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Optimizing micro milling energy consumption for green manufacturing based on cutting strategies

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Abstract. Micro milling is currently being used to make micro-sized products, such as in MEMS, medical devices, etc. But in the process of machining, especially in roughing process, micro milling spends a lot of energy that can still be reduced to contribute to green manufacturing. This study focuses on developing the model of energy consumption during the micro milling processes. The model is then used to map the energy consumption from different cutting toolpaths and strategies. Furthermore this study also comparing and characterizing the energy consumed between macro milling and micro milling of the same part shape but with significant different in size. In conclusion, this study shows different characteristics and comparison in energy consumption between micro milling and macro milling.

1 Introduction

Nowadays, there have been increasing demands for micro components in many industries such as MEMS (Micro Electro Mechanical System), optics, aerospace, and medicine and biotechnology. These parts are widely manufactured by using micro milling method, because of its high precision and efficiency in machining.

Milling is a technology that is used to remove a small thickness in a workpiece. There are micro milling and macro milling, in milling method (micro and macro), the first step to manufacture the part is roughing process. This process is also done in micro milling. Roughing process tends to spend unnecessary energy. This unnecessary energy can lead to problem in environment sector.

It has been reported that manufacturing accounts for over 30% of global CO2 emissions and energy consumption [1]. Environment, resources and population are this era's major problems. Environment is the crucial one, and at any point can leads to the imbalance of the earth. Green technology is the application of one or more of environmental science, green chemistry, environmental monitoring and electronic devices to monitor, model and conserve the natural environment and resources [2]. Understanding and characterizing energy consumption to reduce the energy consumption of machine tools [3]. Kordonowy [4] doing many experiments related to the energy consumption and its verification.

There are many research about developing energy consumption model in machining but there is no research about the effect of cutting strategy through energy consumption in machining, especially in micro milling machine. This paper presents about the effect of cutting strategy through micro milling especially in roughing process and also we will talk about the comparison machining energy consumption in micro milling and macro milling.

2 Methodology

A miniaturized 5-axis micro milling machine, as shown in Fig.1, specification was used as referenced to calculate the energy consumption. However, we only use 3-axis movement which is XYZ because we focus in roughing process. The 3-axis movement, XYZ which has power consumption 4.4 Watt, controlled by three units DS102 from Suruga Seiki which has maximum power consumption 70 Watt. A high-speed air turbine spindle HTS1501S-M2040 was used to rotate the tool up to 150,000 rpm which has maximum power consumption 25 Watt. An air dryer SMC IDFA3E-23 was used to eliminate water content in compressed air which has power consumption 180 Watt.

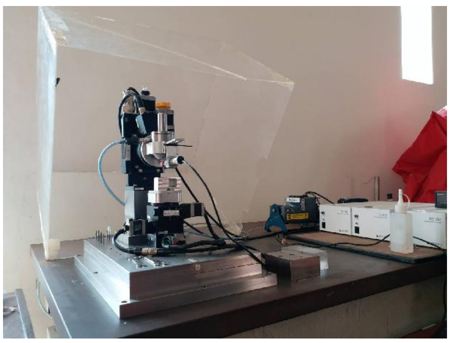

Fig. 1. A miniaturized 5-axis micro milling machine.

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2.1. Parts and simulation

Three parts of prismatic and a part sculpture were used in this study. Prismatic A as shown in Fig.2(a) with dimension 10 mm x 5 mm has a volume 131.2 mm^3. Prismatic B as shown in Fig.2(b) with dimension mm x 13.3 mm x 9 mm has a volume 342.3 mm^3. Prismatic C as shown in Fig.2(c) with dimension 12 mm x 7.5 mm has a volume 183.13 mm^3. The sculpture part as shown in Fig.2(d) with dimension 10 mm x 10 mm has a volume 400 mm^3.

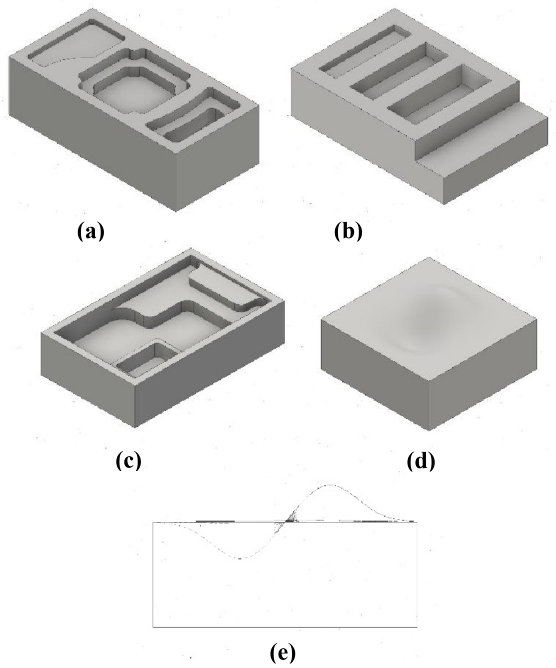

Fig. 2. Parts used for this study: (a) Prismatic A, (b) Prismatic B, (c) Prismatic C, (d) Sculpture, and (e) Sculpture front view.

The prismatic parts and a sculpture were cut by using a Flat-end mill DIXI7432 with diameter 0.5 mm, flute length 0.75 mm, and have 2 flutes. Prismatic parts and a sculpture part were cut with cutting parameter that has been selected based on recommendation from DIXI catalogue as shown in Table.1. In cutting operation, we only use 3 types of cutting strategy which is common in roughing process that is following part, follow periphery, and zigzag.

Table 1. Cutting Parameter.

Cutting Parameter	
Feed rate	500 mm/min
Spindle speed	50000 rpm
Depth per cut	0.03 mm
Width per cut	30% diameter tool

2.2. Energy calculation

Based on Hu et al [5], the energy consumption of NC machining consists of 5 types of energy, that is energy fix, energy from spindle, energy from each feed axis, energy coolant, energy from tool change. In this paper, we only use 2 types of energy, that is energy from spindle and energy from each feed axis. Since we didn't use coolant and tool change in our machine tool in our lab.

$$E_{total} = E_{spindle} + E_{axis} \quad (1)$$

Energy total is the total energy consumption of machine tool to machining a part. Energy fix is type of energy that is fixed or constant along the machining time. In this paper we neglect E_{fix} because it's not too impact to energy consumption calculation.

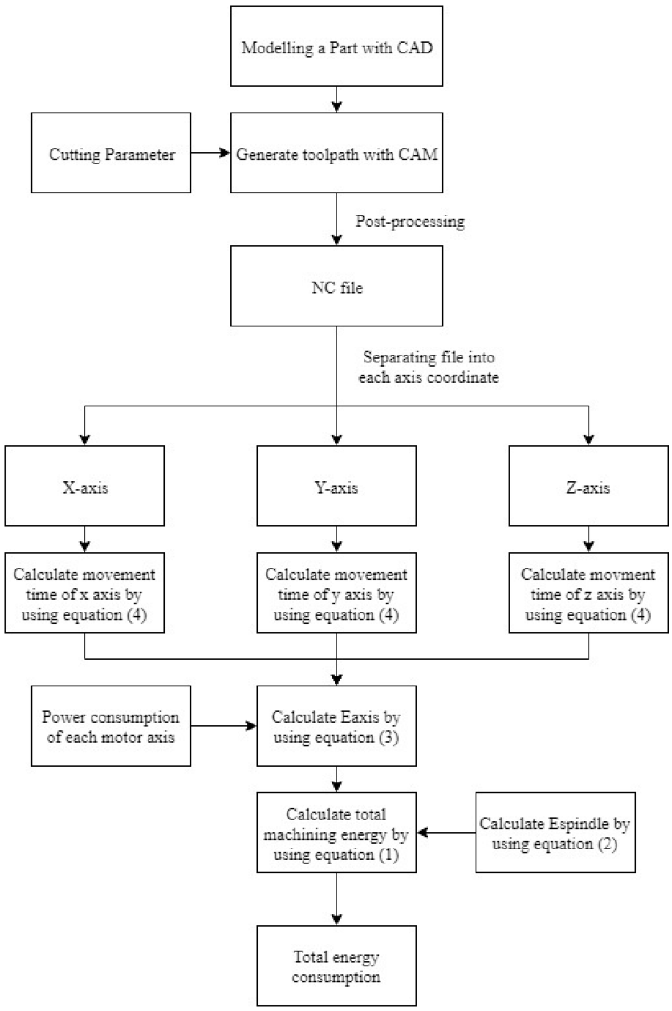

Fig. 3. The workflow of calculation energy consumption.

Energy spindle is an energy needed to rotate the tool at desired speed. In this paper to make simple calculation we assume that energy consumption of the spindle is constant along the rotational speed of spindle. We calculate the estimation energy consumption of spindle by using equation (2) where $P_{spindle}$ is power of spindle motor and $t_{machining}$ is total machining time.

$$E_{spindle} = P_{spindle} \cdot t_{machining} \quad (2)$$

E_{axis} is energy needed to move the workpiece table or the spindle at given speed. In this paper we ignore the effect of workpiece weight. We calculate the estimation energy consumption of each axis by using equation (3) where P_x is the power of motor x-axis, t_x is movement time of x-axis, P_y is the power of motor y-axis, t_y is movement time of y-axis, P_z is the power of motor z-axis, t_z is movement time of z-axis. Movement time of each axis can be calculated by using equation (4) where i represent i-th axis motor.

$$E_{axis} = (P_x \cdot t_x) + (P_y \cdot t_y) + (P_z \cdot t_z) \quad (3)$$

$$t_i = \text{ Total travel axis/Feed rate} \quad (4)$$

The workflow to calculate the energy consumption of machining is shown in Fig.3.

Table 2. Power parameter.

Power Parameter	Value (Joule/minute)
$P_{spindle}$	1500
P_x	264
P_y	264
P_z	264

3 Results and discussion

3.1 Micro milling energy consumption

Micro milling energy consumption has been calculated for three prismatic parts and a sculpture part with three variation of cutting strategies for each part by using workflow in Fig.3. Those cutting strategies are follow part, follow periphery, and zigzag. Fig.4 shows the total energy consumption of each parts and strategies. We can see that among four parts geometry, the cutting strategy follow periphery has slightly less energy consumption rather than 2 other cutting strategies, follow part and zigzag.

Follow periphery cutting strategy is when the tool path depending on the periphery profile and cut materials from outside to inside, while the tool path in follow part cutting strategy depends on the part geometry. So when the geometry part has same shape with its periphery, energy consumption will be the same between follow part and follow periphery. It happens in part Prismatic A. But if the part has significant difference shape, the follow periphery will be the best total energy consumption and it happens in Prismatic B and Prismatic C. The zigzag cutting strategy is when the tool path takes a zigzag path every level of depth. It has the lowest air cutting time, the condition when the tool travel not cutting, among all three strategies.

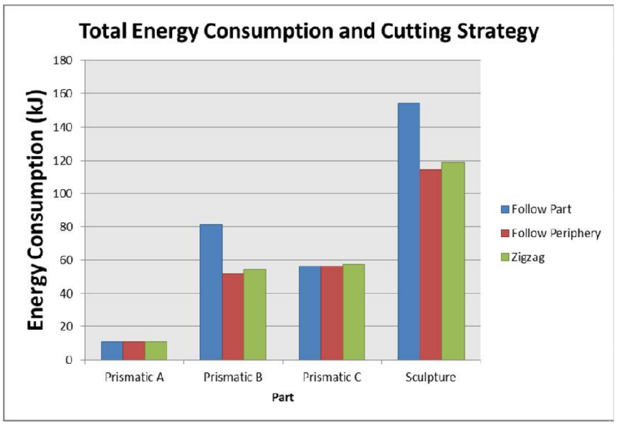

Fig. 4. Total energy consumption and cutting strategy.

In sculpture part, the follow periphery also has the best energy consumption rather than the other cutting strategies, it's because the follow periphery tool path is following the periphery of the part. Table.3. shows the relation between cutting strategy and total energy consumption.

Table.4 shows the relation between machining time to volume cut. Volume cut is volume of the part that needed to be cut to get the desired shape of part. We can see that there is a linear relationship between machining time and volume cut. The larger the volume cut, the longer the machining time. Machining time has an impact on machining energy consumption. The longer the machining time, the bigger energy consumption of the machine.

3.2 Comparison energy consumption between micro milling and macro milling

The difference between micro milling and macro milling is the size of the part that we want to create. Our lab already doing a research about energy consumption in macro milling. We want to compare micro and macro milling energy consumption by using the same part model with only different size scales where macro are 10 times larger than micro parts.

The EMCO VMC 200 machine was used as a reference power consumption parameter to calculate energy consumption in macro milling. The axis motors have power 604260 J/min and the spindle has power 600000 J/min.

Table 3. Cutting strategy and total energy consumption in micro milling.

Part	*Cutting Strategy*	*Total Energy Consumption (kJ)*
Prismatic A	Follow Part	11.01
	Follow Periphery	11.01
	Zigzag	10.94
Prismatic B	Follow Part	81.21
	Follow Periphery	51.63
	Zigzag	54.19
Prismatic C	Follow Part	56.30
	Follow Periphery	56.25
	Zigzag	57.32
Sculpture	Follow Part	154.07
	Follow Periphery	114.92
	Zigzag	119.00

Table 4. Volume-cut and total machining time.

Part	*Volume to cut (mm^3)*	*Total Machining Time (minute)*	*Average Total Machining Time (minute)*
Prismatic A	18.80	6.15	6.13
		6.15	
		6.08	
Prismatic B	76.65	35.80	31.74
		29.16	
		30.27	
Prismatic C	86.87	31.73	31.88
		31.70	
		32.20	
Sculpture	150.00	79.37	70.55
		64.78	
		67.50	

Table 5. Total energy consumption and cutting strategy in macro milling.

Part	*Cutting Strategy*	*Total Energy Consumption (kJ)*
Prismatic A	Follow Part	6289.49
	Follow Periphery	6321.65
	Zigzag	5342.21
Prismatic B	Follow Part	21681.25
	Follow Periphery	19554.47
	Zigzag	17204.92
Prismatic C	Follow Part	18667.26
	Follow Periphery	17292.93
	Zigzag	15170.32
Sculpture	Follow Part	48976.55
	Follow Periphery	49587.96
	Zigzag	49273.59

Table 6. Energy consumption per volume-cut in micro milling.

Micro milling			
Part	Volume to cut (mm^3)	Cutting Strategy	Total energy consumption per volume-cut(kJ/mm^3)
Prismatic A	18.799	Follow Part	0.59
		Follow Periphery	0.59
		Zigzag	0.58
Prismatic B	76.65	Follow Part	1.06
		Follow Periphery	0.67
		Zigzag	0.71
Prismatic C	86.866	Follow Part	0.65
		Follow Periphery	0.65
		Zigzag	0.66
Sculpture	150	Follow Part	1.03
		Follow Periphery	0.77
		Zigzag	0.79
Average			0.73

Table 7. Energy consumption per volume-cut in macro milling.

Macro milling			
Part	Volume to cut (mm^3)	Cutting Strategy	Total energy consumption per Volume to cut(kJ/mm^3)
Prismatic A	18799	Follow Part	0.33
		Follow Periphery	0.34
		Zigzag	0.28
Prismatic B	76650	Follow Part	0.28
		Follow Periphery	0.26
		Zigzag	0.22
Prismatic C	86866.15	Follow Part	0.21
		Follow Periphery	0.20
		Zigzag	0.17
Sculpture	150000	Follow Part	0.33
		Follow Periphery	0.33
		Zigzag	0.33
Average			0.27

We compare the macro and micro milling processes by the Total energy consumption/volume-cut (kJ/mm^3). In other words, we compare how much energy spent to cut a 1 mm^3 in micro and macro milling for roughing process. Table.6 and Table.7 show the average of total energy consumption/volume-cut of micro milling and macro milling. Both tables show that macro milling has lower energy consumption/volume-cut than micro milling. We can see from Table.5 that macro milling have larger total energy consumption rather than micro milling but if we compare from the specific energy consumption of micro milling and macro milling that to produce a part with same shape with a different volume ratio of 1 to 1000, the specific energy consumption of macro milling is less than micro milling for each of the machine tool characteristics mentioned above.

4 Conclusion

This paper has calculated roughing processes energy consumption in micro milling and compare the effectiveness of energy consumption between roughing process in macro milling and micro milling. The findings include the following:

- From three cutting strategies, follow periphery has the least energy consumption among them with specified cutting parameters.
- With the machine tool specification used in this research, macro milling is more effective in the using of energy than micro milling, in terms of total energy consumption/total volume-cut.

In the end, we should take the selection of cutting strategy into our consideration to get the most effective energy consumption in micro milling process to achieve green manufacturing.

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