Sustainable manufacturing by calculating the energy demand during turning of AISI 1045 steel

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Abstract. Sustainable development will become important issues for many fields, including production, industry, and manufacturing. In order to achieve sustainable development, industry should be able to perform of sustainable production processes and environmentally friendly. Therefore, there is need to minimize the energy demand in the machining process. This paper presents a calculation method of energy consumption in the machining process, especially turning process which calculated by summing the number of energy consumption, such as the electric energy consumed during the machining preparation, the electrical energy during the cutting processes, and the electrical energy to produce a cutting tool. A case study was performed on dry turning of mild carbon steel using coated carbide. This approach can be used to determine the total amount of electrical energy consumed in the specific machining process. It concluded that the energy consumption will be an increase for using the high cutting speed as well as for the feed rate was increased.

1. Introduction

Production sustainability has become an important issue in the manufacturing sector. In the literature, it mentioned that sustainable development should include the three pillars, i.e. economic, social and environmental factors. Therefore, the manufacturers should be able to produce products through using sustainable of processes. One way to achieve environmentally sustainable production is to reduce energy consumption in the manufacturing. Sustainable production is a solution to overcome the problem of energy demand and higher costs. This applies in the field of engineering, including machining processes [1]. One important consideration is reducing the energy demand in the sustainable production [2-3]. One of consideration is the reduction in the sustainable production of energy consumption. Machining is an integral part of the production. The reduction of energy consumption in the machine will contribute to the reduction of energy consumption for producing one piece. A prerequisite to targeting the reduction of energy in the process of machining is the ability to determine the total energy used during engine operation. Identification of energy use in the machining process can be done by studying certain machining process in detail [4].

Previous works on identifying and lowering the calculation of the total energy consumption in the machining process have been observed by [3] and [5]. Reference [6] states that specific variations in energy reduction as a function of the different workpiece material, it can provide useful information that
allows estimating machining characteristics for the selected workpiece. Reference [7] suggest the model calculations by classifying the energy consumption of the machine tool into constant power consumption, power consumption in a state of walking to calculate the use of spindle and servo motors, and power consumption for a job position as well as to speed up/slow down the shaft with the specified speed. Reference [8] observed that the total energy consumption can be divided into two parts: the constant energy and the variable energy related to the cutting power.

2. Calculating The Energy Demand

The energy consumed in turning operations can be measured using the power meter which measuring the voltage, the current, the power and energy consumption. Besides, the total energy consumption ($E$) can be calculated using a modeled equation which developed by [9], as the following equation:

$$E = E_1 + E_2 + E_3 + E_4$$

(1)

The energy consumed during the setup operation as $E_1$, during the cutting process as $E_2$, for changing a tool as $E_3$, and for producing cutting tools as $E_4$. In this paper, the energy was used in the calculation of energy consumption during the process of cutting, namely $E_1$ and $E_2$. Thus, equation (1) can be modified as below:

$$E = E_1 + E_2$$

(2)

$E_1$ is the energy that used to set up the machine and can be calculated from the amount of power used during setup time, as shown in the equation:

$$E_1 = P_0 \cdot t_1$$

(3)

where $P_0$ is the power used by the machine module [W]. The motor-driven of lathe machine can be assumed to utilize 20% of maximum power in unloaded condition [10]. Thus, $P_0 = 20\%$ of maximum power on the lathe machine. $t_1$ is the time required to set up the machine [s].

$E_2$ is the energy that used during machining and can be calculated by the amount of power the engine module for the removal of material and energy, as proposed by [11] in the equation below.

$$E_2 = (P_0 + k \cdot \dot{V}_S) \cdot t_2$$

(4)

where $k$ is the specific cutting energy [Ws/mm$^3$], $\dot{V}_S$ is the rate of material removal [mm$^3$/s] and $t_2$ is the time used for the cutting process [s]. The value of energy specific was referred to [12] as shown in table 1. The rate of material removal can be calculated as follows:

$$\dot{V}_S = V_c \cdot f \cdot a_p$$

(5)

### Table 1. The energy specific for cutting (K).

| Material                  | Value of $k$ [Ws/mm$^3$] |
|---------------------------|---------------------------|
| Aluminum alloy            | 0.4 – 1.0                 |
| Cast iron                 | 1.1 – 5.4                 |
| Copper-iron               | 1.4 – 3.2                 |
| High-temperature alloy    | 3.2 – 8.0                 |
| Magnesium alloy           | 0.3 – 0.6                 |
| Nickel alloy              | 4.8 – 6.7                 |
| Refractory alloy          | 3 – 9                     |
| Stainless steel           | 2 – 5                     |
| Steels                    | 2 – 9                     |
| Titanium alloy            | 2 – 5                     |

The cutting time ($t_2$) can be calculated by the formula:
\[ t_2 = \frac{\pi D_{\text{avg}} l}{f \cdot V_c} \]  

(6)

where \( D_{\text{avg}} \) is the average diameter of the workpiece (mm), where \( D_i \) (initial diameter, mm) and \( D_f \) (final diameter, mm), \( l \) is the length cutting (mm), \( f \) is the rate of feeds (mm/rev) and \( V_c \) is the cutting speed (m/min).

Power consumed can be measured using an electrical measurement such as clamp meter and also can be presented as shown in Fig. 1. There are three type of power consumed, i.e. the standby power, unloading power, and cutting power. The standby power is the power that required to starting the lathe machine including lamps, servos, coolant machine (if required) and others component. The unloading power is the power was consumed to preparing the lathe machine including spindle motor without cutting process. The power consumed is required to cutting the workpiece, namely the cutting power.

![Figure 1. Profile of power consumed.](image)

3. Experimental Design

3.1. Materials and Cutting Tool

In this study, the steel of AISI 1045 with a diameter of 65 mm and length of 500 mm will be used as the workpiece material in the turning process. Detail composition of AISI 1045 and some general properties of AISI 1045 was shown in Tables 2.

| AISI 1045 | C   | Mn  | Si  | Cr | V  | Ni | W  |
|-----------|-----|-----|-----|----|----|----|----|
|           | 0.48| 0.70| 0.30| -  | -  | -  | -  |

The machining test was conducted using the PINDAD lathe machine (8.3 kW of house power and the spindle speed ranges from 100 to 1500 rpm) without fluid. The cutting tool inserts were placed on the tool holder designated as TCLNR 2020K12.

3.2. Experimental Setup
This experiment was performed on PINDAD lathe machine using uncoated carbide tools with cutting speed of 180, 330 and 550 (m/min) and feed rate of 0.105, 0.132, 0.158, 0.184 and 0.205 (mm/rev), while the depth of cut is constant at 1 mm for each test. The machining trials were conducted using ø50 x 300 mm of AISI 1045 steel. Schematic of the experimental setup is shown in Figure 2.

4. Results and Discussion
The total of energy demand is obtained using the equation (3). The measurement data of clamp meter, cutting parameters (cutting speed and feed rate), and others data (MRR, cutting time, setup time) are collected and calculated to determine the energy demand. The experimental results for energy demand for different of cutting speed and feed rate are shown in Figures 3 and 4.
Figures 3 and 4 show that the total energy consumed was decreased for the increase of cutting speed and feed rate. This phenomenon was due to increasing of cutting speed that makes the cutting process will be finished quickly. It is confirmed by Calvanese et al. in their investigation on face milling of aluminum alloy that the minimum energy consumption is linked to the maximal feasible feed rate [13]. Another investigation by Camposeco-Negrete when wet turning of AISI 6061 using carbide inserts to optimize the energy consumption and surface roughness, it summarized that the minimum energy consumption will be obtained at a higher feed rate and lower cutting speed [14]. Another investigation was concluded that the power consumption shows a larger increase with the increasing cutting speed and slightly with the increasing feed. In contrast, the energy consumption decreased for an increase in cutting speed and feed rate, it was affected that higher material removal rate requires more power to turn the spindle motor [15-16]. In addition, the energy consumption needed to be performed the energy storage with the SMES system to control the voltage rise [16]. The study of mild steel have been performed by [17], they were performed turning of mild steel with cutting fluid. The cutting fluid used was bio coolant.

5. Conclusion
This paper presents a method for determining the total of energy consumption in the process of machining, particularly in turning of mild carbon steel without flood condition. The energy consumed during standby, the energy during idle condition, and the energy during the cutting operation. This method in calculating energy consumption during machining has been proven applicable for the particular turning of mild carbon steel. It concluded that the total energy consumption was influenced significantly by cutting speed and feed rate. At higher feed rate can obtain the minimum energy consumption.

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7. References
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