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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.

	Rough Cut (x2)	Finish Cut (x1)
Cutting speed, v_c (m/min)	65	65
Feed rate, f (mm/rev)	0.30	0.10
Depth of cut, d (mm)	2.0	0.5

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.

	Roughing	Finishing
Cutting speed, v_c (m/min)	100, 150, 200	
Feed rate, f (mm/rev)	0.45, 0.60, 0.75	0.20, 0.40, 0.60
Depth of cut, d, for rough cuts (mm)	(1x) 3.0	(3x) 0.5
	(1x) 4.0	(1x) 0.5
Depth of cut, d, for finish cuts (mm)	(2x) 2.1	(1x) 0.3
	(2x) 2.15	(1x) 0.2

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_{total}, was estimated using Equation 1:

$$E_{total} = \sum_{i=1}^{k} P_i \Delta t, \tag{1}$$

where k is the total number of data samples, P_i is the ith measured real power demand, and Δt 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 (z) 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:

$$D(t, X_i) = \int_0^t e^{a_0 + \sum_i a_i X_i(t')} \, dt', \qquad (2)$$

where a_0 and a_i are model parameters estimated by statistical analysis, D is cumulative damage (or cumulative exposure), t is time, and X_i is a transformation of the measured load levels; this transformation is the natural logarithm for mechanical loads (Power Law) and the inverse for thermal stresses (Arrhenius Law). Equation 2 was simplified in this analysis to Equation 3:

$$D(\Delta t_i, X_{ij}) = \sum_j e^{a_0 + \sum_i a_i X_{ij}} \Delta t_j. \qquad (3)$$

To estimate the remaining future service life, the extended stress cycles and Equation 3 were integrated into the 2-parameter Weibull distribution given in Equation 4:

$$F(t) = 1 - e^{-\left(t/\eta\right)^\beta}, \qquad (4)$$

where F is the probability of failure due to cumulative damage, β is the load independent form parameter, and η is the load dependent parameter, which was replaced by Equation 3 with the relevant stress cycles for each machining strategy of interest [18]. By analyzing the spindle breakdown times using the Weibull ++ software, β was found to be 0.2 for early breakdowns, which occur 40% of the time, and 2 for late breakdowns, which occur the rest of the time. The statistical breakdown behavior was then determined by implementing Equation 4 into the S-Net simulation software, which utilizes a Monte-Carlo simulation approach [15].

The simulation considered three types of maintenance activities: continuous preventative maintenance, random breakdowns (at an assumed probability of 0.1%), and end-of-life maintenance. Several assumptions were required to run this simulation including: production loss was €4000/hour, the cost of a spindle was €10000, average time between preventative servicing was 3000 hr, cost for each service was €300 and took 4 hours to complete, and service technician costs were €50/hour of labor. Maintenance activities were assumed to be scheduled when 30% of the remaining time before the activity occurs. The forecast itself was simulated for 7700, 6583, 6500, and 6095 hours for the baseline and representative d, f, and v_c cases, respectively. These times represent full machine tool utilization over 1 year and correspond to material removal rates of 78, 78, and 90 cm^3/min for the d, f, and v_c cases, respectively. These specific cases were selected for this analysis since they most stressed the machine tool based on the measured cutting forces. From the breakdown behavior that was simulated, the service costs were finally estimated by considering labor costs, production losses, spare part costs, and service technician labor costs [18].

4   RESULTS

4.1   Electrical Energy

The total specific electrical energy consumed during the baseline scenario was 55.4 kJ/cm^3; the rough and finish cuts of the baseline scenario required 28.3 kJ/cm^3 and 268 kJ/cm^3, respectively. The average cutting power demanded for the baseline scenario was 13.2 kW and 12.2 kW during the rough and finish cuts, respectively. Figure 1 shows how each change to the rough cuts affected the specific electrical energy consumed during cutting. As expected, the

energy consumed during the rough cuts decreased inversely with the material removal rate since an increased material removal rate indicates a reduction in the processing time. This trend was roughly independent of process parameter selection, which agrees with turning results in the literature [19]. At least one recycling pump for the cutting fluid was observed to shut off during some cuts, particularly when the cutting speed was adjusted; this likely caused the slight deviation in the data in Figure 1 since this change would have decreased the difference in power measured between the idle and cutting states. All of these changes demanded greater effort from the machine, though, which was confirmed by the cutting force measurements employed in the service cost analysis. This increased the power required during the cut as the material removal rate increased.
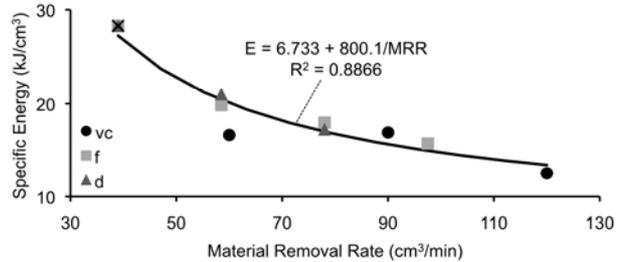

Figure 1: Specific energy consumed during the rough cuts for varied cutting speed, v_c, feed, f, and depth of cut, d; the specific energy for the baseline case is marked by an "X."

Changes to the finish cut created similar results as those to the rough cuts (see Figure 2). Again, the energy consumed decreased inversely with the material removal rate due to the processing time reduction. The trend was also independent of process parameter selection, which agrees with the turning literature [19]. The significantly greater specific energy consumption during the finish cuts was due to the relatively small amount of material removed, which increased the material removal rate. This result matches well with the results shown in Figure 1, which indicates that material removal rate (and by extension the processing time) is the main parameter that determines specific energy consumption. Unlike the rough cut examples, though, none of the changes to the finish cut significantly affected the average power demanded during the cut. This was because the finish cut was very light and thus required almost no extra power relative to the idle machine state.
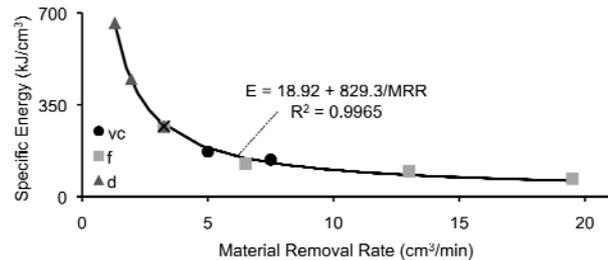

Figure 2: Specific energy consumed during the finish cut for varied cutting speed, v_c, feed, f, and depth of cut, d; the specific energy for the baseline case is marked by an "X."

To help determine the change in electrical energy costs for each strategy, the overall effect on the total energy demanded must be determined (see Figure 3). As Figure 3 shows, increased material removal rates (whether applied to roughing or finishing) inversely decreased total energy consumption. The trend in Figure 3 again

shows how the material removal rate is the main determinant of specific energy consumption. In addition, the leveling of the curve in Figure 3 suggests that increasing machining parameters may not offer any substantial energy savings past a certain point.
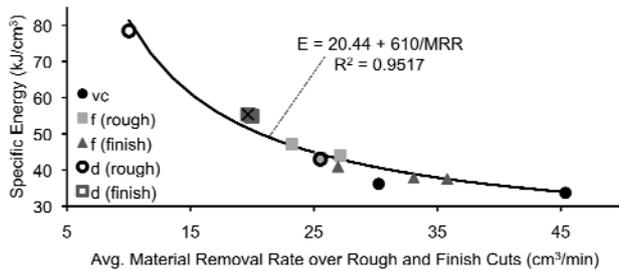

Figure 3: Total specific energy consumed to create one test part for varied cutting speed, v_c, feed, f, and depth of cut, d; the specific energy for the baseline case is marked with an "X."

The electricity-pricing schedule and energy mix in Karlsruhe, Germany was used to evaluate the costs and CO_2 emissions for electrical energy [20], [21]. Because the cost was dependent on energy only, it scaled exactly as the total specific energy consumed shown in Figure 3 and had a minimum/maximum value of €0.05/€0.12, respectively, and the baseline case cost €0.08. The same was true for CO_2 emissions, which had a minimum/maximum value of 90/210 g CO_2, respectively, with the baseline case emitting 150 g CO_2.

4.2 Tool Wear

The measured flank wear land width, VB, after the final roughing pass for the baseline scenario was 106±4 µm. Figure 4 shows how the flank wear width measured after the final rough cut varied for the different machining parameters tested. The flank wear did not appear to significantly change as the depth of cut, d, was increased. Conversely, the flank wear appeared to exponentially increase as the feed, f, and the cutting speed, v_c, increased. Neither result was surprising; titanium's relatively high toughness, high strength, and low thermal conductivity create large thermal gradients at the tool-chip interface, which promotes material diffusion and plastic deformation along the tool edge [22]. As the feed and cutting speed are increased, the temperature at the tool-chip interface should increase as well, which promotes greater tool wear. Also, tool wear is not reported for $v_c = 200$ m/min (material removal rate of ~180 cm^3/min) because of the severe tool breakage that occurred during the first roughing pass.
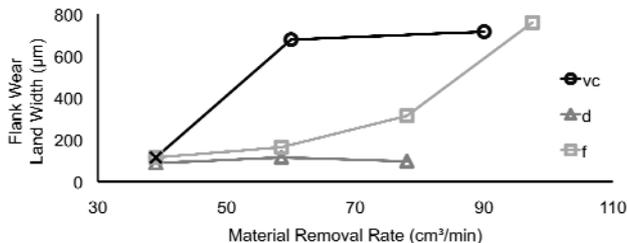

Figure 4: Flank wear land width, VB, measured after the final rough cut for varied cutting speed, v_c, feed, f, and depth of cut, d, during the rough cuts; the baseline case is marked with an "X."

Figure 5 shows how the flank wear width after the final finish cut varied for the different machining parameters tested. Similarly to the rough cut, the flank wear appeared to only be significantly affected by changes in the cutting speed, v_c, and feed, f. Unlike the rough cut, though, the overall flank wear observed was much lower since the finish cuts were relatively light compared to the rough cuts.
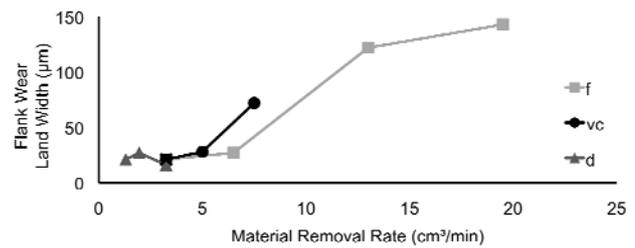

Figure 5: Flank wear land width, VB, measured after the final finish cut for varied cutting speed, v_c, feed, f, and depth of cut, d, during the finish cut(s); the baseline case is marked with an "X."

There are several failure criteria that can affect the tool life and thus tool costs. First, the flank wear land width should not exceed 300 µm for the selected roughing and finishing tool inserts used in this investigation. Figure 4 shows how this criterion is clearly exceeded in the rough cuts by all of the high cutting speed and feed cases, which means that none of these parameter selections are realistic. Alternatively, the entire range of machining parameters that were studied for the finish case remain safe after at least one finish cut as Figure 5 shows. More importantly than the flank wear failure criterion, though, the achieved surface quality often dictates tool failure based on the functional requirements of the finished part. Once the minimum allowable surface quality is determined, the potential reduction in tool life and subsequent increase in costs as process time is reduced can be more easily calculated.

The environmental impact of these changes can also be estimated by considering the embodied energy of the tool insert. The embodied energy for tungsten carbide tools is 400 MJ/kg [23]. This indicates an embodied energy of ~1 MJ/cutting edge for the 10 g tools with four cutting edges used in this study, which could be an important consideration for the overall environmental impact of the process if one or more cutting edges are needed to complete a part.

4.3 Service Costs

The average service cost generated by 10 experimental runs of the statistical breakdown simulation for the identified representative machining parameter sets for feed, f, cutting speed, v_c, and depth of cut, d, is presented in Figure 6. The highest service cost (~€0.52/part-year) occurred for the depth of cut case, which indicates that the spindle was damaged by either a crash or a high stress cycle over the entire processing time. The latter should be expected since this was perhaps the most aggressive strategy pursued (the depth of cut for the rough cut was doubled relative to the baseline scenario to 4 mm). The representative cutting speed case had the lowest service costs (~€0.11/part-year), which is also expected as higher speeds do not necessarily lead to greater mechanical loads (although they may lead to greater thermal stresses). Overall, the largest contributor to the service cost was production losses.

It was also observed during the Monte-Carlo simulation that unexpected breakdowns added significant variability to service costs. This variability was greatest for the baseline case, which varied up to ~€0.05/part-year. Again, this result favors lower risk machining strategies that place minimal stress on the machine tool.
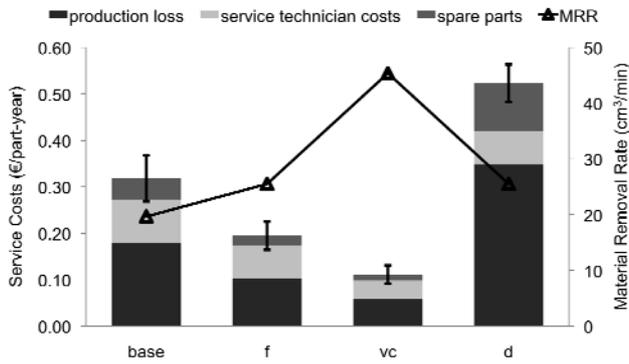
Figure 6: Average simulated service costs per part and year for a representative case of varying feed, *f*, cutting speed, *v_c*, and depth of cut, *d*; the baseline scenario is shown as "base," and the deviation in service costs is represented by the error bars.

4.4 Surface Integrity

Surface integrity can strongly influence the quality and performance of a part, including its frictional and wear behavior, its heat and electrical conductivity properties, and the effectiveness of lubrication when it is used in an assembly [24]. In addition, the surface appearance, appropriateness of the surface for subsequent finishing operations, and fatigue life and corrosion resistance are all directly linked to surface integrity. Titanium alloys are particularly vulnerable to poor surface integrity because of titanium's inherently high toughness and work hardening behavior that create work hardened layers, microstructual changes, and rapid tool wear due to high strains and high thermal and pressure gradients at the tool-chip interface.

Surface integrity can be viewed through three separate types of parameters: mechanical (e.g. residual stress), metallurgical (e.g. microstructure, microhardness), and topographical (e.g. surface roughness) [24]. The effect of cutting parameters on the surface integrity of titanium during milling and turning has been extensively studied in the literature and is presented in Table 1.

	Residual Stress	Ra	Microhardness
↑ v_c	↓	↑ (variable)	↑
↑ f	↑	↑ (moderate)	↑
↑ d	n/a	↑	n/a

Table 3: Summary of the effects of cutting parameters (cutting speed, *v_c*; feed, *f*; depth of cut, *d*) during milling and turning on the achieved surface integrity of Ti-6Al-4V [24].

Even given the surface integrity effects of each machining strategy studied, it is difficult to determine the effect to the total cost of a finished part without specifying the part's function since the value created by superior surface integrity is dependent on this function. For example, small improvements in surface finish in automotive drivetrain components or windmill gears can provide substantial value due to improved operational efficiencies [25]. However, the same may not be entirely true for piston surfaces since a certain amount of roughness is necessary to promote good fuel mixing during combustion.

5 DISCUSSION

The total cost analysis presented in this paper considered energy, tooling, service, and quality costs when evaluating a process time reduction strategy to green machining. By speeding up the machining process, energy costs were found to decrease by up to €0.03/part over the process parameters investigated. Simultaneously, the service costs either decreased by ~€0.21/part-year or increased by up to €0.21/part-year relative to the baseline case depending on the strategy used to reduce the processing time. Tooling costs also increased due to greater tool wear and surface quality was potentially reduced, which would have decreased the inherent value of the completed part. Both of these effects, though, are entirely dependent on the functionality of the part and how the manufacturing process affects that functionality. Tooling costs could be quite significant, though, since several of the strategies investigated required one or more entire cutting edges just to finish one part. In addition, any changes in the scrap rate due to surface integrity effects could also significantly impact costs.

The total costs reported do not entirely capture the full effect of a process time reduction strategy, though. For example, the service costs represent "average" breakdown behavior. But, this analysis showed that variability in breakdown behavior (particularly unexpected failures) could significantly increase service costs. Since a process time reduction strategy places greater strains on a machine tool, the variability in service costs adds extra risk when considering such a strategy.

Given the financial risks involved in adopting a process time reduction strategy, the benefits of such a strategy are unclear especially when considering other resources. The maximum electrical energy savings observed was ~500 kJ, which translated to about 100 g CO_2 emissions. If we compare this to the 1 MJ of embodied energy in a cutting edge, then the savings may be nearly equal if one or more tools are required to finish a part. Also, the 1 MJ of embodied energy potentially includes higher impact processes during material extraction, which could exceed the 100 g CO_2 emissions that were saved by speeding up the machining process. Furthermore, if the surface quality is significantly reduced, then the operational efficiency of the finishing part may be similarly reduced, which creates additional environmental impact.

While the benefits of a process time reduction strategy are unclear, we should consider that electrical energy is not all that would be saved by adopting this strategy. There are other energy overheads that would be reduced, as well as other resources that may be saved depending on the process and part of interest. Also, the process time need not be reduced past a particular point – the energy results clearly show that the benefits of speeding up the process continue to decrease as the process is accelerated further. The tool wear results also show that some process time reduction strategies are entirely unfeasible since they induce flank wear in excess of the flank wear land width failure criterion.

There were also sources of uncertainty in our study that should be addressed in future iterations. First was that this investigation utilized a simple titanium part. Parts with higher complexity not only better represent industrial practice, but could also respond differently to a feasible process time reduction strategy. Titanium is also an already difficult-to-cut material that inevitably will require greater resources, especially tooling. While these results may limit the applicability of a process time reduction strategy for titanium, they do not necessarily translate to other easier-to-cut materials like medium steel or aluminum. Furthermore, this investigation was performed in a non-industrial setting, which meant that other resources that would benefit from speeding up the manufacturing process, such as facility overheads like HVAC and lighting, were not considered. One key factor that was not considered by this study was the functionality of the part and how that functionality affects and is affected by the manufacturing process. Future work should consider these effects for a given set of products to better understand the resources required to achieve adequate surface quality. A more detailed surface integrity analysis should also be conducted.

Ultimately, a holistic perspective is required when considering any strategy to green a manufacturing process. Energy savings should not be the only goal, and even if it is most important, then it is vital to recognize that other aspects of the manufacturing process may be negatively impacted by such a decision. Otherwise, a manufacturer may in fact offset inefficiencies and create a process with even greater impact that the previous status quo.

6 ACKNOWLEDGMENTS

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