Total Cost Analysis of Process Time Reduction as a Green Machining Strategy

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Abstract
Manufacturers have pursued green machining strategies, such as process time reduction, to address the demand for environmental impact reduction. These strategies, though, increase the stresses on the manufacturing system, which can affect availability, service life, achieved part quality, and cost. This study presents a total cost analysis of process time reduction for titanium machining to holistically consider the implications of such strategies. While the results suggest it may not be a viable green machining strategy for titanium machining, the feasibility of process time reduction as a greening solution is highly dependent on the functionality of the finished part.

Keywords:
Turning, Titanium, Life cycle, Green machining, Reliability

1 INTRODUCTION
Growing customer demand and increasing resource costs and government regulations have encouraged manufacturers to pursue different green machining strategies. One such strategy is process time reduction, which decreases the specific energy by better amortizing the energy consumed by peripheral equipment (e.g. pumps and controllers), which have a constant power demand and dominate the electricity usage of NC machine tools. This strategy, though, increases the stresses, forces, and heat generation on the tool, part, and machine, which can impact several aspects of the manufacturing system including availability, service life, achieved part quality, and cost. So, it is important to fully understand the effects of a process time reduction strategy to the electrical energy demand, availability, and service life of the machine tool, the life of the tool, and the surface quality of the finished part so that the total cost of such a strategy may be determined and used to inform manufacturing decision-making.

2 BACKGROUND
Analyses of green machining strategies have typically focused on the use of life cycle assessment (LCA) to quantify environmental impacts, specifically energy [1]. These analyses have subsequently been integrated into process planning and product design and more recent literature has developed strategies to improve the data quality and results of these analyses as well as ease its use in manufacturing decision-making. However, it is important to understand the relevant economic and technical impacts of green machining strategies in addition to any environmental impacts.

Several examples in the literature focus on trade-offs between environmental and economic impacts. Norris [2] discusses methods to combine both LCA and life cycle costing (LCC) using either a “partial solution” (i.e. combining a full LCA with a partial LCC or vice-versa) or a “full solution” (i.e. combining a full LCA with a full LCC). Eco-efficiency is another approach to combine LCA and LCC by normalizing the metrics from both analyses so that a comparison can be made [3]. Target costing approaches have also been used to control either energy- or cost-related targets so that energy and cost efficient products may be developed [4]. Further work has extended traditional machining cost models to include energy and other environmental costs so that machining parameters may be optimized while also considering environmental impacts [5], [6]. Finally, Martinez, et al. [7] provide a specific product example where a combined LCA, LCC, and external cost analysis is used to evaluate the life cycle costs of the eco-design of a medium voltage circuit breaker.

The literature also contains work that focuses on the trade-offs between technical (e.g. manufacturing system performance or achieved part quality) and environmental impacts. Much of this work focuses on manufacturing processes, such as Fratila [8] who describes the effect of dry and near-dry machining strategies on gear milling by studying the achieved surface quality, tool wear, and environmental impacts created by this strategy. Similarly, Helu, et al. [1] evaluate trade-offs in energy consumption, service life, and the associated costs for a process time reduction strategy by combining an energy-based environmental assessment with a life cycle performance (LCP) analysis. In addition, Mativenga and Rajemi [9] use a minimum energy formulation for machining to optimize machining parameters for tool life and explore the cost implications of such an approach. Hermann, et al. [10] focus on manufacturing system planning and devise an energy-oriented simulation that evaluates production criteria with energy and associated costs. Lastly, Kong, et al. [11] discuss a web-based energy estimation tool that relates processing decisions to subsequent environmental impacts.

While each of the previously described approaches has contributed greatly to a more complete understanding of the effects of green machining strategies, it is necessary to find ways to simultaneously consider environmental impacts with both economic and technical impacts to aid in manufacturing decision-making. Sheng and Srinivasan [12] used an analytic hierarchical process to rank relevant metrics so that environmental factors could be balanced with more traditional process planning factors associated with cost and quality. Avram, et al. [13] used a similar approach to study the value of dry and near-dry machining when considering trade-offs in a variety of environmental (e.g. energy, air quality, and cutting fluid usage), technical (e.g. cutting forces and surface roughness), and economic (e.g. tool life, machining time, productivity) factors.

Our goal is to build upon the previous work in the literature by using the approach from Helu, et al. [1] as the basis for studying the total cost implications of a process time reduction strategy. This total cost accounts for changes in the system performance (service life, availability, and tool wear) as well as environmental impact (electrical energy usage) and achieved part quality. By applying this approach on a “baseline” scenario as well as a set of processing alternatives.
the environmental, technical, and financial effects of a process time reduction strategy may be better understood by manufacturing decision-makers.

3 METHODOLOGY

3.1 Experimental Setup

Machining experiments were conducted on a Heller MC16 horizontal machining center that was modified to operate as a lathe; the turning tool was mounted on a Kistler Type 9255B three component dynamometer installed on the workbench and the test part was placed in the tool holder in the spindle. This experimental setup did limit the choice of test part to cylindrical pieces with a maximum initial diameter of 25 mm.

A cylindrical test piece made from a titanium alloy (Ti-6Al-4V) was turned from an initial diameter of 25 mm to a final diameter of 16 mm using two roughing passes and one finishing pass. Each machining pass was 80 mm long. The “baseline” scenario was selected to produce a surface of standard quality based on the tool manufacturer’s recommended specifications; these parameters are given in Table 1. Flood cooling was also used through the duration of each cut.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rough Cut (x2)</th>
<th>Finish Cut (x1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed, ( v_c ) (m/min)</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Feed rate, ( f ) (mm/rev)</td>
<td>0.30</td>
<td>0.10</td>
</tr>
<tr>
<td>Depth of cut, ( d ) (mm)</td>
<td>2.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 1: Machining parameters used for baseline scenario.

To reduce the processing time, the material removal rate was increased by varying the machining parameters for the rough and finish cuts as shown in Table 1. While all of the given parameters should be simultaneously adjusted to ensure a stable cut, each parameter was varied independently in this investigation to better understand the effects of each parameter on the overall system. The different machining parameter values explored are given in Table 2. Different uncoated carbide tool inserts were used for roughing and finishing based on the tool manufacturer’s specification.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Roughing</th>
<th>Finishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed, ( v_c ) (m/min)</td>
<td>100, 150, 200</td>
<td>40, 60, 75</td>
</tr>
<tr>
<td>Feed rate, ( f ) (mm/rev)</td>
<td>0.45, 0.60, 0.75</td>
<td>0.20, 0.40, 0.60</td>
</tr>
<tr>
<td>Depth of cut, ( d ), for rough cuts (mm)</td>
<td>(1x) 3.0</td>
<td>(3x) 0.5</td>
</tr>
<tr>
<td></td>
<td>(1x) 4.0</td>
<td>(1x) 0.5</td>
</tr>
<tr>
<td>Depth of cut, ( d ), for finish cuts (mm)</td>
<td>(2x) 2.1</td>
<td>(1x) 0.3</td>
</tr>
<tr>
<td></td>
<td>(2x) 2.15</td>
<td>(1x) 0.2</td>
</tr>
</tbody>
</table>

Table 2: Machining parameters varied during cutting experiments.

3.2 Electrical Energy Analysis

The overall power demand of the machine tool was measured using a Yokogawa CW240 wattmeter in a three-phase, three-wire, three-current setup. 200 A current transducers were selected and installed with appropriate voltage clips at the power input to the machine tool. The instantaneous real power was measured at a sampling frequency of 10 Hz.

It was observed during the experiments that the internal cooling cycle of the Heller MC16 can cause the overall real power demand to increase from ~7 kW to ~9 kW depending on its use. Based on subsequent idle power measurements, we assumed that this ~2 kW power demand represents a constant or tare demand. Since the machine tool would presumably be used with relatively little interruption throughout a work shift in a plant, we assumed that the internal cooling cycle would be active for all processed parts. So, we adjusted the measured power data so that the idle power level was a consistent 9 kW by determining the average measured idle value for each experiment and adding the difference between that value and 9 kW to each measured power value.

To determine the energy consumed for each experiment, we first assumed that the power demand remained constant between measurements. Thus, the total electrical energy consumed during an experiment, \( E_{\text{total}} \), was estimated using Equation 1:

\[
E_{\text{total}} = \sum_{i=1}^{k} P_i \Delta t_i,
\]

where \( k \) is the total number of data samples, \( P_i \) is the \( i \)th measured real power demand, and \( \Delta t_i \) is the time between measurements. The energy consumed during a tool change was identically measured in a separate experiment and added to the total energy needed to create a finished test piece.

3.3 Tool Wear Analysis

The flank-wear land width, \( VB \), of the major cutting edge was measured after both the final rough and finish cuts using a Carl Zeiss Stemi SV11 light-optical microscope with an AxioCamHRC digital camera. Even though relatively high rake face wear was detected after the rough cuts, this study evaluated only flank wear since the tool insert geometry has chip breakers.

3.4 Service Costs Analysis

The service cost for a machining strategy can be estimated by considering the reliability and load profile of the most critical components of the machine tool [14]. The spindle and its bearings are considered the most critical component of a machine tool in most industrial applications since they are most often in need of service. So, this analysis focused on the statistical failure behavior of the spindle. The stress cycles on the spindle were first estimated from force measurements during the rough and finish cuts. The peak-to-peak stress amplitudes were filtered at 10 Hz for each processing alternative. The highest stress level was along the rotational (2) axis of the spindle, which created both tensile and compressive stresses on the spindle shaft that directly affected the spindle bearings.

Predicting the future breakdown behavior of a machine tool requires an understanding of its historical breakdown behavior. Because this data was unknown for the Heller MC16 machining center used in this study, we relied on one year of historical breakdown behavior collected from comparable machine tool spindles in an industrial setting [15]. This data was scaled based on the measured stress cycles from our experiments. It included both preventative and reactive service activities created by a variety of errors such as temperature sensor defects and cooling features, as well as those that did not result in production loss or complete breakdown.

Once the load profile and breakdown behavior were determined, a reliability model was constructed using the Generalized Log-Linear model commonly used in accelerated life testing for time-varying loads [16], [17]. The form of this model is given in Equation 2: