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An Experimental Investigation into Anisotropic Energy Efficiency of Milling Process

Zhuo Liu[12], Ning Liu[1#], Kaining Shi[3], Biyao Qiang[3], Miaolong Yuan[1], Shanshan Yang[1]

1 Smart Manufacturing Division, Advanced Remanufacturing and Technology Centre, 3 Cleantech Loop, #01-01, CleanTech Two, 637143, Singapore
2 School of Electrical and Electronic Engineering, Nanyang Technological University, 639798, Singapore
3 Key Laboratory of High Performance Manufacturing for Aero Engine, Ministry of Industry and Information Technology, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, China
Corresponding Author / Email: liu_ning@artc.a-star.edu.sg, TEL: +65-96517567

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Machining sector is one of the largest energy consumers in the world, but with relatively low energy efficiency. To achieve sustainable manufacturing, it is a prerequisite to have a comprehensive understanding of the process-specific energy consumption behavior. This study investigates the anisotropic energy consumption behavior in one of the most extensively applied machining processes, i.e., milling process. In this study, an interesting phenomenon is reported that the energy consumption behavior is highly correlated to the feed direction, clearly exhibiting the anisotropic energy efficiency performance of the milling process. To analyze this, the power model is firstly established with zero feed angle cutting experiments, following which another set of cutting experiments were performed with varying feed angles. The influence of feed angle on the energy efficiency is comprehensively studied from viewpoints of both specific energy consumption as well as cutting force coefficients. Finally, an anisotropic energy consumption model is proposed, consisting of 1) a feed angle-independent component characterizing the baseline energy consumption and 2) a feed angle-dependent component to indicate the anisotropic energy efficiency. The established model has been validated to high accuracy. Therefore, it could shed light on sustainable manufacturing topics such energy efficient machining parameter selection and toolpath planning.

NOMENCLATURE

t, r, a = tangential, radial, and axial directions
dF_t, dF_r, dF_a= cutting force in t-r-a
$K_{\cdot c}$, $K_{\cdot e}$ = cutting and edge force coefficients, in N/mm^2 and N/mm, respectively
s_t = feed per tooth, in mm/rev
dS = differential edge length, in mm
θ = cutter rotation angle, in rad
z = edge height, in mm
dz = differential edge height, in mm
ψ = edge rotation angle with reference to feed, in rad
z = edge height, in mm
dP_n = rotating component of differential cutting power, in W
dP_f = feeding component of differential cutting power, in W
d$P_{cutting}$ = total differential cutting power, in W
n = spindle speed, in rpm
f = feed speed, in mm/min
$\overline{P_{cutting}}$ = averaged cutting power
P_{idle} = idle power consumption
θ_1, θ_2 = tool angular engagement limits, in rad
z_1, z_2 = tool axial engagement limits, in mm
$\Gamma(\psi)$ = binary tool engagement function, with 1 indicating in engagement and 0 otherwise.
η = cutting efficiency
MAPE = mean absolute percentage error
γ = the angle between feed and x-axis
P_{iso}= isotropic power consumption, in W
$P_{residual}$ = difference between isotropic power and anisotropic power, in W
P_{aniso}= anisotropic power consumption, in W
i_{max} = maximum polynomial order to characterize

1. Introduction (Times New Roman 10pt)

Sustainability is one of the major topics in Industry 4.0, ignoring which may lead to downgraded core competency [1, 4]. In this paradigm shift, manufacturing enterprises are still suffering from poor sustainability performance due to low energy efficiency [2, 3]. To address this effectively and effectively, it is essential to gain a comprehensive understanding of the energy consumption manner in manufacturing process, which provides both theoretical and empirical guidelines for energy efficiency optimization towards sustainable manufacturing.

However, the majority of the energy consumption models are isotropic, where the fluctuating energy efficiency in different directions is not considered [5–8]. As such, the anisotropic behavior of the machine tool is seldom considered during energy efficiency optimization towards sustainable manufacturing [3, 10–12]. In real production, machining is always associated with different feature-specific toolpaths, where feedrate changes not only in range, but also in direction. In this case, the isotropic energy consumption model will be of limited application potential due to degraded energy consumption prediction accuracy. To bridge this gap, this study provides a comprehensive experimental investigation of the anisotropic energy consumption behavior of the milling process, and proposes a practical modelling approach to characterize the anisotropic pattern. Good agreement with experiment results has been observed in testing study, showing the effectiveness of the proposed approach.

2. Anisotropic Energy Consumption in Milling Process

2.1 Isotropic milling energy consumption

In milling process, the essential energy consumption is required by removing the workpiece material with a certain tool. During the material removal process, cutting force is induced, as shown in Eq. 1.

$$dF_t(\theta, z) = K_{te} dS + K_{tc} s_t \sin\psi \, dz \quad (1a)$$

$$dF_r(\theta, z) = K_{re} dS + K_{rc} s_t \sin\psi \, dz \quad (1b)$$

$$dF_a(\theta, z) = K_{ae} dS + K_{ac} s_t \sin\psi \, dz \quad (1c)$$

For isotropic energy consumption, it is assumed the feed direction is overlapping with world coordinate system (WCS), i.e., dynamometer force registration system. Then,

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_z \end{bmatrix} = \begin{bmatrix} -\cos\psi & -\sin\psi & 0 \\ \sin\psi & -\cos\psi & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} dF_t \\ dF_r \\ dF_a \end{bmatrix} \quad (2)$$

Based on Eq. (1), the cutting power, i.e., essential power to achieve material removal, can be calculated as the summation of rotation power consumption and feed power consumption [6], which is described in Eqs 3 – 5,

$$dP_n = \left| (K_{te} dS + K_{tc} s_t \sin\psi \, dz) \cdot \frac{2\pi n r}{60000} \right| \quad (3)$$

$$dP_f = \left| (dF_t \sin\psi + dF_r \cos\psi) \cdot \frac{f}{60000} \right| \quad (4)$$

$$dP_{cutting}(\theta, z) = dP_n + dP_f \quad (5)$$

Finally, the cutting power can be obtained as the averaged differential cutting power over one cutter rotation.

$$\overline{P_{cutting}} = \frac{1}{2\pi} \int_{\theta_1=0}^{\theta_2=2\pi} \int_{z_1=0}^{z_2=a_p} d\, P_{cutting}(\theta, z) \cdot \Gamma(\psi) \quad (6)$$

Noticing that the cutting power is just the essential power to achieve material removal, additional power is also required by the machine tool. As revealed by [6], the total power can be represented using idle power and additional power proportional to the cutting power.

$$P_{iso} = P_{idle} + \frac{\overline{P_{cutting}}}{\eta} \quad (7)$$

where P_{idle} is a polynomial function of n, which is typically quadratic [5].

In this study, Experiment-I was carried out to calibrate the isotropic power consumption model on VMC-850. It consisted of 27 slotting experiments with cutting parameters varying in 3 levels as shown in Table 1. During the experiments, the feed direction was kept overlapping with x-axis of WCS. To provide mechanical insight, the cutting force profile was continuously monitored using Dynamometer Kistler 9255B. The isotropic energy consumption model is calibrated in two scenarios, 1) Iso-1 from slot-specific cutting force coefficients calibrated using slot-specific cutting force profile, 2) Iso-2 from generic cutting force coefficients using a certain slot (slot-20). The results are shown in Fig. 1. As can be seen, both models exhibit decent accuracy, with 3.33 % MAPE in Iso-1 and 6.23% MAPE in Iso-2. The difference in accuracy is probably that the cutting force coefficient may change with specific cutting conditions. To shed light on this, the slot-specific cutting force coefficients are visualized in Fig. 2. As can be seen, the calibrated cutting force coefficients, especially K_{tc} and K_{rc} are significantly different in slots No. 10 – No. 18, corresponding to the relative inaccurate prediction results in Fig. 1. When using generic cutting force coefficients, such changes may be overlooked, leading to subsequent inaccuracy in power prediction. Nonetheless, even with generic coefficients, the MAPE is still relatively small, indicating a good calibration of the isotropic energy consumption model.

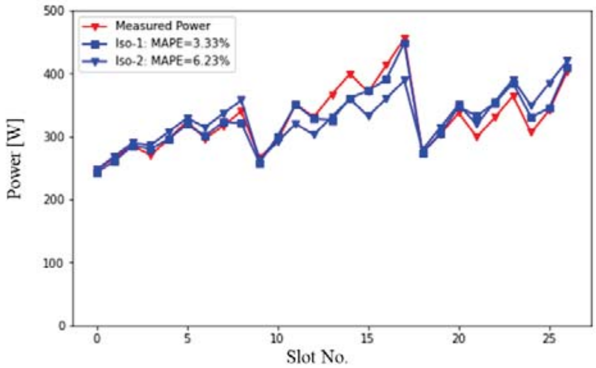

Fig. 1 Isotropic energy consumption model calibration results.

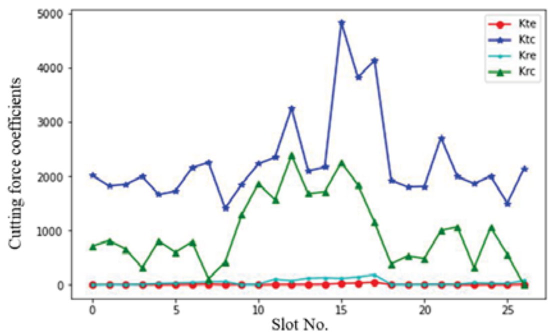

Fig. 2 Slot-specific cutting force coefficients in Experiment-I.

Table 1 Slot milling parameters in Experiment-I.

Cutting parameters	a_p	n	f
Level 1	0.6	1500	200
Level 2	0.8	2000	300
Level 3	1.0	2500	400

2.2 Anisotropic milling energy consumption

When there is an angle between the WCS, i.e., dynamometer coordinate system, as shown in Fig. 2, the following relationship can be obtained, based on which the slot-specific cutting force coefficients can also be calibrated.

$$\begin{bmatrix} F_{x'} \\ F_{y'} \\ F_{z'} \end{bmatrix} = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \tag{7}$$

In order to investigate the anisotropic energy consumption manner of the milling process, four sets of experiments were carried out, with meta parameters (i.e., a_p, n, f) specified in Table 2. For each meta parameter setting, feed direction was changed from 0° to 345 ° with increment of 15°. Therefore, there are 24 slots for each of the four experiments. To quantify the energy efficiency with respect to feed direction, the results are visualized in specific energy consumption (SEC), in the unit of J/mm^3, as shown in Fig. 4.

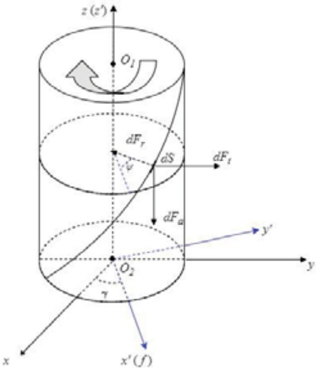

Fig. 3 The slot milling process with varied feed direction.

Obviously, a strong relationship between milling energy efficiency and feed direction can be observed. On the one hand, the energy efficiency clearly differentiates from each other in the four experiments with the same feed direction. The energy efficiency ranking is consistent with an energy efficiency ranking of Experiment-V > Experiment-III > Experiment-IV > experiment-II. This is caused by different material removal rate (MRR) set by the meta parameters. Generally, a large MRR lead to a higher energy efficiency indicated by a lower SEC, which is consistent with previous studies [2, 6]. However, the ranking becomes invalid when considering across feed directions. For example, when γ = 75°, the SEC in Experiment-IV is even higher than many slots in Experiment-II, indicating a lower energy efficiency. In this case, the anisotropic influence induced by feed direction dominates the meta parameter setting. Interestingly, it is noteworthy that a similar anisotropic energy efficiency pattern can be observed. For example, when γ comes close to 75°, 225°, 345°, the SEC values are much higher than others within each experiment. Such findings strongly justify the necessity to take the anisotropic energy consumption behaviour into consideration during sustainable manufacturing.

Table 2 Meta parameters for experiments with varied feed direction

No.	a_p [mm]	n [rpm]	F [mm/min]
Experiment-II	0.5	2000	200
Experiment-III	0.5	2000	400
Experiment-IV	0.5	3000	300
Experiment-V	1.0	3000	300

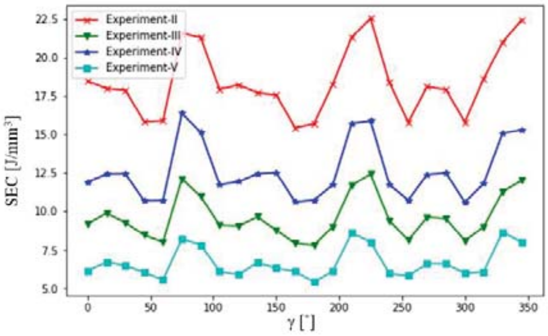

Fig. 4 Experiment results with varied feed direction.

2.3 Practical Modelling of Anisotropic Energy Consumption

It can also be seen from Fig. 4 that the anisotropic energy consumption behavior shows some similarity across meta parameter settings. This is probably caused due to limited stiffness in different directions. As revealed in [9, 13], limited stiffness may influence the actual feed per tooth (i.e., s_t in Eq. 1), thus leading to varied uncut chip thickness. As such, the required cutting force may be affected and so is the power consumption. In-depth study may require mechanistic and kinematic analysis, which is not straightforward in real production. To address this, this paper proposes a practical modeling approach to address the anisotropic energy consumption behavior. Specifically, the residual power consumption, defined as the difference between the measured power consumption and isotropic energy consumption, is modelled using a polynomial expression.

$$\begin{aligned} P_{aniso} &= P_{iso} + P_{residual} \\ &= P_{idle} + \frac{\overline{P_{cutting}}}{\eta} + \sum_{i=0}^{i=i_{max}} C_i \gamma^i \end{aligned} \tag{8}$$

To calibrate the proposed model, i.e., C_i, the 96 slots are randomly divided into a training set of 67 slots and a testing set of 29 slots. In this study, i_{max} is set as 17. To benchmark the effectiveness of the model, a multi-layer perception (MLP) model is also developed, with four-feature input consisting of a_p, n, f and γ. The hyperparameter of the MLP model was optimized via design-of-experiment (DoE) method using the same training and testing sets, and a three hidden layer structure consisting of [200, 400, 200] neurons were employed. Comparative results are visualized in Fig. 5, with Aniso-1 and Aniso-2 representing calibrated models based on isotropic models (i.e., Iso-1 and Iso-2), respectively.

As can be seen, the proposed anisotropic models (Aniso-1 and Aniso-2) exhibits much higher accuracy than the MLP model, clearly indicating the effectiveness of the proposed method. The accuracy of MLP model is as poor as 16.5%. This poor performance probably due to the purely data-driven structure, which is essentially data-hungry and black-box in nature. Therefore, it would be extremely difficult to adjust all the weights properly with a relatively small training dataset consisting of only 67 data points. In sharp contrast, the proposed model is based on the isotropic energy consumption model characterized from cutting mechanisms, thus reducing the dependency on big data.

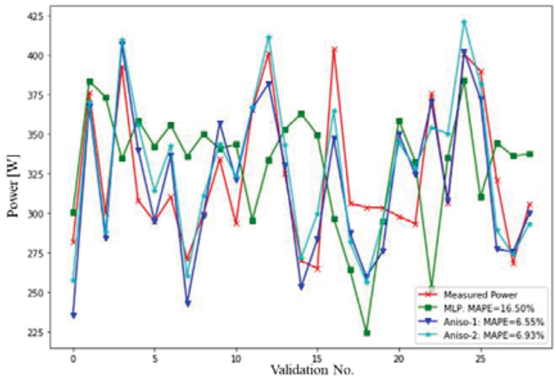

Fig. 5 Model benchmarking over the test set.

3. Conclusions

In this study, the anisotropic energy consumption behavior of the milling process is investigated, which provides great application potential for sustainability-oriented topics like tool path ecolabelling and optimization. The contribution of this paper is summarized as follows.

1. Anisotropic energy consumption behavior has been clearly revealed in the studied milling process. Varied feed direction leads to different energy efficiency even with the same meta parameter setting. In some cases, the influence may be even more significant than the meta parameter setting.
2. Experiments show that the anisotropic energy consumption behavior shares certain similarity, with a similar energy efficiency trend observed across different parameter setting.
3. A practical anisotropic energy consumption modelling approach is proposed. Results show that the prediction accuracy is decent. Compared to data-driven approach like MLP, the proposed model is less data-hungry and more accurate.

In the next phase of the study, an in-depth study will be carried out to shed more light on the anisotropic energy consumption behavior form the perspective of mechanistic and kinematic viewpoints.

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