Modelling and Verification of Energy Consumption in CNC Milling

A. Shokrani, V. Dhokia and S.T. Newman

Abstract Electrical energy consumption forms 99 % of the environmental impact of machining operations. Whilst replacing existing machineries for more energy efficient ones does not deem possible in short term, process planning for machining with energy consumption in mind is a more accessible solution. The effect of cutting parameters on power consumption in CNC milling of 6082 T6 aluminum alloy was investigated in this paper. Mathematical models were developed to estimate the energy and power consumption in CNC milling machines. The analysis indicated that the two less studied parameters of axial and radial depth of cut have significant impact on the total energy consumption of machining processes. Increased axial and radial depth of cut not only increase material removal rate but also increase the portion of machine tool's power consumption dedicated to material cutting. This study indicated that 82 % reduction in energy consumption can be achieved through precise selection of cutting parameters.

Keywords Energy consumption · CNC machining · Milling · Power consumption · Aluminum

1 Introduction

Manufacturing is responsible for 25 % of the global energy consumption [1]. Knowing that a significant portion of the electricity is generated using fossil fuels such as oil and coal, manufacturing and in particular machining are responsible for the generation of a large portion of CO_2, NO_2, SO_2 and other pollutants [2]. It has

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R. Setchi et al. (eds.), *Sustainable Design and Manufacturing 2016*,
Smart Innovation, Systems and Technologies 52,
DOI 10.1007/978-3-319-32098-4_11

been reported that electrical energy consumption is responsible for 99 % of the environmental impacts of machining operations.

Kant and Sangwan [3] defined sustainable machining processes as using the minimum power consumption. Time is directly related to energy consumption as shown in Eq. 1; therefore this notion of sustainability implies that all machining operations will be more energy efficient if the power requirements for all components are reduced. Also, faster tool path designs will generally result in lower energy consumption. Faster tool paths are also consistent with a better surface finish [4]. Energy efficiency is defined by the lowest energy consumption, which is not necessarily correspondent to the lowest power consumption.

$$E = \int_{t_0}^{t} P dt \tag{1}$$

where E is energy in J, P is power in W and t is time in s.

There have been many attempts to formulize a mathematical model for estimating energy consumption for different manufacturing techniques [5–7]. Some derived models produce large degrees of inaccuracy, up to two orders of magnitude, whereas others include so many coefficients requiring such extensive empirical results, that often quantifying power consumption specifically is easier than modelling. Li and Kara [8] studied cutting speed, feed rate and axial depth of cut and developed an empirical model relating the specific energy consumption to material removal rate as shown in Eq. 2.

$$SEC = C_0 + \frac{C_1}{MRR} \tag{2}$$

where SEC is specific energy consumption, C_0 is the coefficient of the inverse model and C_1 is the coefficient of the predictor.

A great deal of studies has been conducted on modelling of the cutting forces and power demand at the tool tip dealing with science of machining [6]. These models have shown that there is a relationship between the energy required for machining and the workpiece material properties and cutting parameters [9]. The specific cutting energy of various materials are used to model the energy demand at the cutting tool tip [10]. The specific cutting energy defines the amount of energy required for machining a unit volume of material. However, these material specific models do not consider the amount of energy which is required for running a machine tool. The studies by Aramcharon and Metivenga [4] and Gutowski et al. [11] indicated that the machine tools' idle energy consumption is a single significant factor affecting the total machining energy consumption. Therefore, they recommended reducing the none material cutting time during machining and optimizing the machine tools to minimize their power consumption when running idle [12].

This paper investigates the effects of cutting parameters on energy and power consumption in end milling of 6082 T6 aluminium alloy. Four major cutting parameters in milling operations namely, cutting speed, feed rate, axial depth of cut and radial depth of cut in machining are studied in this paper.

2 Methodology

In order to assess the effect of each machining parameter on the total energy consumption, four input parameters of cutting speed, feed rate, axial depth of cut and radial depth of cut were identified. A TiB_2 coated solid carbide end mill with 12 mm diameter and 2 flutes was used for each machining experiment. The workpiece used for each experiment was a block of 6061 T6 aluminum with the dimension of 150 × 50 × 50 mm as shown in Fig. 1.

In order to include the interactions between parameters, a full factorial design of experiments (DoE) was developed based on 2 levels of cutting speed and feed rate and 3 levels of axial depth of cut and radial depth of cut. Further emphasis was put on the axial and radial depth of cut as these are the least studied parameters in machining. The three levels of the axial depth of cut correspond to 0.5D, D and 1.5D, where D is the cutting tool diameter. For the radial depth of cut, 30 % (3.6 mm), 45 % (5.4 mm) and 60 % (7.2 mm) cutting tool engagement were used. The DoE used for this investigation consisted of 36 machining experiments as shown in Table 1.

The machining experiments were side end milling in order to remove an 18 mm depth of material from the top surface of the aluminum blocks as shown with hatched lines in Fig. 1. This would allow for identical comparison of machined volume of material between experiments. The machining strategy was climb milling using unidirectional tool paths along the length of the workpiece starting the feed move 10 mm before the workpiece material continuing 10 mm after. Rapid

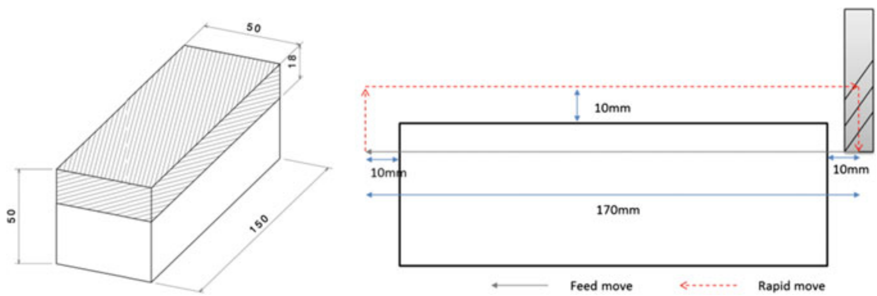

Fig. 1 Illustration of the workpiece used for the machining experiments with hatched machining volume (*right*) and the machining process plan

Table 1 DoE for machining experiments

Exp	a_e (%)	a_p (mm)	f (mm/tooth)	v (m/min)	Exp	a_e (%)	a_p (mm)	f (mm/tooth)	v (m/min)
1	60	18	0.08	70	19	30	9	0.09	70
2	60	18	0.08	90	20	30	9	0.09	90
3	60	18	0.09	70	21	30	6	0.08	70
4	60	18	0.09	90	22	30	6	0.08	90
5	60	9	0.08	70	23	30	6	0.09	70
6	60	9	0.08	90	24	30	6	0.09	90
7	60	9	0.09	70	25	45	18	0.08	70
8	60	9	0.09	90	26	45	18	0.08	90
9	60	6	0.08	70	27	45	18	0.09	70
10	60	6	0.08	90	28	45	18	0.09	90
11	60	6	0.09	70	29	45	9	0.08	70
12	60	6	0.09	90	30	45	9	0.08	90
13	30	18	0.08	70	31	45	9	0.09	70
14	30	18	0.08	90	32	45	9	0.09	90
15	30	18	0.09	70	33	45	6	0.08	70
16	30	18	0.09	90	34	45	6	0.08	90
17	30	9	0.08	70	35	45	6	0.09	70
18	30	9	0.08	90	36	45	6	0.09	90

moves were used for all none material cutting movements. The details of the machining process plan are shown in Fig. 1.

A Bridgeport VMC 610 vertical CNC milling center was used to conduct the machining experiments. The machine tool was equipped with a Hioki Clamp-on Tester power demand analyzer with a sampling rate of 1 s. The power consumption of the machine tool was monitored for the duration of the machining experiment. The energy consumption of the machine tool was calculated from the power consumption using Eq. 1. In order to eliminate the effects of coolant pump on the power consumption, a minimum quantity lubrication system with vegetable oil at the rate of 70 ml/h at 6 bar pressure was used.

3 Results

After machining experiments, the data for power consumption was collected for each experiment. Figure 2 illustrates the power consumption graph for experiment 1 and indicates the critical points for power consumption of idle, rapid move and feed without material cutting and with material cutting. Since the radial width of cut for experiment 1 was 60 % (7.2 mm) and the depth of cut was 18 mm, only 7

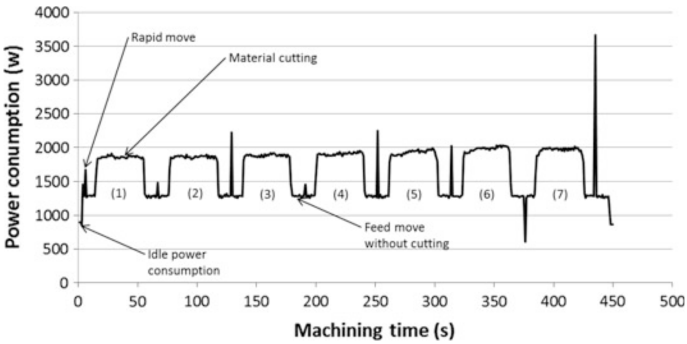

Fig. 2 Power consumption graph for experiment 1

machining paths were required in order to achieve the objective of the experiment (machining 18 mm depth of workpiece) as shown in Fig. 2.

By definition, the area below the power consumption represents the total energy consumption of the machining process including none material cutting moves inherent to machining. Using Eq. 1, the energy consumption of the machining process for each experiment was calculated and illustrated in Fig. 3.

The power consumption of the none material cutting moves were removed from the data for power consumption and the average power consumption for cutting material was also calculated. The results of the average power consumption for material cutting are shown in Fig. 3.

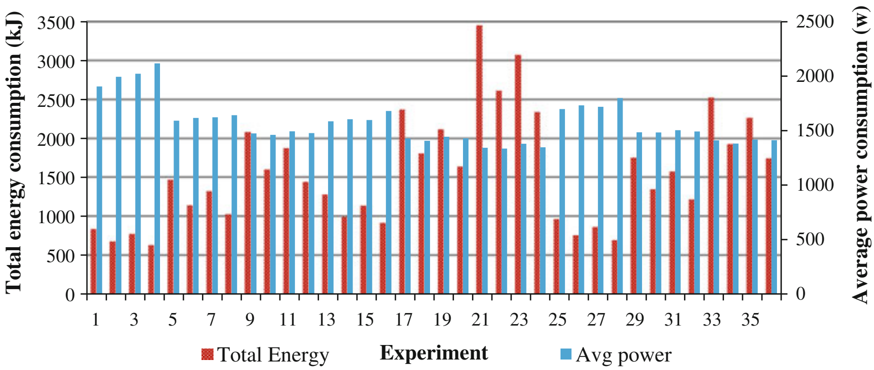

Fig. 3 Energy consumption and power consumption graphs of the experiments

4 Analysis and Discussion

The main effect plot and interaction plots were generated for the data presented in the results section. As shown in Fig. 4, the analysis indicated that increased productivity through adoption of higher levels of feed rate, cutting speed and axial and radial depth of cut reduces the energy required for machining a part. This is in agreement with previous studies stating that enhanced material removal rate reduces the energy consumption. Analysis of the results indicated that about 890 W power is required to run the machine tool. This equates to 42–66 % of the total power consumption of the machine tool for cutting material based on the parameters used in this study. Referring to Eq. 1, reducing the machining time through increased material removal rate can significantly decrease the total energy consumption.

The analysis of the energy consumption results indicated that there is no significant interaction between the input parameters within the studied range. Furthermore, they indicated that almost 82 % reduction in energy consumption can be achieved by precise selection of the cutting parameters.

As shown in Fig. 5, all cutting parameters have significant effect on power consumption whilst no significant interaction was found between the parameters. Axial and radial depth of cut were identified to be more significant in this study. As opposed to the energy consumption, power consumption can only be reduced by 37 %. This can be explained by the fact that a significant portion of the power consumption is used for running the machine tool which is not affected by the cutting parameters. Moreover, the effect of cutting speed and feed rate is more significant on the machining time and therefore energy consumption than on the power consumption.

In addition to the power consumption of the machine tool when cutting material, the power consumption when a material is not being cut was also measured. Deducting 890 W power consumption of the machine tool in idle mode, this would highlight the power consumption for running the spindle and servos at given feed rates and cutting speeds. Figure 6 illustrates the percentage of power consumption dedicated to cutting material for each machining experiment as compared to the

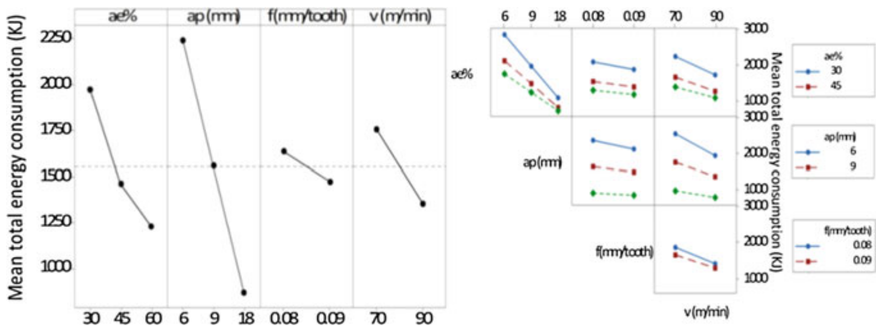

Fig. 4 Main effect plot (*left*) and interaction plot (*right*) for total energy consumption

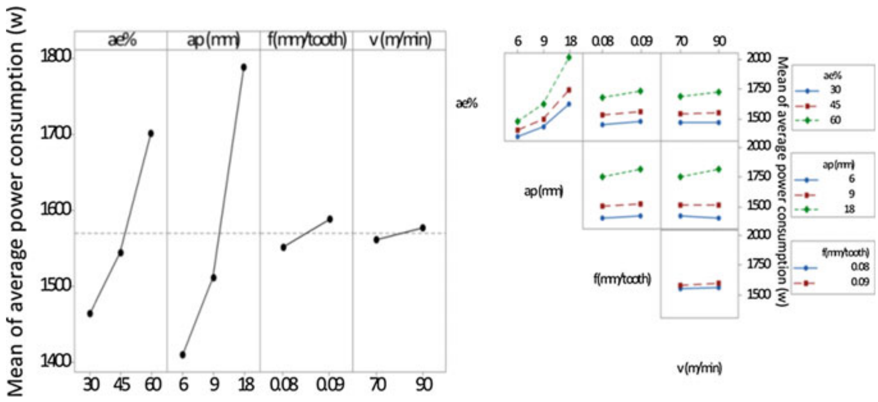

Fig. 5 Main effect plot (*left*) and interaction plot (*right*) for power consumption

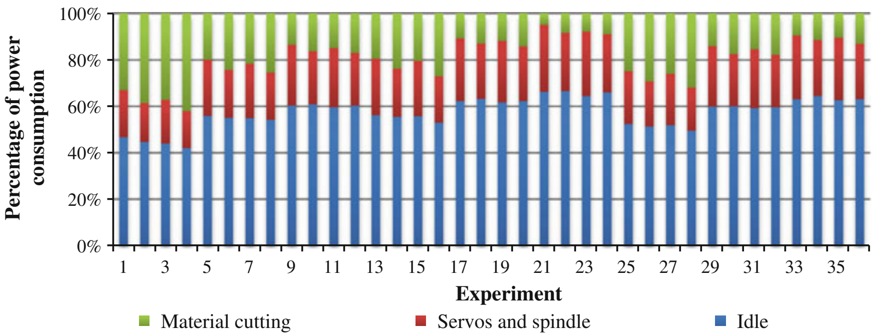

Fig. 6 Comparison between power consumption for material cutting, running servos and spindle and machine tool's idle state

power used for running the machine tool in idle mode and servos and spindle. This graph shows that a very small portion of the power consumed by the machine tool is used for cutting material. Compiling this data indicated that, depending on the cutting parameters, only 4.9–42.1 % of the machine tool's power consumption is used for cutting material.

Figure 7 demonstrates the relative power consumption for cutting at worst case scenario in experiment 21 where all input parameters are minimum. Moreover, the best case scenario is attributed to the experiment 4 where all input parameters are at maximum level. As shown in Fig. 7, on average, only 19.3 % of the total power consumption is used for material cutting whilst 57.5 % is used for running the machine tool.

Analyzing the power consumption indicates that higher levels of cutting parameters are more desirable in order to maximize the percentage of the power dedicated to material cutting. As shown in Fig. 8, higher cutting loads through

Fig. 7 Dynamic breakdown of the power consumption by Bridgeport VMC 610 based on the results

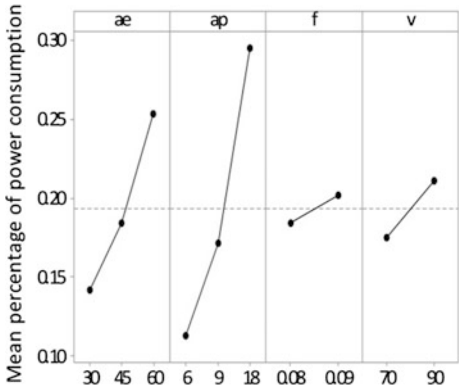

Fig. 8 Main effect diagram of percentage of power consumption used for material cutting

employing larger depth of cut and cutting speed increases the contribution of material cutting into the machine tool's power consumption. This is in agreement with the analysis for energy consumption and indicates that machining time is not the only major factor for selecting higher levels of material removal rates.

Material removal rate (MRR) was calculated using Eq. 3 for each experiment.

$$MRR = \frac{1000\, n\, a_p\, a_e\, v f}{D\pi} \quad (3)$$

where MRR is material removal rate in mm^3/min, D is cutting tool diameter in mm, n is number of teeth, a_p is axial depth of cut in mm, a_e is radial depth of cut in mm, v is cutting speed in m/min and f is feed rate in mm/tooth.

As shown in Fig. 9, the average power consumption is in an almost linear relation with MRR. On the other hand, total energy consumption is in an inverse relation with MRR. Therefore, regression analysis was performed in order to

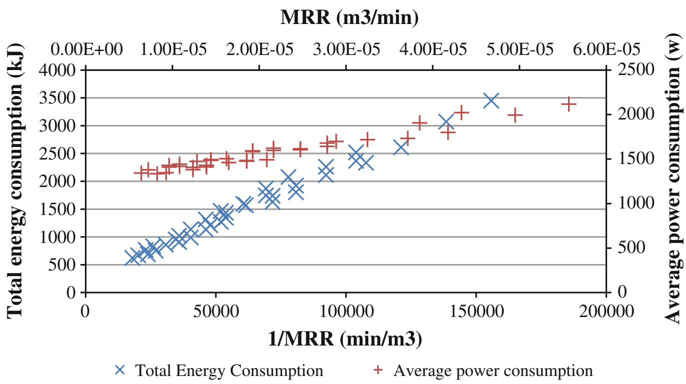

Fig. 9 Total energy consumption and average power consumption graphs versus MRR

develop a mathematical model for each parameter in order to estimate the values based on MRR.

Equations 4 and 5 illustrate the regression models for total energy consumption and average power consumption.

$$E_t = 270.6 + \frac{0.02043}{MRR} \quad (4)$$

$$P_a = 1237 + 15536354\, MRR \quad (5)$$

where E_t is total energy consumption and P_a is average power consumption.

Analysis of variance for the generated models indicated that the models are capable of estimating experimental values to a very high accuracy. As shown in Table 2, the model for total energy consumption explains about 98 % of the variation in energy consumption. Similarly, the model for average power consumption fits 95 % of the experimental data. The regression model for total energy

Table 2 Analysis of variance for the regression models of total energy consumption and average power consumption

Total energy consumption					
Source	DF	SS	MS	F	P
Regression	1	17131486	17131486	2181.23	0.000
Error	34	267037	7854		
Total	35	17398523			
R^2 = 98.5 % adjusted R^2 = 98.4 %					
Average power consumption					
Source	DF	SS	MS	F	P
Regression	1	1316115	1316115	661.32	0.000
Error	34	67664	1990		
Total	35	1383779			
R^2 = 95.1 % adjusted R^2 = 95.0 %					

consumption is similar to the model suggested by [6]. However, they did not identify the linear relation between average power consumption and MRR. Dividing the E_t would provide an estimation for specific energy consumption for the Bridgeport VMC 610xp machine tool.

Equation 3 for MRR can be incorporated into the mathematical models in Eqs. 4 and 5. Following suggestions by Li and Kara [8] and substituting the models' coefficients with generic machine tool dependent variables result in a milling specific model relating cutting parameters and cutting tool diameter to total energy consumption and average power consumption.

$$E_t = C_0 + \frac{C_1 D\pi}{1000 n a_p a_e v f} \tag{6}$$

$$P_a = C_2 + C_3 \frac{1000\, n\, a_p\, a_e\, v f}{\mathrm{D}\pi} \tag{7}$$

The investigations by Li and Kara [8] together with the investigations presented in this paper has shown that the coefficients of the models in Eqs. 6 and 7, namely C_0, C_1, C_2 and C_3 are machine tool dependent variables. These coefficients can be used for assessing the environmental performance of various machine tools and can be supplied by the manufacturers for energy labeling of the machine tools.

5 Conclusions

A series of machining experiments were conducted to investigate the effect of cutting parameters on power and energy consumption. A systematic methodology was developed using a full factorial design of experiments using four input parameters of cutting speed, feed rate, axial depth of cut and radial depth of cut. The analysis of the results showed that minimizing machining time by employing higher material removal rate is desirable for reducing total energy consumption. However, the investigations indicated that machining time is not the only factor for improving machining efficiency. The amount of power used for cutting material forms a limited portion of the total machining power consumption as opposed to the power required for running the machine tool without cutting material. Therefore, increasing the percentage of the power used for cutting can increase the efficiency of machining. It has been identified that by precise selection of cutting parameters, 82 % reduction in total energy consumption can be achieved.

Mathematical equations were developed which can accurately estimate the total energy consumption and average power consumption of a CNC milling machine tools. The coefficients of these models can be used for assessing and rating the energy performance of machine tools.

Furthermore, the data collected for this experiment will be used for developing and validating a mathematical model representing all cutting parameters involved in milling operations. This model will provide a guideline for energy efficient process planning in CNC milling.

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