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Impact of green machining strategies on achieved surface quality

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ABSTRACT

Green machining strategies can affect several aspects of a manufacturing system including part quality, which must remain sufficient to ensure the product's value. Improved part quality can also reduce life cycle environmental impacts through increased resource efficiency, which adds a further consideration. This paper quantifies the impact of these strategies on the achieved surface quality of turned titanium in the context of various resource costs including electrical energy, tool wear, and service costs. The results suggest that the final surface quality is most influenced by the finish cut(s) and feed rate. Part functionality is also an important consideration for resource efficiency.

1. Motivation

Manufacturers have used various green machining strategies to respond to increasing pressures for sustainability. These strategies include process time reduction to better amortize constant power demands from peripheral equipment and non-traditional lubrication techniques such as dry machining or minimum quantity lubrication (MQL) to reduce the consumption of oil, water, and energy. Unfortunately, these strategies can also affect other aspects of a manufacturing system including availability, service life, and part quality, all of which must be fully understood to inform manufacturing decision-making [1].

Of the different impacts to manufacturing systems, effects on part quality are particularly important to consider since part quality must remain sufficient to ensure that the product meets its intended function and provides value to the manufacturer and customer. Recent research has also shown how the finished surface quality imparted by a machining process may have significant impacts on other product life cycle stages besides manufacturing [2,3]. Thus, there is a need to change the manufacturing paradigm from minimizing resource costs to maximizing resource efficiency (i.e., maximizing production output or value-added while minimizing resource inputs and costs) both in the manufacture and use of products [4]. This paper seeks to explore the impact of green machining strategies on the resource efficiency of machined products over their entire life cycle by focusing on the effects of these strategies on the achieved surface quality.

2. Related work

Recent research has focused on quantifying and reducing energy consumption to improve resource efficiency. For example, Kara and Li [5] and Diaz et al. [6] independently developed unit process models that relate energy consumption to process variables for machining. Mativenga and Rajemi [7] also focus on the machining process by using a minimum energy formulation to optimize machining parameters for tool life. Weinert et al. [8] and Hermann et al. [9] both focus instead on the production system by developing methods to simulate and minimize energy consumption and maximize productivity through manufacturing and process planning. Branker et al. [10] extend energy minimization to financial costs through the development of a microeconomic model to optimize a machining process based on labor, setup, tooling, material, and energy costs, while Mori et al. [11] extend energy minimization to more traditional machining metrics by studying strategies and designs to reduce machine tool energy consumption within suggested operating ranges to ensure that tool life and part quality may be maintained. While each of these approaches may succeed in improving machining resource efficiency, they do not generally fully explore part quality and other production outputs as alternative means to improve resource efficiency and ensure successful, saleable products.

Jawahir et al. [12] provide an excellent review of the state-of-the-art in surface quality research that shows how most of the research in this field focuses on the development of predictive and measurement methods for surface integrity parameters (e.g. residual stress, hardness, and roughness) in machining. Other recent work has tried to consider the resource costs (both environmental and financial) required to achieve a finished surface in the context of traditional machining metrics such as tool life and machining time [13–15]. However, this work typically focuses on the implications of non-traditional lubrication techniques and analysis methods rather than measured data. Helu et al. [1] provide a total cost analysis of a process time reduction strategy based on experimental data that considers electrical energy, tool wear, and service costs with only superficial coverage of surface integrity. Thus, this paper seeks to build upon Helu et al. [1] by extending the analysis to consider the achieved surface quality of process time reduction and dry machining strategies.

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Table 1
Machining parameters used for baseline scenario (from [1]).

	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

3. Experimental approach

The experimental procedure proposed in Helu et al. [1] was repeated for this study. Machining experiments were conducted on a 4 axis horizontal machining center with an ~0.25 m^2 work volume, 40 kW spindle, and pallet changer. This machining center was modified to operate as a lathe by placing the turning tool on the workbench and the test part into the spindle.

Titanium alloys have become important materials for aerospace and other industries as the need to reduce frictional and wear losses and improve resource efficiency has encouraged the use of lightweight, strong components with high surface quality [4]. So, a Ti–6Al–4V titanium alloy was used for this study [1]. The material was hot rolled, annealed at 730 °C, and air cooled to reach a 0.2% proof stress of 907 MPa and a tensile strength of 991–996 MPa. Each test piece was turned from an initial diameter of 25 mm to a final diameter of 16 mm using two rough and one finish pass of length 80 mm as shown in Table 1. This “baseline” case was selected to produce a part with standard surface quality based on the recommend specifications for the uncoated carbide inserts used in this study; separate inserts were used for roughing and finishing. Flood cooling was also used for the duration of each cut, except for the dry machining case.

The material removal rate was increased to reduce the processing time by varying the cutting speed, feed rate, and depth of cut for the rough and finish cuts as shown in Table 2 [1]. While all of these parameters should be simultaneously adjusted to ensure a stable cut, each parameter was individually changed to study the effects of each parameter during the cut.

4. Electrical energy and tool wear

4.1. Process time reduction

Helu et al. [1] presented the electrical energy, tool wear, and service costs associated with a process time reduction strategy applied to turning the titanium alloy Ti–6Al–4V. The total specific electrical energy consumed for the baseline case was 55.4 kJ/cm^3, with the rough and finish cuts requiring 28.3 kJ/cm^3 and 268 kJ/cm^3, respectively. These values decreased as the process time decreased due to increased cutting speed, feed rate, or depth of cut. The specific electrical energy varied at the same rate for each process parameter, which agreed with results presented in the literature [5,6]. Overall, the specific energy varied between 10 and 30 kJ/cm^3 for the rough cut, 60–700 kJ/cm^3 for the finish cut, and 30–80 kJ/cm^3 for the overall cutting process. Electricity costs and CO_2 emissions followed the same trend as specific energy; using an electricity pricing schedule and energy mix from Karlsruhe, Germany, €0.08 and 150 g-CO_2 emissions were needed to produce the baseline part. A range of €0.05/90 g-CO_2 to €0.12/210 g-CO_2 was observed for the other process parameters investigated.

Table 2
Machining parameters varied during cutting experiments (from [1]).

	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 (rough cuts – mm)	(1x) 3.0 (1x) 4.0	(3x) 0.5 (1x) 0.5
Depth of cut, d (finish cuts – mm)	(2x) 2.1 (2x) 2.15	(1x) 0.3 (1x) 0.2

The measured flank wear land width after the final rough and finish cuts for the baseline scenario was 106 ± 4 μm and 17 ± 2 μm, respectively [1]. While the depth of cut appeared to have a negligible effect on tool wear, increasing the cutting speed and feed rate both significantly increased the flank wear land width up to 800 μm and 150 μm after the rough and finish cuts, respectively. Given that the tool manufacturer recommends that the flank wear land width should not exceed 300 μm, the higher cutting speeds and feed rates tested during the rough cuts were not feasible. Ultimately, the achieved surface quality often dictates the tool failure criterion, which complicated further investigation of tooling costs. The environmental impacts of tooling were estimated, though, based on the reported embodied energy of tungsten carbide tools (400 MJ/kg) [16]. This indicated an embodied energy of ~1 MJ/cutting edge since the tools used in this study had a mass of 10 g with 4 cutting edges [1].

4.2. Dry machining

The total specific electrical energy consumed when flood cooling was eliminated was 44.3 kJ/cm^3, with the rough and finish cuts requiring 22 kJ/cm^3 and 206 kJ/cm^3, respectively. Dry machining required less energy than the baseline case since the series of pumps needed to filter and deliver coolant were no longer needed. If the embodied energy of the coolant itself were also considered, then the energy difference between the baseline and dry machining cases would be greater. Again using an electricity pricing schedule and energy mix from Karlsruhe, Germany, €0.07 and 120 g-CO_2 emissions were needed to produce the test part without flood coolant.

The flank wear land width increased as anticipated for the dry machining case to 130 μm and 24 μm after the rough and finish cuts, respectively. The lack of coolant and lubricant at the tool-chip interface increases thermal gradients, friction, and cutting forces, which all contribute to increase tool wear through material diffusion and plastic deformation.

5. Service costs

Helu et al. [1] found that unexpected breakdowns added significant variability to service costs, which supported lower risk machining strategies that placed minimal stress on the machine tool. Including unexpected breakdowns, the Monte Carlo simulation performed estimated that the service cost of the baseline case was ~€0.32/part-year. Subsequent simulations estimated the service costs for representative cutting speed, feed rate, and depth of cut cases to be ~€0.11/part-year, ~€0.19/part-year, and ~€0.52/part-year, respectively.

Given the service cost variability found by Helu et al. [1], this analysis was re-performed for this study excluding unexpected breakdowns. The Monte Carlo simulation considered the load profile on the machine tool created by each machining case combined with the maintenance process specified by the machine tool manufacturer; these results are shown in Fig. 1. The lower service costs for those strategies with higher material removal rate

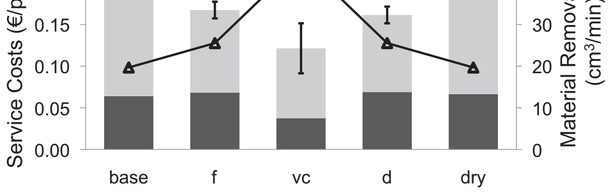

Fig. 1. Average simulated service costs per part and year for a representative case of varying feed, f, cutting speed, v_c, and depth of cut, d; the baseline and dry machining cases are labeled “base” and “dry,” respectively, and the range of service costs is shown by the error bars.

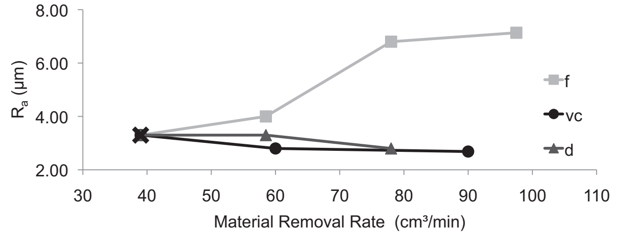

Fig. 2. Measured surface roughness after the final rough cut for varied feed rate, *f*, cutting speed, v_c, and depth of cut, *d*, during the rough cuts; the baseline case is marked with an "×".

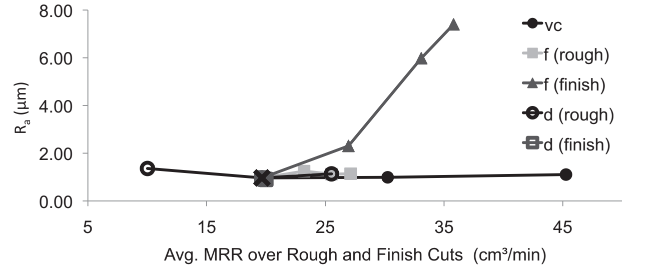

Fig. 4. Final measured surface roughness for varied feed rate, *f*, cutting speed, v_c, and depth of cut, *d*, during either the rough or finish cuts as indicated; the baseline case is marked with an "×".

were due to the larger production volume over the course of a year. The most important cost drivers were the costs associated with the service technician and the resulting production loss if the maintenance activity cannot be performed during non-operation time.

6. Part surface quality

6.1. Surface roughness

The surface roughness of the part was measured after the final rough and finish cuts in the cutting direction using a Concept Contur PST-MSE stylus type instrument with a stylus type PCV 175-M/8 mm. The scan length was set to 10 mm at a scanning speed of 0.5 mm/s.

The measured surface roughness after the final rough cut of the baseline case was 3.30 μm. Fig. 2 shows how each change to the rough cuts affected the measured surface roughness. The surface roughness did not appear to be significantly affected by either the cutting speed or the depth of cut. The depth of cut result was not surprising given that the depth of cut was also not found to significantly affect tool wear [1]. However, increasing cutting speed was found to increase tool wear. The measured surface roughness, though, appeared to be caused by feed marks in combination with the cutting edge radius. So, increased cutting speed did not affect surface roughness since the cutting speed was not observed to significantly affect the cutting edge radius. Alternatively, increasing the feed rate did increase the surface roughness since the roughness was generated mostly by feed marks and increased cutting forces. Similar trends for all three process parameters were observed when the surface roughness was measured after the final finish cut (see Fig. 3). The measured surface roughness after the final finish cut of the baseline case was 0.97 μm.

Fig. 4 shows the final measured surface roughness after the completion of machining for all process parameter variations of the rough and finish cuts. The final surface roughness was observed to be almost entirely influenced by the finish cuts, which suggests that there is greater flexibility in adjusting the rough cuts to decrease resource costs. However, changes to the rough cuts may significantly affect other surface quality metrics, such as residual stress, which can counteract any observed improvement in resource efficiency by lowering the quality of the finished part. Another option to decrease resource costs is to increase the cutting speed or depth of cut since neither seems to affect the final surface roughness. However, increased cutting speed leads to high tool wear and increased depth of cut can significantly increase service costs [1].

The measured surface roughness after the final rough and finish cuts of the dry machining case was 3.10 μm and 1.22 μm, respectively, which was not significantly different from the measured surface roughness of the baseline case. This suggests that dry machining could be a reasonable means to reduce resource costs. However, tool wear was observed to increase slightly, which can offset any improvements in resource efficiency depending on the tool material and its subsequent costs.

6.2. Full width at half maximum

X-ray diffraction analyses were conducted using a Ψ-diffractometer to measure the full width at half maximum (FWHM) of the resultant X-ray interference patterns. The FWHM is a measure correlated to the degree of cold working imparted to a material by varying the machining process since the FWHM increases as dislocation density increases. By conducting a FWHM analysis on the machined surface after the final finish cut, the effect of the process parameter selection on the local strain hardening was determined.

The {2 1 3}-diffraction lines of the α-phase were studied using Ni-filtered Cu Kα radiation at a nominal position, 2θ, of 139.317° over the range of $136.5^\circ \leq 2\theta \leq 145.5^\circ$ with a step size of $\Delta 2\theta = 0.05^\circ$. The diffraction lines were recorded at 5 different tilt angles, Ψ, between −10° and 10° to improve the statistical analysis. The primary aperture utilized a pinhole collimator of nominal diameter 1 mm while a 2 mm slit in front of the detector was placed in the secondary beam. The diffraction lines were fitted using a Pearson VII double peak fit with the Kα-doublet. So, the Kα-portion was used for calculation of the FWHM. The mean of the FWHM for the 5 different tilt angles was used for each surface sample.

Fig. 5 shows the measured FWHM after completion of machining for representative process parameter variations for the rough and finish cuts. Increasing the feed rate during the finish cut had the most significant effect on the FWHM and thus strain hardening. This is likely due to increased elastic-plastic

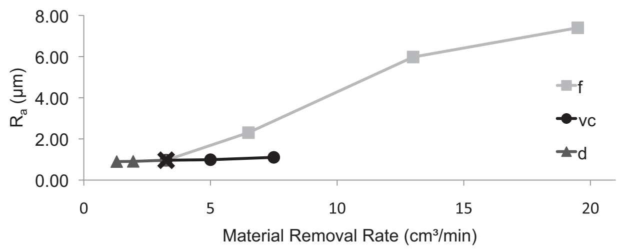

Fig. 3. Measured surface roughness after the final finish cut for varied feed rate, *f*, cutting speed, v_c, and depth of cut, *d*, during the finish cuts; the baseline case is marked with an "×".

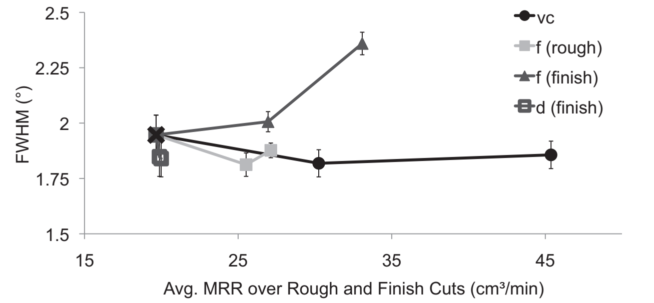

Fig. 5. Measured full width at half maximum on the finished surface for varied feed rate, *f*, cutting speed, v_c, and depth of cut, *d*, during either the rough or finish cuts as indicated; the baseline case is marked with an "×".

deformation that results at the shear zone, as well as the observed increase in tool wear and surface roughness. Thus, while high feed rates may increase tool wear and surface roughness, the resulting increase in work hardening can lead to improved fatigue performance, which could increase resource efficiency by extending service life.

Similarly to the other process parameter variations studied, the dry machining case did not cause the measured FWHM (1.8136°) to vary much relative to the baseline case (1.9466°). The shear zone temperature for each of these cases should have been high due to titanium's toughness and strength, which would have counteracted the strain hardening process. In addition, the lack of variation in the FWHM observed for changes to the rough cuts further indicates that final surface quality of the part was most influenced by the finish cuts.

7. Conclusions

This analysis has shown how surface quality and thus resource efficiency can be significantly impacted by choice of green machining strategy as well as how that strategy is implemented. Considering only surface quality, these results indicate that it is best to focus greening efforts on the rough cut(s) since the finish cut is mostly responsible for the final surface quality. Also, the feed rate of all process parameters has the greatest influence on the final surface quality. However, neither of these conclusions should be considered solely as changes to the rough cuts or other process parameters can potentially have detrimental effects to energy, tool wear, and service costs, all of which can actually reduce resource efficiency [1].

Given the environmental, technical, and financial tradeoffs inherent for any green machining strategy, the extent to which any of these strategies should be implemented strongly depends on the functionality of the finished part and how the manufacturing process affects that functionality [1]. For example, the finished quality of specific titanium parts can have a significant impact on the efficiency of various aerospace devices. So, any improvement in surface quality can be leveraged into greater overall resource efficiency even if resource consumption increases during the manufacturing phase [2]. Future work will seek to consider these potential improvements by analyzing how changes to surface quality may impact use phase resource usage. In addition, future work will investigate the machining parameters necessary for optimal surface quality to determine the manufacturing resource costs required to maximize resource efficiency during use.

The analysis presented still contains some limitations that should be addressed in future work. For example, flank wear was only considered when analyzing tool wear while the surface roughness results indicate that the cutting edge radius should also be monitored. The surface roughness analysis itself only considered the feed direction, and there are several other surface quality metrics that would be important to consider for many aerospace or related applications such as geometrical accuracy and residual stress. Also, the test part itself had a relatively simple geometry that was machined in a non-industrial setting; better mimicking an actual production part in an actual production environment may lead to other benefits or risks not apparent in this analysis. Ultimately, though, this analysis shows how different green machining strategies may have far reaching effects on a product's resource efficiency, all of which must be considered to ensure that a manufacturer is actually improving the sustainability of a process or product.

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References

[1] Helu, M., Behmann, B., Meier, H., Dornfeld, D., Lanza, L., Schulze, V. (2012) Total Cost Analysis of Process Time Reduction as a Green Machining Strategy. Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, 299-304.

[2] Helu M, Vijayaraghavan A, Dornfeld D (2011) Evaluating the Relationship Between Use Phase Environmental Impacts and Manufacturing Process Precision. *CIRP Annals – Manufacturing Technology* 60(1):49–52.

[3] M'Saoubi R, Outeiro JC, Chandrasekaran H, Dillon OW, Jawahir IS (2008) A Review of Surface Integrity in Machining and Its Impact on Functional Performance and Life of Machined Products. *International Journal of Sustainable Manufacturing* 1(1/2):203–236.

[4] Neugebauer R, Wertheim R, Harzbecker C (2011) Energy and Resource Efficiency in the Metal Cutting Industry. *Proceedings of the 8th Global Conference on Sustainable Manufacturing* 247–257.

[5] Kara S, Li W (2011) Unit Process Energy Consumption Models for Material Removal Processes. *CIRP Annals – Manufacturing Technology* 60(1):37–40.

[6] Diaz N, Redelsheimer E, Dornfeld D (2011) Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use. *Proceedings of the 18th CIRP International Conference on Life Cycle Engineering*, Braunschweig, Germany, 263–267.

[7] Mativenga PT, Rajemi MF (2011) Calculation of Optimum Cutting Parameters Based on Minimum Energy Footprint. *CIRP Annals – Manufacturing Technology* 60(1):149–152.

[8] Weinert N, Chiotellis S, Seliger G (2011) Methodology for Planning and Operating Energy-Efficient Production Systems. *CIRP Annals – Manufacturing Technology* 60(1):41–44.

[9] Herrmann C, Thiede S, Kara S, Hesselbach J (2011) Energy Oriented Simulation of Manufacturing Systems – Concept and Application. *CIRP Annals – Manufacturing Technology* 60(1):45–48.

[10] Branker K, Jeswiet J, Kim IY (2011) Greenhouse Gases Emitted in Manufacturing A Product – A New Economic Model. *CIRP Annals – Manufacturing Technology* 60(1):53–56.

[11] Mori M, Fujishima M, Inamasu Y, Oda Y (2011) A Study on Energy Efficient Improvement for Machine Tools. *CIRP Annals – Manufacturing Technology* 60(1):145–148.

[12] Jawahir IS, Brinksmeier E, M'Saoubi R, Aspinwall DK, Outeiro JC, Meyer D, Umbrello D, Jayal AD (2011) Surface Integrity in Material Removal Processes: Recent Advances. *CIRP Annals – Manufacturing Technology* 60(2):603–626.

[13] Avram O, Stroud I, Xirouchakis P (2011) A Multi-criteria Decision Method for Sustainability Assessment of the Use Phase of Machine Tool Systems. *Journal of Advanced Manufacturing Technology* 53(5–8):811–828.

[14] Fratila D (2009) Evaluation of Near-dry Machining Effects on Gear Milling Process Efficiency. *Journal of Cleaner Production* 17(9):839–845.

[15] Sheng P, Srinivasan M (1995) Multi-objective Process Planning in Environmentally Conscious Manufacturing. *CIRP Annals – Manufacturing Technology* 44(1):433–437.

[16] Dahmus JB, Gutowski TG (2004) An Environmental Analysis of Machining. *Proceedings of the ASME International Mechanical Engineering Congress and RD&D Expo*, Anaheim, CA, 1–10.