Improving Energy Consumption Efficiency in Milling Processes by Optimizing the Machining Parameters

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***Abstract*—This study aims to improve the energy consumption efficiency in milling processes through the optimization of machining parameter. The empirical analysis was approached to investigate the correlation between machining parameter and energy consumption efficiency during milling process. Furthermore, the energy consumption efficiency model was created. The verification experiment was carried out to verify the proposed model. The results showed that the material removal rate (MRR) and depth of cut has the most significant effect on energy consumption efficiency**

***Keywords*—energy consumption efficiency, optimization, milling process**

I. Introduction

Energy conservation has become a crucial concern in various fields due to the global energy shortage. The manufacturing industry is one of the major energy-consuming sectors [1]. For instance, the metal product and machinery industry is a significant consumer of electricity, and its demand has increased significantly over the years. The release of CO2 during the generation of electricity from carbon-rich fuels makes electrical power a significant contributor to environmental harm [2]. Statistical reports indicate the urgent need to decrease energy consumption and adopt energy-efficient manufacturing techniques to improve process performance and minimize negative effects. Consequently, the manufacturing industry is confronted with the task of conserving energy, and the implementation of energy-efficient machining systems.

Previous research has primarily concentrated on developing energy-efficient machining processes to reduce energy consumption in the manufacturing sector [3,4]. In machine tool production, computer numerical control (CNC) machines are commonly utilized to fabricate high-precision products, yet they consume significant amounts of energy while operating at lower efficiency and productivity levels [5-6]. Typically, the larger the machining capacity and the longer the machining duration, the greater the energy consumption.

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In the past, the enterprises prioritized minimizing machining time to increase machine utilization and productivity, but this led to poorer surface roughness. Enhancing surface roughness and process efficiency can be accomplished by conducting experiments with various cutting parameters, such as cutting speed, feed rate, and depth of cut, to determine the optimal limits for each factors and achieve the desired output. Consequently, further investigation into machine tool efficiency, the effect of cutting parameters on surface roughness and energy consumption, and the development of an energy efficiency optimization system is necessary.

Optimization requires considering machining efficiency, energy consumption, and surface roughness as crucial factors. The chosen machining parameters directly affect energy consumption, surface roughness, and machining efficiency. Therefore, careful choose the process parameters and their variations are very important. Improving energy efficiency encompasses not only production costs but also reducing machining time to simultaneously achieve machining accuracy and lower energy consumption.

CNC machine tools components can be divided into two types based on their energy consumption: (a) constant energy consumption which is required to operate the machine tool, and (b) variable energy consumption which arises due to material removal and axial acceleration and deceleration. The amount of material removed during machining is influenced by the motion of the spindle and the feed axes, and the power demand for these operations is determined by the cutting resistance [7]. Moreira et al. [8] reported the major components that consume power in the machine tools included spindle, coolant pump, servo motor, tool change system, controller, and hydraulics. Furthermore, the study indicated that the energy consumed during actual material removal processes varied greatly between different machine tools, ranging from 24.2–65.8%.

A significant amount of research has been directed towards the theoretical modeling of machine tool operation power consumption [9-13]. It showed that the power consumption is highly dependent on the complexity of machine tool, size, mechanical structure, motor performance, and energy supply characteristics of different CNC machine tools. Nonetheless, due to the complexity of CNC machine tools, many unknown parameters in theoretical models are hard to acquire. Consequently, measurements are necessary to obtain power models through statistical analysis.

The aim of this research is to develop a model that can improve energy consumption efficiency during milling process by optimizing the machining parameters. The paper structures as follows: Section 2 elucidated the experiment design for different cutting parameters and energy consumption data collection. Section 3 Analyzed and discussed the modeling of material removal energy consumption according to the measurement results. Finally, the conclusions of the work were presented in section 4.

II. METHODOLOGY

CNC machining industry is highly competitive, but also it meets the demand of energy saving and carbon reduction. In order to protect the competitive advantage, the optimization and best combination machining parameters are necessary to achieve the machine tool with higher production efficiency, lower production cost, lower energy consumption cost as well as cost effectiveness. To analyze the relationship between machine processing conditions and power consumption, the investigation and analyzing of spindle motor and servo motor were important.

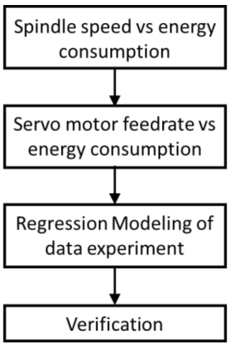

Fig. 1. Flowchart of research

Flowchart of research is displayed in Fig. 1. The first, created an experimental model based on the relationship between motor characteristics and energy consumption considering various cutting parameters. Second, statistical analysis technique was used to develop theoretical model based on the experimental data to identify coefficient of input parameters. The third, a new combination of process variables was used to validate the proposed model.

A. *Experiment Setup*

CNC 3-axis milling machine model YTM-763 manufactured by Yang Iron Precision Corp. with travel range X/Y/Z of 760/400/350 mm, maximum spindle speed of 12,000 rpm, maximum spindle power of 6.7 kW, maximum cutting feedrate of 12,000 mm/min, X, Y, Z-axis servo motor power of 2, 2, 3 kW respectively, was chosen for experiment. Medium carbon steel AISI 1045 with hardness of 88HRB was selected as workpiece material, while AlTiN coated carbide end-mill tool with diameter of 10 mm was used as cutting tool. Energy consumption of the spindle and servo axis motor were measured using PA310 Clip-on CT smart power meter manufactured by Arch Meter Corp. Data were collected using data acquisition and recorded using the ServeBox.

B. *Experiment Design*

The experiments were conducted in four sections. The first, idle energy was measured, which refers to the energy consumed by the machine tool when it is in ready position waiting for the machining process. Second, the energy demand characteristics of the spindle and feed axis during the air cutting stage were studied. The spindle speed was varied from 0 to 12,000 rpm, and the X/Y/Z feed axes were varied from 0 to 12,000 mm/min. Third, extensive cutting experiments were carried out using different combinations of cutting parameters, including spindle speed, feed rate, depth of cut, and width of cut. In this study, chip load values was varied by 20 percent higher and lower than manufacturer’s recommendation values. Each combination of cutting parameters was repeated three times, then the average values was used for analysis. The intervals of cutting parameters and combinations of spindle speed and feed rates are shown in Tables I and II. The Fourth, a new combination machining parameters was used to validate the energy consumption models with the same material removal rate but two different levels of spindle speed and feed rate.

TABLE I. INTERVAL CUTTING PARAMETERS

Parameters	Values
Spindle speed, N (rpm)	2050 ～ 5400
Feed rate, f, (mm/min)	197 ～ 778
Width of Cut, ae (mm)	2, 4
Depth of Cut, ap (mm)	1, 3

TABLE II. COMBINATION OF SPINDLE SPEED AND FEED RATES

Spindle speed (rpm)	(1) Feed rate (mm/min)	(2) Feed rate (mm/min)	(3) Feed rate (mm/min)
2050	197	246	295
2300	221	276	331
2550	245	306	367
2800	269	336	403
3050	293	366	439
3400	326	408	490
3650	350	438	526
3900	374	468	562
4150	398	498	598
4400	422	528	634
4650	446	558	670
4900	470	588	706
5150	494	618	742
5400	518	648	778

III. RESULT AND DISCUSSION

A. *Energy Consumption for Idle and Air-cutting Motions*

The idle energy consumption of the machine tool refers to the energy consumed by the machine tool when it is in the operational stage, and it is ready for the machining process. The idle energy consumption of spindle and X/Y/Z axis servo motor was shown in Fig. 2. It can be seen that the spindle and three-axis servo motors have different idle energy consumption with average values of 18W, 22W, 23W, and 70W, respectively. The X- and Y-axis servo motors demonstrated similar energy consumption characteristics.

However, the Z-axis servo motor exhibited higher energy consumption than that of X- and Y-axis due to the need of maintaining the spindle head in a specific position. The idling consumes power whenever the machine tool is started up or is running so that it will consume energy till the machine turns off, thus, the energy consumption of the idling will be determined by the machine tool activation time.

Air-cutting stage. In this stage machine tool runs with no load, including spindle rotation and feeding. The spindle rotation is one of the largest energy consuming motions. The energy consumption of the spindle was measured using a power meter at different speeds without any cutting load. The spindle speed was varied in increments of 500 rpm from 200 to 12000 rpm, and each experiment was conducted six times for 90 seconds each. The average energy consumption value was used for analysis as shown in Fig. 3. As seen, the energy consumption is higher with the increasing of spindle speed.

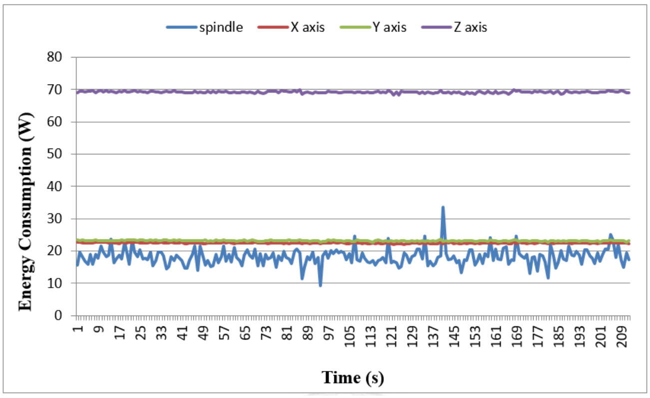

Fig. 2. Idle energy consumption for spindle and servo motor.

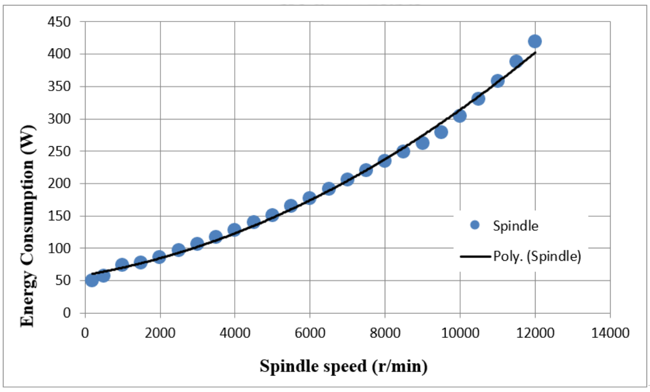

Fig. 3. Energy consumption of spindle at various speeds.

To understand the impact of feed rate on the energy consumption of the feed axis, motion tests were conducted at various feed rates without any cutting load. The tests were performed for X/Y/Z axis at different feed rate values, ranging from 200 to 12000 mm/min with an increment of 500 mm/min. The feed rates were varied in both positive and negative directions for each axis. Each experiment was repeated six times to ensure the consistency and repeatability of the data. During the assessment of feed axis energy consumption, the spindle was turned off so that its power consumption was not measured. The measured energy consumption of feed servo motor for X/Y/Z axis motion are shown in Fig. 4. The power consumption for X+ and X- as well as Y+ and Y- directions did not differ significantly, so the average power value was calculated for these axes. Fig. 4. Showed that the Y-axis feeding requires more energy than the X-axis. The reason is the X-axis table is mounted on the Y-axis, so the Y-axis carries more weight than the X-axis. However, at lower feed rates, the power consumption of both axes is nearly the same. Similarly, the energy consumption of the Z-axis to lift the spindle upward was greater than the downward. The reason is the energy required to feeding downward is only to balance the spindle gravity. The mathematic modeling for spindle and feeding energy consumption without cutting load were developed using second-order polynomial regression and empirical data in Fig. 3 and 4 as shown in table III.

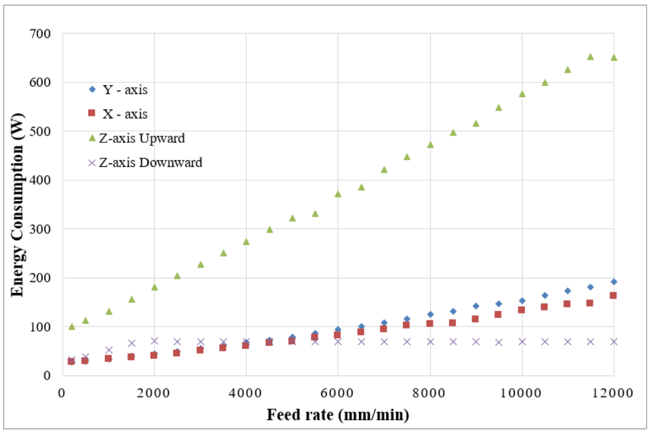

Fig. 4. Energy consumption of feed servo motor at various feed rates.

TABLE III. Energy Consumption Prediction Models of Spindle and Feeding Without Cutting Load

Subject	RPM / Feedrate	Regression Models	R^2
Spindle	$0 < N \leq 12000$	$P_{spindle}$=1.56E–06.N^2+0.0099N+58.623	0.995
X-axis	$0 < f \leq 12000$	$P_{feed - X}$ =3.095E–07.f^2 +0.0074f +25.427	0.998
Y-axis	$0 < f \leq 12000$	$P_{feed - Y}$ =3.881E–07.f^2 +0.0092f +24.336	0.999
Z-axis Upward	$200 < f \leq 12000$	$P_{feed - Z}$ =0.0487f + 81.416	0.998
Z-axis Downward	$200 \leq f \leq 2000$	$P_{feed - Z}$ =2.26E–02.f + 28.01	0.957
Z-axis Downward	$2000 < f \leq 12000$	$P_{feed - Z}$ =-3.676E–05.f + 69.71	0.699

where Pspindle is the spindle energy consumption w/o cutting load (W), Pfeed is feed energy consumption w/o cutting load (W), N is the spindle speed (r/min), and f is feed rate (mm/min).

B. *Energy Consumption for Material Removal*

In order to understand the effect of cutting parameters on the energy consumption, the linear cutting path with length of 260 mm along X-axis and Y-axis were carried out. Each run was repeated three times. The correlation between cutting parameters and energy consumption was determined by performing ANOVA and regression analysis on the experiment results data. Furthermore, the contribution of each independent variable to the energy consumption was analyzed.

From the cutting experiments result, the energy consumption of material removal was shown in Fig. 5-8 for X- and Y-axis. It can be seen that the energy consumption was higher for more material removal. The Y-axis feed servo energy consumption was higher than X-axis, which can be attributed to the different weight between the axes (X-axis table mounted on Y-axis). Furthermore, the spindle energy consumption during cutting was much higher than the feeding energy consumption, and both increased almost linearly at high spindle speed and feed rates. However, the energy consumption of both the spindle and feed servo varied with different combination of width of cut and depth of cut at spindle speed 3900 rpm. The reason might be due to the effect of the spindle vibration and cutting dynamic. As shown in Fig. 6 and 8, the transition was occurred at spindle speed of 3650 and 3900 rpm, so that the data was divided into three section to obtain more accurate regression model.

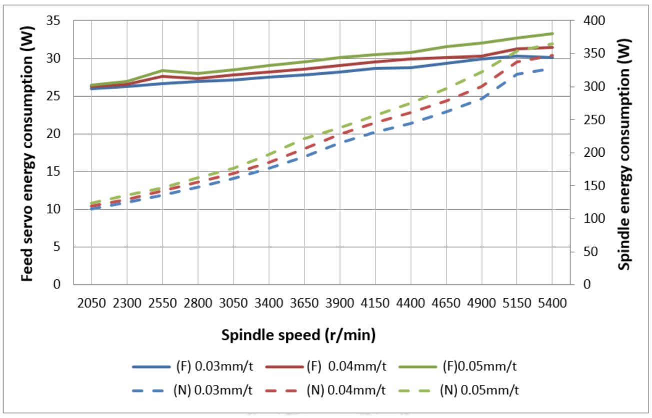

Fig. 5. Energy consumption of spindle and X-axis feed servo motor for a_p=1mm, a_e=2mm.

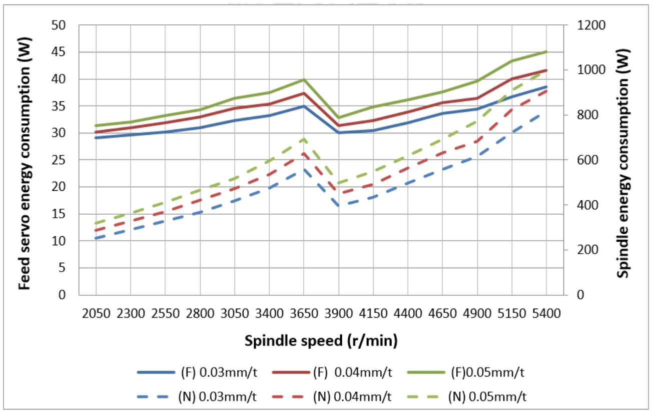

Fig. 6. Energy consumption of spindle and X-axis feed servo motor for a_p=3mm, a_e=4mm.

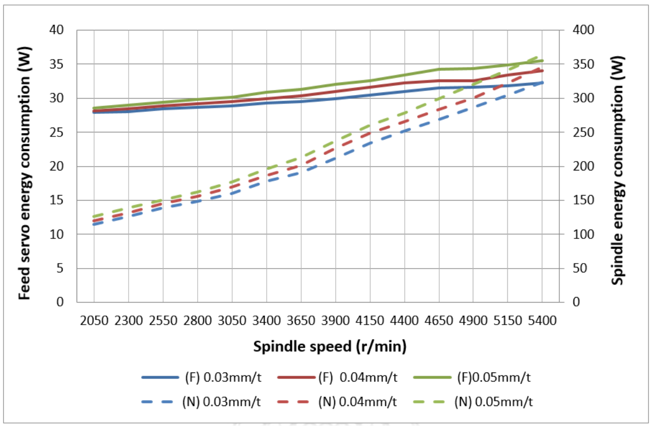

Fig. 7. Energy consumption of spindle and Y-axis feed servo motor for a_p=1mm, a_e=2mm.

Table IV showed regression model of energy consumption with cutting load. As seen in Table IV, the R-square value of all models exceed 0.82, which indicated the accuracy of the model. The P-value has lower than α = 0.05 (confidence level of 95%), indicates there is a true relationship between those process parameters and material removal power consumption, and the regression model is significant. For the X-axis energy consumption, the depth of cut significantly impact on energy consumption for lower feed rate, on the other hand the feed rate may significantly impacts on energy consumption when fast motion (higher feed rate). The similar trend of energy consumption was also found in the Y-axis. Regarding spindle energy consumption, the material removal rate (MRR) was found as the most influential factor for energy consumption with contribution up to 79%.

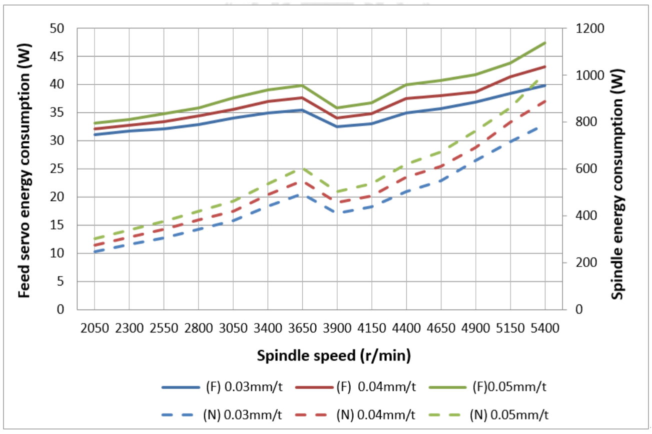

Fig. 8. Energy consumption of spindle and Y-axis feed servo motor for a_p=3mm, a_e=4mm.

TABLE IV. Energy Consumption Prediction Models of Spindle and Feeding With Cutting Load

X axis feeding				
Regression model	***Contributions C(%)***			
	Feed rate(f)	***DOC (a_p)***	***WOC (a_e)***	***Error***
$P_{feed-X1}$=16.87+0.017f +1.69a_p + 1.19a_e R^2=0.82	27.64	37.29	18.31	16.76
$P_{feed-X2}$=15.29+0.02f +2.25a_p + 0.58a_e R^2=0.83	46.25	40.25	2.67	10.83
$P_{feed-X3}$=16.98 + 0.017f + 1.97a_p +0.88a_e R^2=0.84	52.39	30.03	6.03	11.55
Y axis feeding				
$P_{feed-Y1}$=19.05 + 0.018f + 1.7a_p + 1.05a_e R^2=0.92	34.31	42.57	16.22	6.9
$P_{feed-Y2}$=17.28 + 0.021f + 2.66a_p + 0.24a_e R^2=0.87	41.59	49.75	0.43	8.23
$P_{feed-Y3}$=19.07 + 0.018f + 2.18a_p + 0.64a_e R^2=0.88	52.88	35.08	3.1	8.94
Spindle				
Regression model	***Spindle speed***	***MRR***	***Error***	
$P_{spindle-1}$= - 40.85 + 0.048N + 4.89MRR R^2=0.97	20.84	79.01	0.15	
$P_{spindle-2}$= - 391.51 + 0.134N + 4.01MRR R^2=0.89	24.98	75	0.02	
$P_{spindle-3}$= - 68.27 + 0.063N + 4.25MRR R^2=0.92	44.26	55.65	0.09	

C. Verification

To verify the accuracy of the energy consumption model, new combination of cutting parameter were used to compare the predicted energy consumption with the measured value. The material removal rate (MRR) was found to be a significant factor affecting spindle energy consumption during machining. The experiment results showed that increasing MRR or spindle speed caused an increase in energy consumption. However, as MRR increased, the total machining energy consumption decreased corresponding to the decreasing of machining time. Nevertheless, higher MRR will affect to the surface roughness. To investigate the effect of cutting parameters on energy efficiency, the verification experiment was carried out by varying the cutting parameters while maintaining the same MRR. The spindle speed was set at two different levels and the ratio of depth of cut and width of cut was divided into four levels as shown in Table V. Each experiment was repeated three times, then average the energy consumption values for analyzing. Three type of developed models were tested to predict the energy consumption.

The experiment results showed that Model-1 provided an average accuracy of 99%, 92%, 86%, and 64% for test 1, test 2, test 3, and test 4, respectively. Meanwhile, the average accuracy of Model-3 was 96%, 84%, 92%, and 56% for test 1, test 2, test 3, and test 4, respectively. However, the average accuracy of Model-2 was only 78% and 50% for test 2 and test 4, respectively. The reason might be the depth of cut has a greater contribution than the width of cut for the X and Y axis feeding energy consumption. Overall, Model-1 achieved over 90% accuracy in predicting energy consumption and was suitable for all cases. Model-3 provided better accuracy for test 3.

This process optimization modeling can be used to predict the machining time, power consumption, and total machining cost. If this modeling combine with online monitoring system so the real-time power consumption, machining time, and total machining cost can be obtained, which is useful for practical application.

TABLE V. Cutting Parameters for Verification Experiment

Items	**Spindle speed (r/min)**	**Feed rate (mm/min)**	**a_p/a_e**				**MRR (mm^3/sec)**
Test 1	2500	300	10/0.6	8/0.75	6/1	4/1.5	30
Test 2	5000	600	10/0.3	8/0.375	6/0.5	4/0.75	30
Test 3	2500	300	0.6/10	0.75/8	1/6	1.5/4	30
Test 4	5000	600	0.3/10	0.75/8	0.5/6	0.75/4	30

IV. Conclusion

This study focuses on developing an energy consumption model for end milling processes and examining the effects of cutting parameters on energy consumption. The energy consumption components of machine tool such as spindle and three axes servo motors during cutting and no-cutting were investigated. The results showed that the spindle energy consumption can be correlated to the material removal rate, while a multiple regression model of process parameters can accurately predict the spindle and feeding energy consumption. The most significant factors for energy consumption was the depth of cut and the MRR. Overall, this study provides insights into optimizing cutting parameters to reduce energy consumption in milling processes. However, the energy consumption model can be improved by considering different material, different process (drilling, face milling etc.), and different machine. Also the relationship between energy consumption and toolpath strategies need to be investigated in future.

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