Software Support for Environmentally Benign Mold Making Process and Operations

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Abstract

To face increasing concerns about energy and environmental impact in product manufacturing, effective estimation of the processes' impact is necessary as a way of improvement. In this paper, software support is suggested for the mold making process. We analyzed energy consumption in two major operations in mold making, computer numerically controlled (CNC) milling and electric discharge machining (EDM). Software tools were developed to evaluate possible energy consumption and environmental impact among different process plans. Estimation based on nominal conditions can lead to underestimation due to changing conditions of machining. By the software support, more reliable estimation was achieved with considering various operational parameters and conditions.

Keywords:

Mold Making; CNC Milling; EDM; Energy Consumption; Simulation

1 INTRODUCTION

Molds and dies (molds) are popular mass production tools. With the reversely machined shape of molds, design products can be repetitively produced with high efficiency. For many products including consumer electronics, automobiles, and kitchen tools, molds are main production methods. As design gets more important in market competition, molds of higher precision and quality became a key component in manufacturing design products. As a result, a large market exists in global scale for molds, which are manufactured and consumed with amount of €65B in 2008 [1] and many products are influenced by molds in various aspects of manufacturing technology.

Inflating cost of raw material and increasing concern about environmental impact raised environmental sustainability to one of important criteria for product developers. Resource efficient and environmentally benign manufacturing technology is getting more attention from the product manufacturers. Due to the molds' position in product manufacturing, the environmental impact of mold-making is an important issue both for molds makers and product developers. According to an industrial report, molds are responsible for about 5% of the related products' cost [2]. For a manufacturing method, this is not a small number. On the contrary, this is another fact representing the important position of molds.

Molds are produced by various precision machining processes and actually the biggest buying sector of some precision machine tools: more than 80% of EDM tools are used for molds [3]. Generally, mold making requires various and complex information for processing and many software in industry support molds in various ways, Shape design (CAD), operation planning (CAM), and various analyses (CAE) are supported. Environmental analysis of manufacturing process is also such a complicated work that software support is indispensible for effective measure. However, environmental impact is a new topic for the software developers and their support is not sufficient yet. On the other hand, because molds are manufacturing intensive products, to evaluate the energy consumption and environmental impact of mold making, related process consideration is indispensible.

Life cycle assessment (LCA) is generally accepted as an effective mean to measure environmental impact. However its requirement of the large amount of time, data, and resources are pointed out as a barrier to practical usage [4]. In case of mold making, more emphasis on process analyses is required and various operation conditions need to be considered. While many LCA tools generally use statistic estimation of manufacturing operations, there is a large gap between nominal- and actual process performance in terms of material removal rate and the cycle time. As a result, analysis with existing LCA tools does not provide useful information yet. In this paper, we present a software-based approach to supplement general LCA tools by handling more details of mold making processes on environmental impacts

2 LITERATURE REVIEW

Machine tools consume significant amount of electric power during their use phase, which CECIMO claimed to be the biggest source of environmental impact [5]. Enparantza et al. showed that energy consumption cost takes about 80% of purchase price of a grinding machine according to the life cycle cost (LCC) analysis [6]. Diaz et al. found that about 70% of the total emissions of machine tools result from the use phase [7]. For these, energy consumption analysis attracted many researchers in concern of environmental impact. Munoz et al. analyzed the mechanism of a material removal process and designed an integrated energy consumption model that includes process energy consumption, process rate, and waste-stream flow [8]. Dahmus et al. investigated the energy demand of individual function parts of a machine tool and found that rather than cutting energy, peripheral functions, which include computer, fans and tool change, take considerable part in energy consumption of machine tools [9].

To analyze the energy consumption of machine tools, various manufacturing processes have been analyzed and related models have been suggested. Models for injection molding [10] and casting [11, 12] have been suggested. These models can be applied to the practice with similar statistic analyses thanks to their mass production characteristics. Cutting processes like milling and turning processes also have been analyzed by many researchers. However, these processes are more dynamic in practice and statistic approaches cannot have similar efficacy to mass production technologies, Dietmair et al. introduced a model to predict energy consumption during a machining operation [13].

Software-based simulation tools have also been suggested as an effective ways of estimating energy consumption and resultant green house gas (GHG) emissions. Narita et al. developed an "environmental burden analyzer" with numerical data and showed how each component of CNC machining comprises environmental burden [14]. Heilala et al. focused on the analysis of the environmental impact, automation level and ergonomics of the manufacturing system [15]. They proposed a hybrid method using discrete event simulation and analytic calculation. Shao et al. summarized the procedure of developing virtual simulation tools of machining [16].

3 MOLD MAKING PROCESS

Molds are manufacturing intensive products. According to the research about a progressive die, 37% of its life cycle cost is due to manufacturing and 45% due to maintenance [17]. Because such maintenance is generally carried out by additional machining, it is possible to assume manufacturing activity covers more than 80%. Among various unit processes, CNC milling and EDM play an important role in mold making. According to Peças' work about mold manufacturing time analysis, two processes were found to take almost 80% of total production time as displayed in Figure 1 [18].

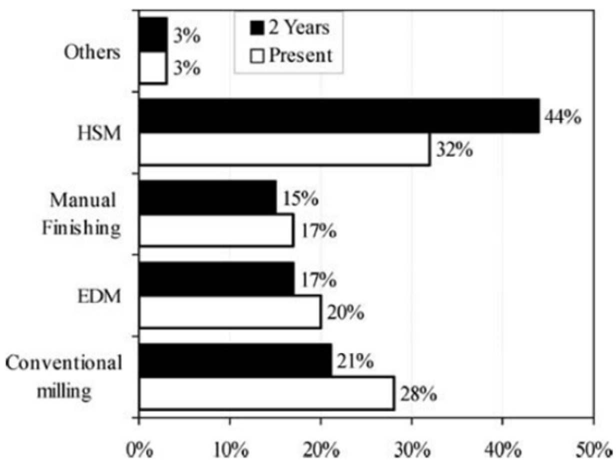

Figure 1: Distribution of production time in mold manufacturing [18].

For its capacity, CNC milling is preferred in machining complex design surfaces with high accuracy. Its computational support for handling huge amount of data makes it possible to address the geometric complexity of fabricated products. Simulation software that utilizes computer graphics and numerical analysis has been successfully used to improve the productivity and quality of milling operations. Early work at Berkeley included Cybercut [19] and this was extended to include basic environmental tradeoffs in follow on work [20].

Electric discharge machining (EDM) is the most popular non-conventional machining technology. EDM removes material from work-piece irrespective of the shape and hardness by the thermal energy caused by the spark between the electrode and work-piece immersed in dielectric fluid. Because there is no physical contact in machining, difficult shapes like a deep slender hole can be fabricated by EDM even with hard material like Titanium alloy. However, MRR for EDM is generally so low that the resultant long cycle time makes the process a bottle neck in process planning. Due to relatively simple motions in EDM, software support for EDM is limited in modelling electrodes and verifying positional error in machining rather than analysis of operation performance.

These two processes are especially popular in manufacturing plastic mold products, where complex design shapes and slender ribs and holes are generally required. While there is the case where the other processes play an important role such as the case of CNC grinding in glossy surface machining, processes with milling and EDM can explain much about mold making process without losing generality. Hence we focused on these two processes in this work.

4 MOLD MAKING EVALUATION

Computer based simulation is generally used in manufacturing processes to manage huge amount of manufacturing information and various computation. From cutting quality confirmation to tool collision detection, many issues are tested and fixed with software tools to avoid the problems before execution. The environmental sustainability and energy efficiency are new issues in conventional manufacturing. The intangibility and complexity of the environmental impact make it hard for engineers to take new criteria in the manufacturing planning. However such difficulty explains why software support is important regarding the issues. Incorporating environmental impact or sustainability concerns into existing simulation coverage is required to improving related manufacturing processes and addressing the increasing demand for sustainable product development.

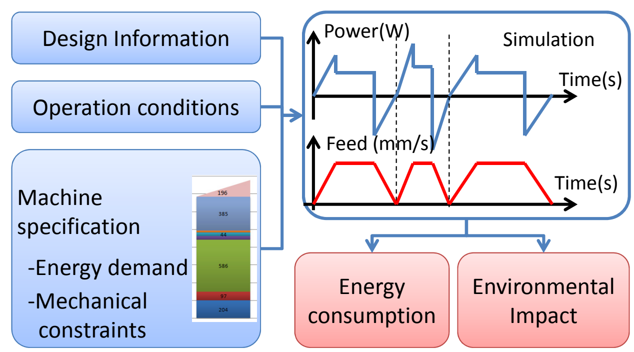

Figure 2: Information flow for process sustainability analysis.

Figure 2 shows the information flow for the process simulation in this work. Design information, operating conditions, and machine tool specifications are three input data and energy consumption and environmental impact are output. Based on the related machine characteristics, different contents and logics will be put to the corresponding data segments: in case of milling, tool paths and the cutting tool geometry would be the part of design information. With this information, the process is simulated and analyzed to estimate resultant energy consumption and environmental impact. Overall impact of mold making process can be evaluated by gathering analyzed results of all the sub-processes.

A software tool was implemented on the basis of Esprit CAM™ and its API. Table 1 shows such information available within Esprit CAM. Because Esprit CAM™ supports the milling process from tool path design to verification, many functions are available for the process analysis. Hence, more integrated analysis can be implemented with the information flow in Figure 2. On the other hand, Esprit CAM™ doesn't support EDM. (This paper handles die-sinking EDM. This is the different type from wire-EDM which is supported by Esprit CAM™.) Considering this, we used the pocket feature for the milling process instead. Because EDM is generally used for machining deep cavities and the pocket feature can provide useful geometric information for the cavities, this can be a good alternative.

	Process information
Milling	cutting tool geometry, feed rate, spindle RPM, width of cut, depth of cut, tool path points
EDM	section area, top/bottom depth, periphery length, volume, draft angle

Table 1: Process information supported by Esprit CAM.

4.1 Evaluation Methods

Among various works, two methods are popular in concern of energy consumption in machine tools. One uses power demand structure of machine tool components. The other uses the process specific energy.

Every component of machine tools has specific functions to serve and various operations are performed by combined work of components. Dahmus investigated the power demand of each functional part of a machine tool and analyzed power demand variation across different operation conditions. He found that most of the total energy is consumed for supportive functions and peripheral devices and claimed that almost 76% of the total energy is constantly wasted regardless of the machining status [9]. Despite some advances in the machine tool design, such inefficiency has not been overcome yet [21].

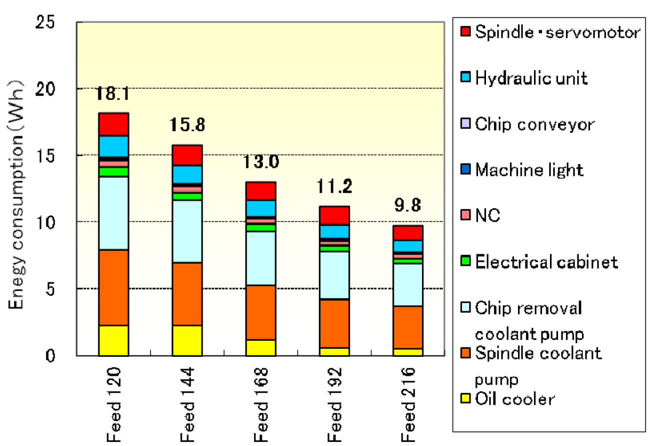

Figure 3: Energy consumption of Moriseiki milling operations [22].

Considering power demand components and operating status of machine tools, it is possible to estimate required power for specific operations as like the example of Figure 3, where different feed speeds affect running time of each component and the resultant energy consumption. Hence, various machine tools were analysed and various relations were identified between operation conditions and components. Generally, three different categories are used for different components: constant (energy consumed by the functions that are not directly related to the machining), run-time (energy consumed for machining functions with fixed value regardless of the varied cutting conditions), and cutting energy portion (energy consumed by the material removal action of a machine tool, which is dependent on the load applied to the machine tool). Based on these works, more efficient machine tool designs and operation strategies were suggested. Because the peripheral devices still accounts for larger portion of the total energy consumption than the material removing behaviour, appropriate information of power demanding structure of machine tools is necessary for energy estimation and analyses of machine tools.

Specific energy is defined as the energy consumed for machining unit volume of material. Different from the power demand components' case, a simple equation shown below is used as reference and the specific energy is calculated with corresponding material removal rate. Coefficients C1 and C2 were empirically defined in many research.

$$E_{spec} = \frac{C_1}{MRR} + C_2 \tag{1}$$

Energy consumption can be estimated with simple multiplication of target removal volume and specific energy for the machine tool. Because this is generally applicable to any process, specific energy is useful in comparison of different operations. However, when the variance of material removal rate is large, reliability of this method is limited. About this limitation, Diaz et al. used sub-divided intervals for changing material removal rate in milling [23]. On the other hand, when the machine is idle or standby status, this method cannot provide relevant information for users because no material is removed in such case. Hence, using another method to cover non-machining time would be more effective in mold making analysis.

Regarding the variety of mold making, we used the power demand structure as a basis for this work and compensate its weakness with additional consideration of the machining process.

4.2 Breakdown of Energy Consumption

Compared to machining devices, operating status of peripheral devices is very simple. Many peripheral devices like lightning have only two different modes of on and off. Hence the variance of power demand in peripheral devices is very small and the demand can be considered as constant.

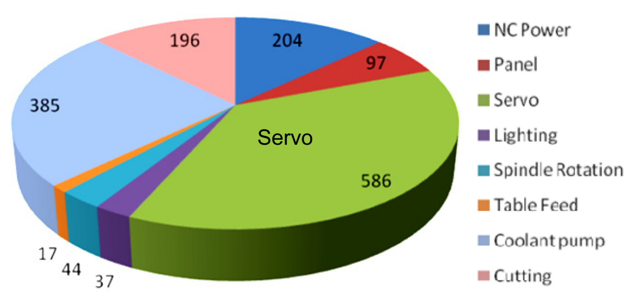

Figure 4: Power demands of Moriseiki NVD1500 [24].

Taniguchi et al. analyzed and broke down the power demand of Moriseiki NVD 1500 CNC machine and the result is displayed in Figure 4. In their work, NC power, panel, servo, and lighting are peripheral devices and others are machining devices. We tested the same kind of machine tool and measured power demand in various milling operations with Yokogawa 240W power meter. Power demand in idle status was measured about 940W, which matches the sum of power demands of peripheral devices in Figure 4. Based on this, it would be possible to handle the power demand of a peripheral device as an inventory data. With this inventory data, energy consumption of the device can be calculated by multiplying the inventory data and the corresponding operation time. In case of machining devices, power demand cannot be treated with one simple value and operation status and load conditions are needed to be considered for estimating energy consumption.

Kellens et al. investigated power demands of EDM in different operation modes as shown in Figure 5. In their work, power demand of the pump ranged from 50 up to 72% of the total power demand and was found to be the biggest portion and the current generation for machining contributes only about 10%. They also compared time shares of three different modes and found that 66% of time is consumed for operation [25]. Agie-Charmilles, a major EDM manufacturer, developed ECO software to improve their products by considering the power demand structure and avoiding non-necessary power waste in idle mode. They claimed that they reduced 90% of electricity consumption. In this paper, we will consider only deep cavity machining with jump and side flushing. This strategy is very popular in small consumer electronics mold making and the difficulty of process planning is well known in this case.

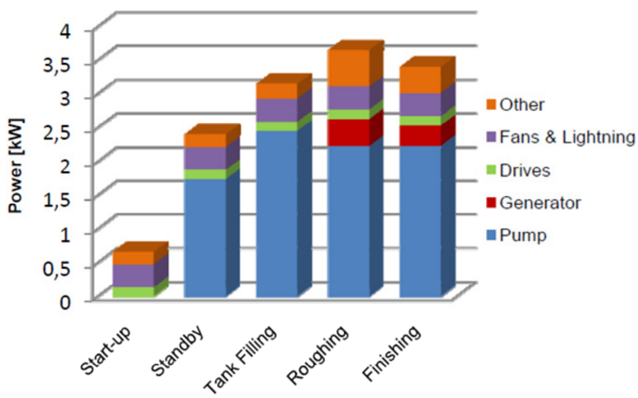

Figure 5: EDM power consumption [25].

4.3 Material Removal Rate (MRR)

Because CNC milling and EDM are both subtractive processes which remove material from a workpiece, MRR represents the capacity and performance. Therefore, MRR plays an important role in the estimation of energy consumption. Generally, as explained in the specific energy method, higher MRR can reduce the cycle time and energy consumption.

MRR in CNC milling is geometrically defined as follows. Because depth of cut and width of cut are defined with tool paths and cutting tool geometry, if feed speed can be controlled and monitored, MRR can be easily calculated with this equation. This assumption is effective in case of simple tool path shape with long segments. However, as will be explained in the next section, actual feed speed is not easy to control.

$$\mathrm{MRR}_{\mathrm{mill}} = \frac{\text{depth}}{\text{of cut}} \times \frac{\text{width}}{\text{of cut}} \times \text{feed}/\text{min} \quad (2)$$

In case of EDM, many different factors influence MRR in EDM: the peak current size, gap voltage, spark gap, material property of work-piece and electrode and dielectric fluid are included in these factors. Hence MRR in EDM cannot be simply defined. While discharge energy, which is defined by the gap voltage, the current size and discharge duration time, is known to be proportional to MRR [26], Okada et al. pointed out that only 10~13% of the energy transferred to work-piece and used for material removal and that more than half of energy is wasted [27]. Hence efficiency factor is needed in MRR definition. On the other hand, the discharged current and voltage in EDM have pulsed waveform. This pulse cycle is comprised of pulse on and pulse off time. Discharge current flows and material is removed only in pulse on time. Considering these two efficiency factors, material removal rate in EDM operation can be described as follows.

$$\mathrm{MRR}_{\mathrm{edm}} = \alpha \times \left(\frac{\text{discharge}}{\text{current}} \times \frac{\text{discharge}}{\text{voltage}} \times \frac{\text{pulse on time}}{\text{total time}} \right) \quad (3)$$

Because melting or evaporation by thermal energy is the main reason for material removal in EDM, the following empirical relationships were established [26]. In this equation, M_w represents melting point of the workpiece material. This equation enables the users to compare EDM performance in different workpiece materials..

$$\mathrm{MRR} = \frac{\text{discharge}}{\text{current}} \times \left(6.64 \times 10^{-7} \times M_W^{-1.23} \right) \quad (4)$$

With nominal feed speed in milling and pulse information in EDM, material removal rate can be evaluated and compared with target removal volume to extract the operation cycle time and related energy consumption.

4.4 Performance Variance

In the general procedure, the cycle time is estimated with the average MRR defined in specific process conditions. The removal volume can be calculated with CAD tools in concern of stock and target geometries. By dividing this volume with the average MRR, the required cycle time of the process can be estimated. This procedure is simple and effective when the average MRR can represent the process performance. However, if this condition is not satisfied, e.g. if the feed speed in milling operation and associated MRR vary too much during machining, this method cannot provide reliable estimation quality.

While the definition of MRR looks simple, CNC milling is a very dynamic process. Many different strategies can be planned for the target shape and the cycle time, surface quality and accuracy can be affected by the strategy. Tool paths are composed of many different lengths of line segments. Due to the mechanical constraints of servo motors, table feed speed to each direction and spindle rotation cannot move ideally. Because feed speed is an important factor of MRR, this limitation is directly related to MRR. Because tool path segment length limits maximum possible feed in milling machine tools [28], distribution of tool path segment lengths make it difficult to estimate the actual feed speed and MRR of the process. Because acceleration and deceleration rates are defined as machine tool constant, the rates are independent of tool path lengths [29]. Hence, when the tool paths are composed of many short length segments, more time is wasted for acceleration or deceleration and low feed movements. This explains why cycle time estimation and energy consumption analysis based on nominal feed speed cannot provide reliable results in complex tool paths.

The cycle time estimation is also a difficult problem in EDM. While material removal capacity is determined by discharge condition, discharge cycle varies and MRR changes. Dielectric fluid contamination is known to be main reason for this change. During the EDM operation, removed material from work-piece or electrodes is accumulated as particles in dielectric fluid. This contamination increases the probability of arc discharge which defects work-piece. To avoid this defect, actual machining rate is decreased. In Figure 6, flushing conditions with different electrode jump height (H_j) were compared with regard to machining rate and it was found that removal performance is dramatically weakened with the contamination density over a threshold [30]. According to this analysis, poorly designed flushing condition decreases actual performance and increases the cycle time much more than designed value.

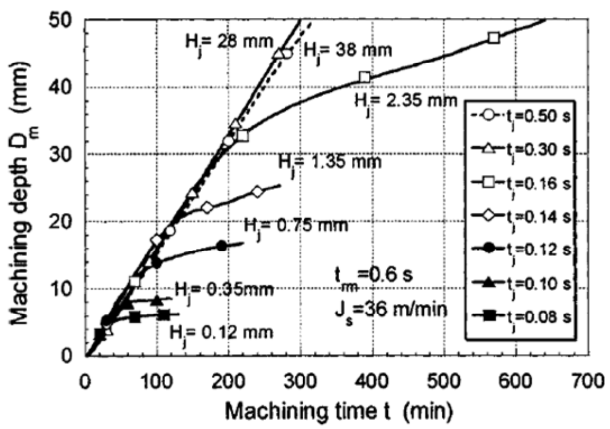

Figure 6: Jump height and depth relation in EDM [30].

4.5 Process Evaluation

Kong et al. explained how different tool path strategies can affect the cycle time and energy consumption [31]. Five different tool path strategies for a rectangular pocket were compared with a software tool. Figure 7 shows the estimated processing time and energy consumption for the milling process. While the same values were used in feed speed, width of cut and depth of cut, the chart shows the difference in each case. The tool path pattern affects the number of segments and distribution in segment lengths. As shown in the graph, in the worst case, different tool path strategies can make 25% difference in the cycle time or 100% in energy consumption for the same pocket milling.

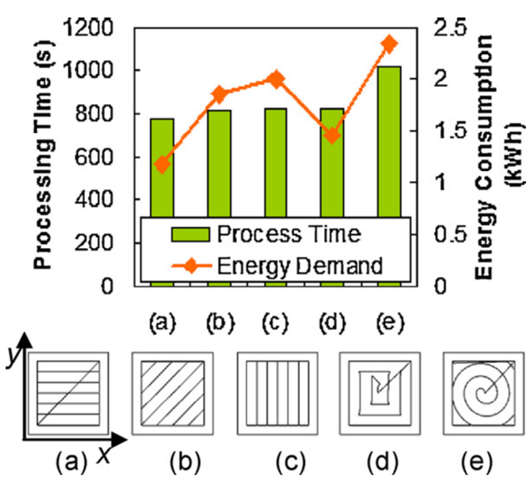

Figure 7: Processing time and energy consumption of various tool-paths [31].

In terms of EDM, two different depths of cavities were compared with different flushing conditions based on Kellens' and Cetin's works. Table 2 shows the estimated cycle time and energy consumption for each case. While other conditions like the peak current size, voltage, and pulse cycle were set to the same condition, different jump heights affect flushing conditions and resultant machining performance of EDM operations. This result shows why appropriate estimation is needed for EDM operations in concern of the cycle time and energy consumption.

Jump Height		0.35	0.75	1.35	2.35
Depth 30mm	Time (min)	-	830	410	180
	Ratio (%)	-	461%	228%	100%
	Energy (kWh)	-	21.1	10.7	4.8
Depth 20mm	Time (min)	1300	360	120	120
	Ratio (%)	1090%	300%	100%	100%
	Energy (kWh)	32.4	9.2	3.1	3.2

Table 2: Inventory of products assessed.

5 CONCLUSION

Estimation method for energy consumption in the mold making process was suggested and implemented with a software tool. For this, two important processes of CNC milling and EDM were analyzed. Most energy is consumed for peripheral devices regardless of machining status and variance of the power demand for the devices is trivial. These characteristics are useful for building life cycle inventory for the process analysis and software tools. On the other hand, variance in machining performance leads to poor process analysis in both cases. Because many different factors affect the performance, software support is necessary in handling the process information and estimating the cycle time and energy consumption effectively. Furthermore, CAD/CAM integrated software tools can be an effective way of adopting energy consumption and environmental sustainability as new manufacturing criteria into mold making practice.

While CNC milling and EDM cover many cases of the mold making process, there are more factors to consider for better estimation. More experimental work is required to support the model. Regarding the popular high speed milling, the analysis of smoothly connected tool paths is required. Due to the tendency of using less number of electrodes, more complex shape of electrodes need to be considered in EDM analysis. Besides, other processes like grinding and utilities like HVAC, lighting and water are also important factors.

6 ACKNOWLEDGEMENT

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