Cutting Path-associated Energy Consumption of Milling Machining Process

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Abstract. Manufacturing industries face numerous challenges, such as reducing their energy consumption. Minimising energy usage is one of the initiatives towards sustainable manufacturing. Many researches have studied the surface quality of machined part, but studies on energy consumption during machining process are limited. Different cutting paths operations may influence energy consumption during machining. The objective of this research was to investigate the effect of cutting tool paths and parameters on energy consumption during machining. Aluminium 6061 alloy was face-milled using high-speed steel tool with different tool paths, namely, morphed spiral, parallel and spiral paths. The design of experiment technique was applied to optimise the experimental work, and response surface methodology was used to analyse the experimental result. Results showed that feed rate is the most influential parameter on the energy consumption of machining. Machining energy models were also generated for morphed spiral, parallel and spiral cutting paths. The $R^2$ of each model was higher than 0.92, which indicates that the model equations are applicable in predicting the energy consumption of a milling operation.

1. Introduction

All machines consume energy and most machines spend large amounts of energy for the production process. In accordance with the 2011 Annual Energy Review, 31% of electricity in the United States is consumed by the industrial sector, and manufacturing processes, such as machining, forging and casting use around 90% of electricity in the industrial sector. It was recorded that 33% of energy in Malaysia (29,838 ktoe) was applied in the industrial sector in 2015, which is the second largest consumption after transportation [1].

Contributions to reducing energy in manufacturing and promoting sustainable machining in the aspect of pollution prevention can come from better use of energy in machining operations. Reduction of material extraction requirements for energy generation and lower environmental impact can be obtained from lower energy consumption during machining [2,3]. Carbon monoxide which pollutes...
the environment leaves the operation of coal-fired power plants. The machine tool life cycle assessment shows that high energy consumption takes place during machine use and raw material extraction [4]. High level of energy consumption throughout use of machine tools takes place during machining activity, such as cutting metal or moving material. Decreasing the energy during machining will raise the machine tools’ energy efficiency thereby increasing profits and reducing operating costs [5].

Many elements of machining, such as material type, cutting parameters, and cutting strategy, need to be treated for energy reduction. Spindle speed, feed speed, and cutting depth, as cutting parameters, can affect energy use and should be optimized to reduce energy consumption [6, 7, 8]. The process and features of machine tools can influence the energy efficiency of machine tools [9, 10, 11]. Present research recognized that the relationship is nonlinear between energy and material transfer rate (MRR) while MRR depends on the configuration of cutting parameters as denoted in Equations (1) and (2). The equal MRR can be generated from various sets of cutting parameters and will display levels of energy consumption [12]. Increasing the energy efficiency of machine tools is helped by awareness of the interaction between cutting conditions and machining energy. The optimization model proposed by Wang H. et al. is based on the energy calculation method using the work steps in STEP-NC. The comprehensive machining scheme becomes the resulting solution for low energy demand to solve optimization problems and increase efficiency by 25% [13]. The investigations of Hu L. et al. on the feed rate and the effect of spindle rotation on the consumption of energy of the turning process and construct the excellent solution for the reduction of machining energy by 19.2% [14]. Rahman, H. A. et al. linked consumption of energy build upon the design of experiment (DOE) method with milling cutting parameters and produced the model in Equation (3), which has an accuracy of 98% [15].

\[
\text{Energy (Joule)} = SEC \times Q
\]

(1)

where;

\( Q = \text{Total material removal (mm}^3) \)

\( SEC = \text{Specific energy consumption (J/ mm}^3) \)

and,

\[ SEC = \frac{P}{MRR} \]

(2)

where;

\( MRR = \text{Material Removal Rate (cm}^3/ \text{min}) \)

\( P = \text{Power (kW)} \)

\( SEC = \text{Specific energy consumption (J/ mm}^3) \)

End mill slot milling energy,

\[
\text{Energy (J)} = 588800 + 0.42N - 52.3V_f - 5256d + 0.000065N^2 + 0.01223V_f^2 + 2656d^2 - 0.000362NV_f - 0.532Nd + 1.16V_fd
\]

(3)

where;

\( d = \text{Depth of cut (mm)} \)

\( N = \text{Spindle speed (RPM)} \)

\( V_f = \text{Feed rate (mm/min)} \)

The milling process has different types of cutting tool paths include spiral, zigzag, morphed spiral and parallel paths. The spiral, morphed spiral and parallel cutting paths as shown in Figure 1. The paths may have different energy usage because of the different paths and directions that the tool travels in.
The response surface methodology (RSM) is a method that establishes the set of design factors to increase the response or performance of a process. This method is broadly applied in specific circumstances where several input variables have the potential to affect performance measures or quality characteristics of a process. Because it has important applications in the design, development, and formulation of new products and in improving the design of existing products, RSM has become the most popular optimization method. The input variable used is the independent variable and the dependent variable is the output or RSM performance measure. Response surface methodology consists of experimental strategies to delve into independent variables or process spaces. Response surface methodology can produce empirical statistical modeling to build the right approach relationship between output and input variables. This RSM procedure can be applied to find the optimization of the input variables to develop the intended output response value. The results of the analysis can be depicted as a curve plot or 3D axis graph which can help optically interpret the synergy of each output and input response variable [16]. In this study, milling parameters such as feed rate, depth of cut, and spindle speed were employed as input variables, and the output response was the energy consumed for each cutting path. Response surface methodology is used to design experiments, analyze output (energy), and create models of machining energy conforming to specific tool paths.

2. Methodology

Four flutes and a 10 mm diameter high-speed steel (HSS) end mill was used to cut Aluminium 6061. Various cutting parameters, namely, feed rate, depth of cut, and spindle speed, was used to cut the flat surface of the aluminium block. Table 1 lists the values of the cutting parameters.

| Factors                | Level          |
|------------------------|----------------|
| Feed rate, f (mm/min)  | 550 – 1000     |
| Depth of cut, d (mm)   | 0.5 – 1        |
| Spindle speed, N(rpm)  | 1000 – 3000    |

Table 1. Selected levels and variable parameters

To optimize the experimental setup of machining operations, the DOE approach is used via RSM. As shown by Table 2, a list of 20 experimental works consisting of the various arrangements made by RSM for milling operations. These setting parameters were used to cut the Al 6061 using morphed spiral, spiral and parallel cutting paths. The machining time during each experiment was documented while power consumption was calculated using a Fluke 345 PQ clamp meter.
Table 2. List of experimental cutting parameter for parallel, spiral and morphed spirally cutting paths.

| Number of experiment | Depth of cut (d) mm | Spindle speed (N) rpm | Feed rate ($V_f$) mm/min |
|----------------------|---------------------|-----------------------|--------------------------|
| 1                    | 0.75                | 2000                  | 550                      |
| 2                    | 0.50                | 1000                  | 1000                     |
| 3                    | 1.00                | 2000                  | 775                      |
| 4                    | 0.75                | 2000                  | 775                      |
| 5                    | 0.75                | 2000                  | 775                      |
| 6                    | 1.00                | 1000                  | 550                      |
| 7                    | 0.50                | 1000                  | 550                      |
| 8                    | 0.75                | 2000                  | 775                      |
| 9                    | 0.50                | 2000                  | 775                      |
| 10                   | 1.00                | 3000                  | 1000                     |
| 11                   | 1.00                | 1000                  | 1000                     |
| 12                   | 0.75                | 2000                  | 1000                     |
| 13                   | 0.75                | 2000                  | 775                      |
| 14                   | 0.75                | 3000                  | 775                      |
| 15                   | 1.00                | 3000                  | 550                      |
| 16                   | 0.75                | 2000                  | 775                      |
| 17                   | 0.75                | 1000                  | 775                      |
| 18                   | 0.75                | 2000                  | 775                      |
| 19                   | 0.50                | 3000                  | 1000                     |
| 20                   | 0.50                | 3000                  | 550                      |

3. Results and Discussions

The machining energy, machining time and machining power spent throughout machining for parallel, spiral and morphed spiral cutting paths are arranged in Table 3. The data were picturized by RSM using a 3D surface plot as displayed in Figures 2, 3 and 4 for parallel, spiral and morphed spiral cutting paths.

Table 3. The result of experimental cutting parameter

| Cutting Parameter | Spindle speed (N) rpm | Feed rate ($V_f$) mm/min | Depth of cut (d) mm | Machining time (s) | Power (kW) | Energy (kJ) | Machining time (s) | Power (kW) | Energy (kJ) | Machining time (s) | Power (kW) | Energy (kJ) |
|-------------------|-----------------------|--------------------------|---------------------|--------------------|-------------|-------------|--------------------|-------------|-------------|--------------------|-------------|-------------|
| Morph Parallel Spiral |

2000 | 550 | 0.75 | 107 | 5.46 | 583.71 | 68 | 5.54 | 376.44 | 67 | 5.23 | 350.56 |
1000 | 1000 | 0.5 | 61 | 5.43 | 331.47 | 38 | 5.58 | 212.21 | 36 | 5.60 | 201.74 |
2000 | 775 | 1 | 76 | 5.41 | 411.08 | 49 | 5.67 | 277.91 | 49 | 5.60 | 274.32 |
2000 | 775 | 0.75 | 79 | 5.39 | 426.06 | 49 | 5.56 | 272.36 | 51 | 5.47 | 278.87 |
2000 | 775 | 0.75 | 75 | 5.46 | 409.79 | 49 | 5.24 | 256.74 | 45 | 5.42 | 243.93 |
1000 | 550 | 1 | 105 | 5.53 | 581.00 | 69 | 5.67 | 391.38 | 52 | 5.47 | 284.38 |
1000 | 550 | 0.5 | 105 | 5.55 | 582.31 | 73 | 5.54 | 404.72 | 65 | 5.38 | 349.63 |
2000 | 775 | 0.75 | 75 | 5.54 | 415.68 | 49 | 5.32 | 260.72 | 54 | 5.38 | 290.58 |
2000 | 775 | 0.75 | 77 | 5.51 | 424.11 | 50 | 5.14 | 256.75 | 56 | 5.72 | 320.52 |
3000 | 1000 | 1 | 58 | 5.54 | 321.36 | 39 | 5.45 | 212.56 | 46 | 5.60 | 257.76 |
1000 | 1000 | 1 | 57 | 5.62 | 320.42 | 39 | 5.50 | 214.65 | 46 | 5.39 | 247.97 |
2000 | 1000 | 0.75 | 58 | 5.57 | 322.85 | 39 | 5.52 | 215.15 | 39 | 5.40 | 210.72 |
2000 | 775 | 0.75 | 75 | 5.57 | 417.41 | 49 | 5.56 | 272.40 | 56 | 5.26 | 294.61 |
3000 | 775 | 0.75 | 75 | 5.57 | 418.06 | 50 | 5.39 | 269.52 | 55 | 5.30 | 291.30 |
3000 | 550 | 1 | 105 | 5.50 | 577.02 | 69 | 5.39 | 371.77 | 69 | 5.19 | 357.88 |
2000 | 775 | 0.75 | 75 | 5.62 | 421.19 | 49 | 5.59 | 273.88 | 48 | 5.33 | 255.85 |
1000 | 775 | 0.75 | 74 | 5.49 | 406.25 | 50 | 5.54 | 277.20 | 51 | 5.37 | 274.08 |
2000 | 775 | 0.75 | 74 | 5.51 | 407.76 | 48 | 5.50 | 263.93 | 51 | 5.41 | 275.68 |
3000 | 1000 | 0.5 | 58 | 5.43 | 314.98 | 38 | 5.49 | 208.65 | 41 | 5.22 | 214.17 |
3000 | 550 | 0.5 | 104 | 5.51 | 572.95 | 69 | 5.44 | 375.35 | 67 | 5.21 | 348.99 |
In consonance with Figure 3 (a), by increasing the spindle speed, machining energy will be marginally reduced but will immediately decline with growing feed rate. From Figure 3 (b) it is shown that escalating the depth of cut linearly will raise the energy consumed. Energy usage during machining is reduced by increasing the feed rate as shown in Figure 3 (c).

Figure 2. 3D surface plot of the interaction between CNC milling parameters and energy usage for the morphed spiral cutting path: (a) feed rate and spindle speed versus energy, (b) feed rate and depth of cut versus energy and (c) spindle speed and depth of cut versus energy.

Figure 4 shows the energy interactions of the spiral cutting path. From Figures 4 (a) and 4 (c), it is shown that the reduction in energy consumed will be obtained from an increase in the feed rate. Figure 4 (b) illustrates the slight change in energy caused by variations in cutting depth and spindle speed.

Figure 5 shows the energy plot for parallel lines. Improving the feed rate as indicated in Figures 5 (a) and 5 (c) diminishes machining energy. As shown in Figure 5 (b), the spindle speed also affects energy consumption, which indicates that an increase in the spindle speed will emanate in a contraction in energy.
Figure 3. 3D surface plot of the interaction between CNC milling parameters and energy usage for the spiral cutting path: (a) feed rate and spindle speed versus energy, (b) feed rate and depth of cut versus energy and (c) spindle speed and depth of cut versus energy.

Figure 4. 3D surface plot of the interaction between CNC milling parameters and energy usage for the parallel cutting path: (a) feed rate and spindle speed versus energy, (b) feed rate and depth of cut versus energy and (c) spindle speed and depth of cut versus energy
Table 4 describes for each cutting path, the ANOVA of machining parameters against consumption of energy. Based on the table, feed rate become the most significant factor for consumption of energy at $P < 0.05$.

RSM generates a mathematical model of the machining energy and is indicated in Equations (4), (5), and (6) for parallel, spiral paths and morphed spiral. Because the three types of cutting paths have $R^2 \geq 0.92$, that is, an accuracy of $\geq 92\%$, then these models are considered to be exact. This value shows that the energy model generated can be utilised as an energy prediction model for milling machine.

For parallel path:

$$E_{\text{Parallel}} = 987381 - 49.7N - 1312V_f - 26030d + 0.00515N^2 + 0.5450V_f^2 - 14041NV_f + 5.6Nd + 51.7V_fd$$

(4)

For spiral path:

$$E_{\text{Spiral}} = 709298 + 14.2N - 312V_f - 634087d - 0.002N^2 + 0.08V_f^2 + 203834d^2 - 0.0281NV_f + 35.7Nd - 325V_fd$$

(5)

For morphed spiral path:

$$E_{\text{Morph}} = 1304319 + 7.6N - 1686V_f - 44861d - 0.00242N^2 + 0.7287V_f^2 + 19235d^2 - 0.00126NV_f + 11.41Nd - 16.5V_fd$$

(6)

where,

- $E_{\text{Spiral}} = $ energy for spiral cutting path (J)
- $E_{\text{Morph}} = $ energy for morphed spiral cutting path (J)
- $E_{\text{Parallel}} = $ energy for parallel cutting path (J)
- $V_f = $ feed rate (mm/min)
- $N = $ spindle speed (RPM)
- $d = $ depth of cut (mm)

| Table 4. ANNOVA analysis of energy consumption for morphed spiral, spiral and parallel cutting paths |
|---------------------------------|-----------------|-----------------|-----------------|
| **P-VALUE** | **SPIRAL** | **PARALLEL** | **MORPH SPIRAL** |
| **SQUARE MODEL** | 0.0906 | 2.50710^{-11} | 0.0050x10^{-10} |
| Depth of Cut (mm) | 0.90 | 7.711x10^{-11} | 0.0005x10^{-10} |
| Feed Rate (mm/min) | 0.0840 | 0.6692 | 0.5064 |
| Spindle Speed (RPM) | 0.9787 | 0.0269 | 0.4495 |
| Feed rate (mm/min) | 0.23210^{-11} | 0.725x10^{-11} | 0.0005x10^{-10} |
| **LINEAR MODEL** | 0.8817 | 0.2048 | 0.6815 |
| Depth of cut (mm) | 0.7610 | 0.3045 | 0.7098 |
| Spindle Speed (RPM) | 0.7051 | 0.0717 | 0.9115 |
| Spindle Speed (RPM) | 0.5390 | 0.6132 | 0.2667 |
4. Conclusion
This paper investigates the consequence of milling parameters toward energy expenditure. The results acquired can further boost energy expenditure throughout machining. Experiments were carried out by cutting Al 6061 utilizing an HSS end mill on a CNC milling machine. The resulting machining energy at the various cutting paths is analyzed by the Response Surface Methodology (RSM). The results of this study concluded that energy is inversely proportional to the feed rate. Machining energy and machining time reduced as a result of a high feed rate. Feed rate become the most significant factor that affects the consumption of energy during milling operation, then the spindle speed and depth of cut stem from the results of the ANOVA. For parallel, spiral paths and morphed spiral cutting paths, the mathematical models for were acquired to foresee the energy of machining during milling operation. The ingrained model has 92% and higher accuracy. Depth of cut is comparable to energy consumption. Expanding the depth of cut will raise energy consumption. This case, when cutting in a high-depth framework, may develop because of the higer load or cutting force needed.

5. References
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