have undertaken to investigate the modeling of specific cutting energy of whirling milling process, and the relationship between cutting parameters and specific cutting energy has been rarely analyzed.

Therefore, the aim of this work is to develop a specific cutting energy model of whirling milling with cutting parameters (e.g., cutting speed, workpiece speed, number of cutting tools, tool nose rotation radius). Based on the model, the effects of cutting parameters on specific cutting energy are clearly investigated and analyzed to provide guidance for the selection of cutting parameters to minimize specific cutting energy for manufacturing sustainability.

2. Modeling of specific cutting energy of whirling milling

Whirling milling is an efficient material removal milling process for machining screw by a combination of workpiece rotation, cutting tools rotation and cutting tools axial feed motion. Fig. 1 shows the kinematics and mechanics of whirling milling process. Workpiece keeps turning at a very low rotating speed (hereinafter referred to as workpiece speed n_w). It is encompassed by the whirling tool holder with the eccentricity e, which controls the depth of cut and makes the material successively cut by the cutting tools. The whirling tool holder is rotated at very high speed (hereinafter referred to as cutting speed n_t compared to workpiece speed. Several cutting tools (number of cutting tools Z) evenly clamped on the whirling tool holder rotate at the cutting tools nose rotation radius R. The lead of the screw p is determined by both the lead angle φ and the small axis feed speed of whirling tool holder v_f [17]. Moreover, due to the specificity and complexity of the whirling milling process, there are some simplifications as follows [18]: (1) the effect of small lead angle is neglected and the workpiece axis is assumed perpendicular to the tool holder; (2) due to the low n_w and the small v_f, it is assumed that only cutting tools are rotating during the (n-1)-th cutting, and then workpiece would rotate a corresponding angle β to continue the n-th cutting.

According to geometries and mechanics of whirling milling process, the workpiece speed n_w and the rotating speed of tool holder n_t (namely cutting speed) are synchronized and coordinated to generate the lead of thread. Thus, four cutting parameters that affect the un-deformed chip formation can be identified, including workpiece speed n_w, cutting speed n_t, cutting tools nose rotation radius R and number of cutting tools Z. Based on these four cutting parameters, the model for predicting specific cutting energy of whirling milling process can be developed.

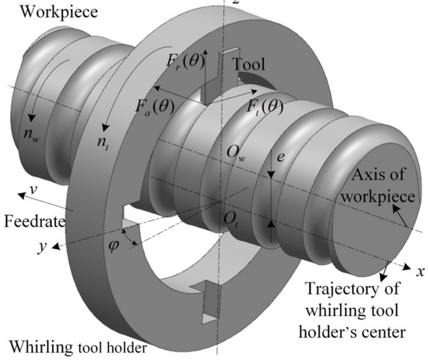


Fig. 1. Kinematics and mechanics of whirling milling process.

2.1. Modeling procedure

As defined by Bayoumi et al. [7], specific cutting energy is the energy consumed to remove a unit volume of material, which is calculated as the ratio of cutting energy E to material removal volume V. In this research, Fig. 3 shows the procedure involved in modeling of the specific cutting energy in whirling milling process. The cutting parameters are identified based on geometries and mechanics of whirling milling process, which can be used to calculate the material removal volume. Meanwhile, the cutting force model is established to formulate the cutting energy with the identified cutting parameters. The specific cutting energy model is then developed as a function of cutting parameters through the cutting energy and material removal volume. The measurement of cutting forces is carried out to determine the forces coefficients which are used to predict the specific cutting energy. The experimental specific cutting energy could be obtained as the ratio of cutting power $P_{cutting}$ in cutting experiments to material removal rate (*MRR*) (i.e., $P_{cutting}/MRR$), and the cutting power can be decomposed from the power curve monitored during machining experiments [12,19]. Subsequently, the predicted specific cutting energy can be calculated. Finally, the comparison between predicted and experimental specific cutting energy has been conducted to validate the presented model.

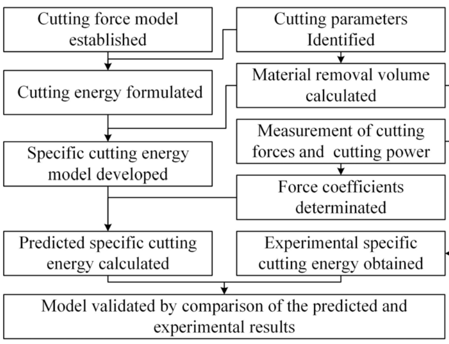


Fig. 3. Procedure involved in the modeling of SCE.

2.2. Cutting force model

The cutting energy can usually be obtained based on cutting forces acting on the tool edge and speeds of cutting motions [7,14]. Thus, the cutting force model whirling milling is developed as a basis. It has been demonstrated that the cutting forces can be calculated by using un-deformed chip cross section area and tool-workpiece contact length [20].

According to Fig. 1, un-deformed chip geometrical details of whirling milling is shown in Fig. 2. The un-deformed chip is formed due to the previous cutting (namely n-1 th cutting) and the subsequent cutting (namely n th cutting). The polygon AFCB is the un-deformed chip, and Arc A-C, B-C and A-B are the trajectories of the n-th cutting, trajectories of the (n-1)-th cutting and workpiece outer circle, respectively. Further, in the whirling milling process, the un-deformed chip cross-section area $A(\theta)$ is the area of polygon GEHD′ and tool-workpiece contact length $l(\theta)$ is the length of arc G-H. Then the $A(\theta)$ and $l(\theta)$ can be calculated based on the un-deformed chip geometrical details as shown in Fig. 2.

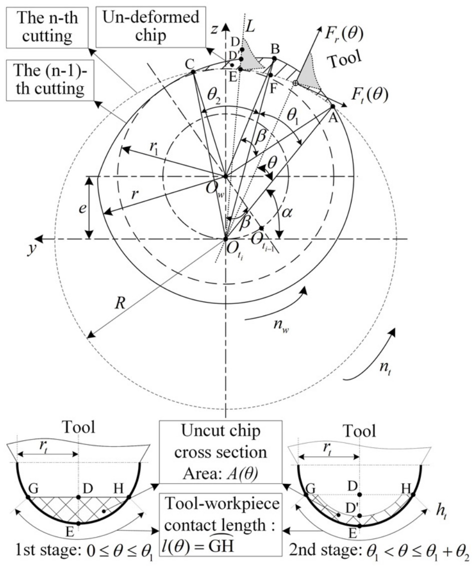


Fig. 2. Un-deformed chip geometrical details of whirling milling.

The cutting forces exerting on the cutting tool can be decomposed into tangential force component $F_t(\theta)$, radial force component $F_r(\theta)$ and axial force component $F_a(\theta)$, as shown in Fig. 1. It can be calculated as follows [20]:

$$\begin{cases} F_t(\theta) = K_{ts} \cdot A(\theta) + K_{tp} \cdot l(\theta) \\ F_r(\theta) = K_{rs} \cdot A(\theta) + K_{rp} \cdot l(\theta) \\ F_a(\theta) = K_{as} \cdot A(\theta) + K_{ap} \cdot l(\theta) \end{cases} \tag{5}$$

where K_{ts}, K_{rs} and K_{as}(N/mm^2) are the cutting force coefficients in tangential, radial and axial direction, respectively; K_{tp}, K_{rp} and K_{ap}(N/mm) are the specific edge force coefficients in tangential, radial and axial direction, respectively; $A(\theta)(mm^2)$ and $l(\theta)(mm)$ are the un-deformed chip cross section area and tool-contact length at angular position θ, respectively. The force coefficients can be both determined using the standard linear least squares (LLS) method [14] based on the measured cutting forces data.

2.3. Development of specific cutting energy

In whirling milling process, cutting energy E is consumed by whirling cutting motions which include two main kinds of motions related to feed and rotation of whirling tool holder. Since the radial force component $F_r(\theta)$ is perpendicular to both cutting velocity in rotation motion and axis feed speed v_f in feed motion, hence, there is no energy consumed by $F_r(\theta)$. The tangential force component $F_t(\theta)$ and axial force component $F_a(\theta)$ are paralleled to tangential cutting velocity and axis feed speed v_f, respectively. Therefore, the cutting energy E can be divided into rotation energy E_t expended by $F_t(\theta)$ and axis feed energy E_f expended by $F_a(\theta)$. Total cutting energy E within per cutting of whirling can be formulated as:

$$E = E_t + E_f \tag{6}$$

$$E_t = \int_0^{\theta_1+\theta_2} F_t(\theta)\cdot R d\theta = \int_0^{\theta_1+\theta_2} [K_{ts}\cdot A(\theta) + K_{tp}\cdot l(\theta)] R d\theta \tag{6a}$$

$$\begin{aligned} E_a &= \int_0^{\theta_1+\theta_2} v_f \cdot F_a(\theta) \frac{d\theta}{w_t} \\ &= \int_0^{\theta_1+\theta_2} v_f \cdot (K_{as}\cdot A(\theta) + K_{ap}\cdot l(\theta)) \frac{d\theta}{w_t} \end{aligned} \tag{6b}$$

where axis feed speed v_f can be expressed as $v_f = p \cdot n_w$; n_w is the workpiece speed; p is the lead or pitch of the screw thread depending on specification.

According to the definition of specific cutting energy (SCE) by Bayoumi et al. [7], SCE can be written based on Eq. (6) as shown in Eq. (7):

$$SCE = \frac{E}{V} = \frac{E_t + E_f}{V} \tag{7}$$

where V is the material removal volume and it can be formulated as:

$$V = \int dV = \int_0^{\theta_1+\theta_2} A(\theta) R d\theta \tag{8}$$

Finally, considering Eq. (6) and Eq. (8), SCE of whirling milling process can be given by:

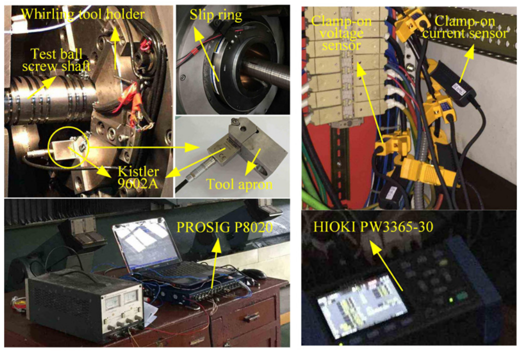
$$SCE = K_{ts} + \frac{v_f K_{as}}{2\pi R n_t} + (K_{tp} + \frac{v_f K_{ap}}{2\pi R n_t}) \frac{\int_0^{\theta_1+\theta_2} R l(\theta) d\theta}{\int_0^{\theta_1+\theta_2} R A(\theta) d\theta} \tag{9}$$

3. Experimental validation

This section involves detailed experiment design and setup used to determine the cutting force coefficients and the cutting energy. The predicted specific cutting energy was calculated using the cutting parameters and determine cutting force coefficients by measured forces. The experimental specific cutting energy was obtained as the ratio of cutting energy decomposed from the measured power curve to material removal volume. Accordingly, the results of predicted and experimental specific cutting energy were compared to validate the specific cutting energy model.

3.1. Experiment details

The whirling milling experiments were carried out in whirling milling a ball screw shaft on a CNC whirling machine, HJ092×80, which was developed by Hanjiang Machine Tool Co., Ltd, China. The new and sharp PCBN cutting tools (r_t = 3.304 mm) with about 85% CBN were used in these experiments for dry cutting. The test workpiece material selected for experiments was hardened bearing steel AISI 52100. The test sample was cylindrical bar with a dimension of Ø78.5 mm × 2000 mm. The experimental data measurement configuration is shown in Fig. 4. A piezoelectric force sensor (Kistler 9602A) with integrated charge amplifier electronics was installed on the tool apron simultaneously rotating with a cutting tool to measure the three-component cutting forces. Due to the rotation of the force sensor with a cutting tool, a slip ring was used to connect the force sensor and the data acquisition equipment. A data acquisition equipment (PROSIG P8020, Prosig Ltd, USA) was used to collect the cutting force data with a sampling frequency of 50 kHz. The power consumption of CNC whirling machine HJ092×80 in whirling milling was measured with HIOKI PW3365-30 clamp-on power quality analyzer meter produced by HIOKI Company.



(a) Measurement of cutting forces (b) Measurement of power

Fig. 4. Experimental measurement configuration.

As stated earlier in Section 2, the cutting parameters are cutting speed n_t, workpiece speed n_w, number of cutting tools Z and tool nose rotation radius R. In addition, the values of these parameters were selected according to the screw surfaces' forming requirements and capacity of whirling machine tools with the recommendation of its manufacturer. The experiments were performed with the four parameters (n_t, n_w, Z and R) at three levels. There are 81 parameter settings in total without any design of experiment (DOE) method. Thus, the Taguchi method was chosen in experiment design due to the widely accepted benefits [21]. The combinations of the cutting parameters in experiments can be determined by using the Taguchi method as shown in Table 1. Each set of the cutting parameters was repeated three times in experiments to reduce random experimental errors.

Table 1. Cutting parameters in experiments.

Test group no.	Cutting speed n_t (*r/min*)	Workpiece speed n_w (*r/min*)	Number of cutting tools Z	Cutting tool nose rotation radius R (mm)
1	500	2	4	40
2	500	5	6	45
3	500	8	8	50
4	1000	2	6	50
5	1000	5	8	40
6	1000	8	4	45
7	1500	2	8	45
8	1500	5	4	50
9	1500	8	6	40

3.2. Comparison between predicted and experimental specific cutting energy

The predicted and experimental specific cutting energy were both obtained to validate the proposed model. To calculate the predicted specific cutting energy, the tangential and axial force coefficients were determined using 1000 measured experimental data points of $F_t(\theta)$ and $F_a(\theta)$, respectively, for test group 1 in table 1. Based on the LLS described in Section 2.1, the obtained results of force coefficients were K_{ts} =1040.54 (N/mm^2), K_{tp} =2.47 (N/mm), K_{as}= 300.85 (N/mm^2) and K_{ap} =2.00 (N/mm). Moreover, to verify the effectiveness of the obtained cutting force coefficients, the predicted cutting force profiles were compared with the measured profiles of $F_t(\theta)$ and $F_a(\theta)$ in test group 6 as shown in Fig. 5. It shows a good agreement between the predicted cutting forces and the measured data both in tendency and magnitude. Accordingly, the predicted specific cutting energy can be obtained according to Eq. (9) based on the cutting parameters and obtained cutting force coefficients.

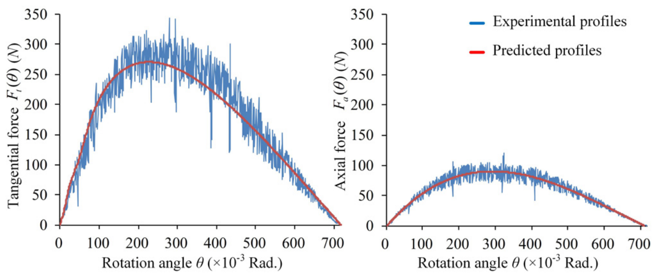


Fig. 5. Experimental and predicted cutting force profiles.

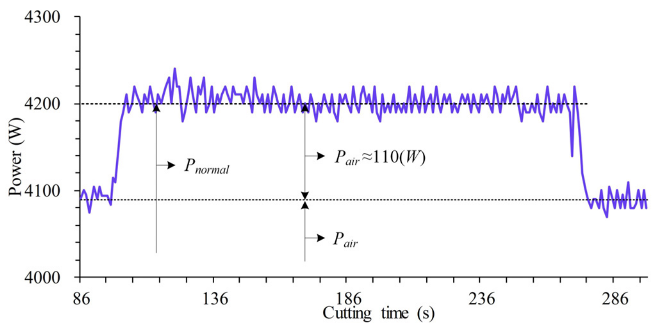


Fig. 6. Decomposition example of cutting power Pcutting.

As mentioned in Section 2.1, to obtain the experimental specific cutting energy, the cutting power $P_{cutting}$ under different tests (see Table 1) was decomposed from the power curve measured during machining experiments. Fig. 6 presents a decomposition example of cutting power using the measured power curve of test group 1 in whirling milling. The cutting power $P_{cutting}$ can be calculated as the difference between normal power P_{noamal} and the air cutting power P_{air}, and *MRR* was calculated using material removal volume and cutting time. Then, the predicted and experimental specific cutting energy were determined and compared under each test group of cutting parameters as shown in Table 2. The predicted specific cutting energy is generally higher than the measured values. This phenomenon could be explained by that the measured SCE values are obtained based on the widely used and larger theoretical *MRR* values compared to the actual values. The theoretical *MRR* values are larger than the actual values because the material removal in actual cutting can not occur for some of the edges when the un-deformed chip thickness is much smaller than the minimum chip thickness [22]. Furthermore, the theoretical *MRR* values is widely used by researchers due to the actual values are difficult to obtain after the chip deformation in machining. In table 2, it can be observed that the accuracy is over 90%, which shows that the proposed model can be effectively used to predict specific cutting energy for a given set of cutting parameters in whirling milling.

Table 2. The comparison of the predicted and experimental SCE in whirling milling.

Test group no.	Predicted values S_p ($\times 10^{-2}$ J/mm^3)	Experimental values S_e ($\times 10^{-2}$ J/mm^3)	Accuracy (%) [1-$\lvert S_p - S_e\rvert / S_e$] ×100%
1	135.3	130.0	96.0
2	115.9	110.5	95.2
3	112.1	117.2	95.7
4	151.9	139.7	91.3
5	153.9	141.6	91.3
6	113.9	107.3	93.8
7	221.0	204.5	91.9
8	123.2	117.4	95.0
9	139.1	127.3	90.7

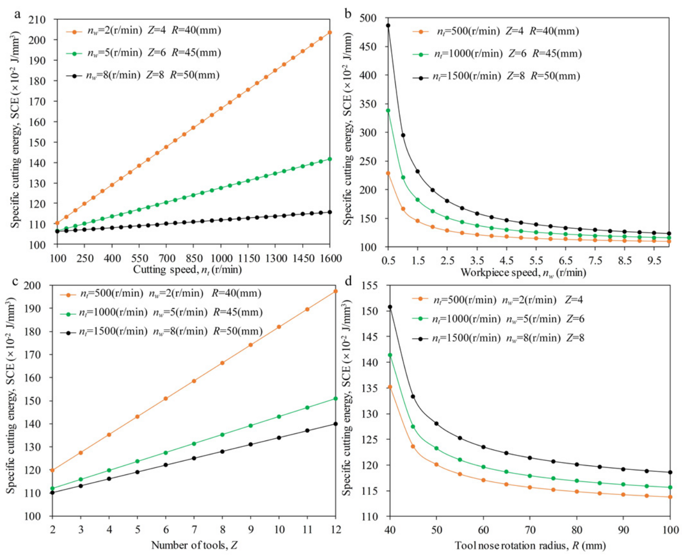


Fig. 7. (a) effect of cutting speed n_t on SCE; (b) effect of workpiece speed n_w on SCE; (c) effect of the number of tools Z on SCE; (d) effect of tool nose rotation radius R on SCE.

4. Discussion

According to the proposed model, the effects of cutting parameters on the specific cutting energy of whirling milling are presented as shown in Fig. 7. It can be found that it increases linearly with the increase in the cutting speed n_t, as shown in Fig. 7 (a). Also, Fig. 7 (c) shows the similar linear increasing variation of specific cutting energy with an increase in the number of cutting tools Z. In contrast, the nonlinear decreasing variations of specific cutting energy with workpiece speed n_w and number of cutting tools Z are shown in Fig. 7 (b) and (d) respectively. The specific cutting energy decreased sharply with the increase of n_w as shown in Fig. 7 (b) but remained steady with the increase of R as shown in Fig. 7 (d). In particular, it should be noted from Fig. 7 (b) that the specific cutting energy decreased over three times (i.e., from over 450 $\times 10^{-2}$ J/mm^3 to less than 150 $\times 10^{-2}$ J/mm^3) with the workpiece speed n_w increasing from 0.5 to 5 (r/min), and then it became fairly constant despite a further increase of n_w from 5 to 10 (r/min). It means that when the workpiece speed n_w was less than 5 (r/min), it had a dominant effect on specific cutting energy compared to n_t, Z and R. Moreover, it can be seen from Fig. 7 that the effects of n_t, n_w, Z and R were on nearly the same order of magnitude for specific cutting energy when $n_w \geq 5$ (r/min).

5. Conclusion

It has already been approved that the specific cutting energy greatly affected by cutting parameters within different machining processes. In previous studies, the specific cutting energy model in typical machining processes (e.g. turning and milling) have been developed and its relationship with cutting parameters has also been investigated. However, the specific cutting energy of whirling milling process is unknown so far.

This paper proposed an analytical model for predicting specific cutting energy of whirling milling process as functions of cutting parameters. To develop this model, the cutting force model was presented to obtain cutting energy, and the material removal volume was also calculated using cutting parameters. The presented model was applied for specific cutting energy prediction in whirling milling experiments of the ball screw shaft, and results show that the model can be effectively used to predict the specific cutting energy with the accuracy over 90%.

Furthermore, the effects of the cutting parameters on specific cutting energy were analyzed. The results could be used for the optimal selection of cutting parameters. It can enable process planners and operators to select low cutting speed n_t, small number of cutting tools Z, high workpiece speed n_w (especially $n_w \geq 5$ (r/min)) or large tool nose rotation radius R to reduce specific cutting energy.

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