# Product and Process Impacts of Green Machining Strategies

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## Introduction

- Green machining strategies decrease environmental impacts, but may also:
  - Increase stresses, forces, and heat generation on tool, part, machine
  - Impact several aspects of manufacturing system such as:
    - Availability
    - Service life
    - Achieved part quality
    - Cost
- Current analyses of green machining strategies focus on:
  - Environmental impacts, primarily energy, using LCA approaches
  - Trade-offs between environmental and economic impacts (e.g., combined LCA + LCC, eco-efficiency, and target costing approaches)
  - Trade-offs between environmental and technical impacts, primarily for processes (e.g., Life Cycle Performance evaluation and manufacturing process and system planning tools)
  - Trade-offs between environmental, economic, and technical impacts using multi-objective optimization, specifically analytic hierarchical processes

## Objectives

- Build upon previous work in the literature by extending manufacturing analyses to evaluate:
  - Environmental impact (electrical energy usage)
  - System performance (availability, service life, tool wear)
  - Achieved part quality (surface roughness, local strain hardening)
- Apply this approach to a *baseline* scenario and a set of processing *alternatives* to turn Ti-6Al-4V test parts ($D_i$ = 25 mm; $L_{cut}$ = 80 mm) using uncoated carbide inserts and flood cooling:

| ***Baseline*** | 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 |

| ***Alternative 1*** | Baseline, but w/ no cutting fluid |
|---|---|

| ***Alternatives 2*** | 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* (mm) | (1x) 3.0 | (3x) 0.5 |
| | (1x) 4.0 | (1x) 0.5 |
| | (2x) 2.1 | (1x) 0.3 |
| | (2x) 2.15 | (1x) 0.2 |

## Methodology

### Electrical energy analysis:

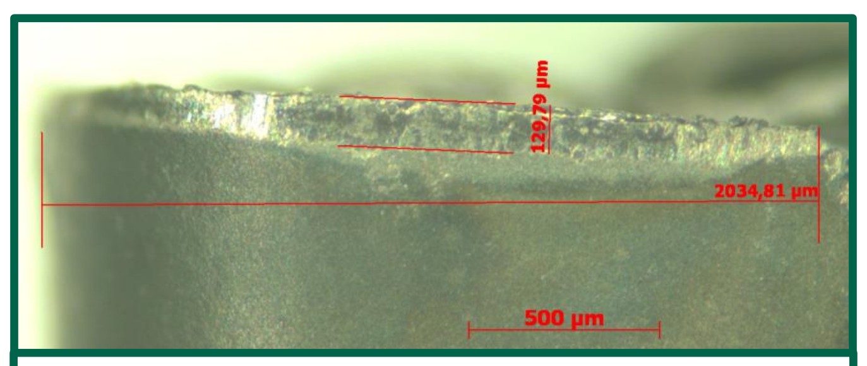
- Measured Real power at 10 Hz
- Adjusted for internal cooling
- Included tool change
- Used Karlsruhe energy mix:
  - 418 g-$CO_2$/kWh
  - €0.2332/kWh

### Service cost analysis:

- Focused on spindle
- Analyzed statistical failure behavior (Weibull approach)
  - Stress cycles along turning axis measured with Kister 9255B three component dynomometer
  - Historical breakdown behavior from similar machine tool
- Averaged results of Monte Carlo simulation assuming full utilization of machine tool

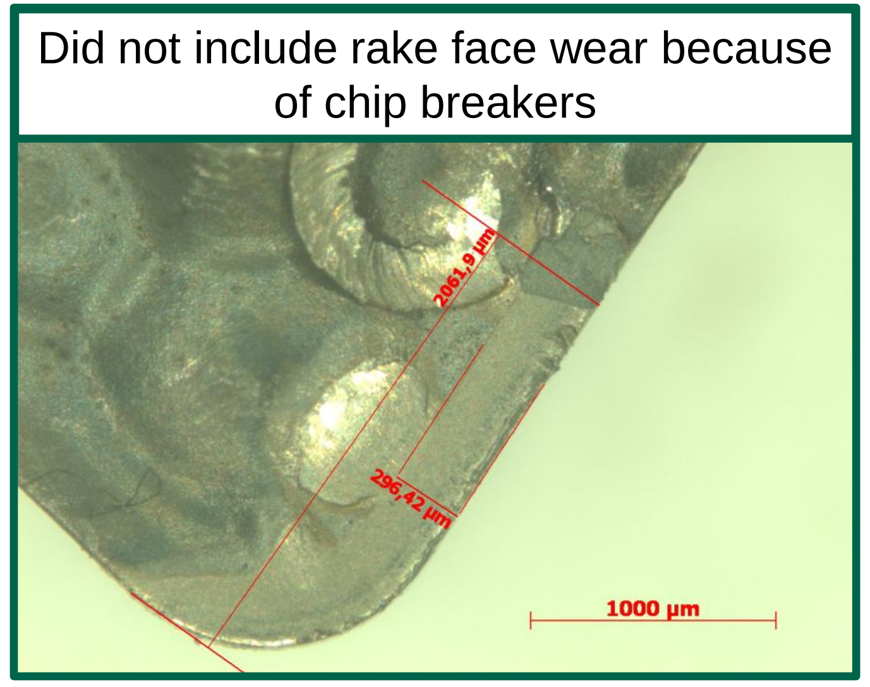
| ***Simulation Variables*** | | | |
|---|---|---|---|
| Early breakdowns | 40% of total | Service cost | €300 |
| Probability of random breakdowns | 0.1% | Service duration | 4 hours |
| Production loss | €4000/hour | Service technician cost | €50/hour |
| Spindle cost | €10000 | Service scheduled | 30% of time remaining |
| Avg. time b/t service | 3000 hour | | |

### Tool wear analysis:



Measured flank wear land width (VB) of major cutting edge after both final rough and finish cuts using microscope

Did not include rake face wear because of chip breakers



### Surface roughness measurement:

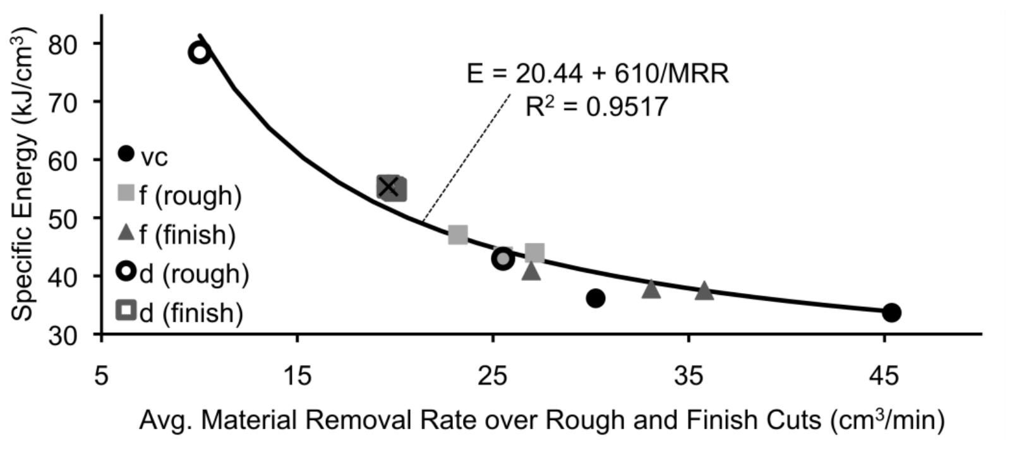
- Measured after final rough and finish cut
  - Averaged values from tip and shoulder of part
- Utilized Concept Contur PST-MSE stylus type instrument
  - Scan length = 10 mm (in feed direction)
  - Scan speed = 0.5 mm/s
  - Stylus tip radius = 25 µm

### Local strain hardening measurement:

- Measured full width at half maximum (FWHM) of x-ray interference patterns after final finish cut
  - {2 1 3}-diffraction lines of α-phase were studied using Ni-filtered Cu Kα radiation
  - Average of 5 tilt angles reported
  - FWHM increases as dislocation density increases

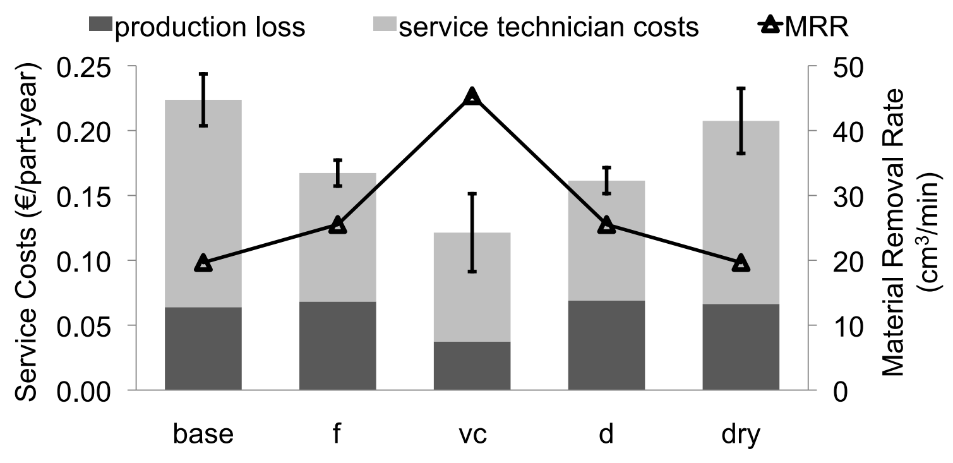
## Results (Baseline Marked by "X")

### Electrical energy:



- Cost and emissions scale with energy
  - Baseline = €0.08 and 150 g-$CO_2$
- Dry machining needs less energy (44.3 kJ/$cm^3$)
- Benefits decrease as MRR increases

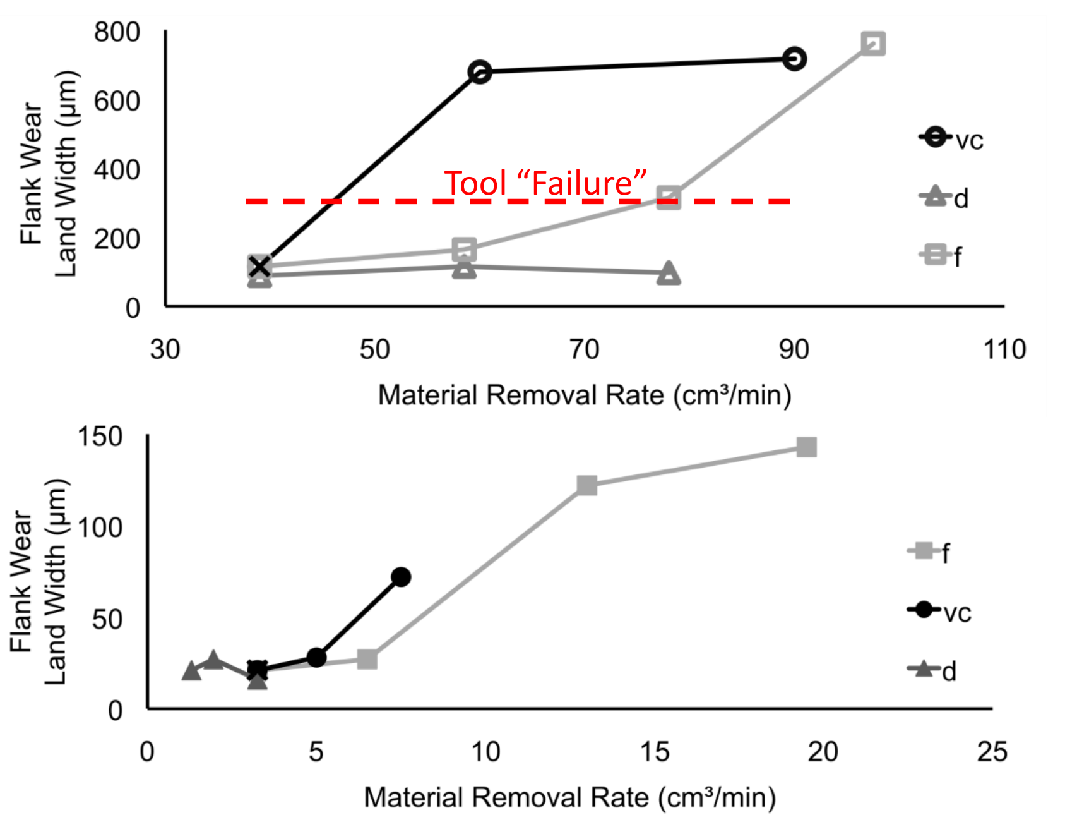
### Service costs:



- ↑ *d* has highest service costs
  - Most aggressive strategy on spindle
- ↑ $v_c$ has lowest service costs
  - Lower mechanical loads, but potentially higher thermal loads
- Largest costs due to production loss
- Unexpected breakdowns add variability

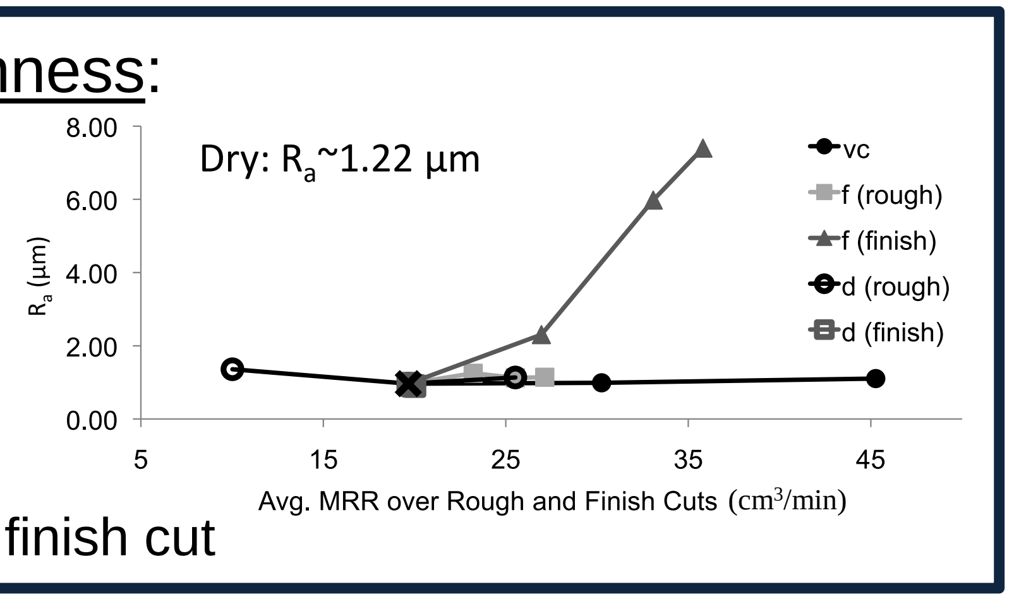
### Tool wear:

Dry: Rough ~130 µm; Finish ~24 µm



- Flank wear most influenced by $v_c$, *f*
  - ↑ thermal gradients = ↑ material diffusion and plastic deformation
- Tool life difficult to determine
  - Generally surface quality based decision
- Tool use = high impact: ~1 MJ/cutting edge

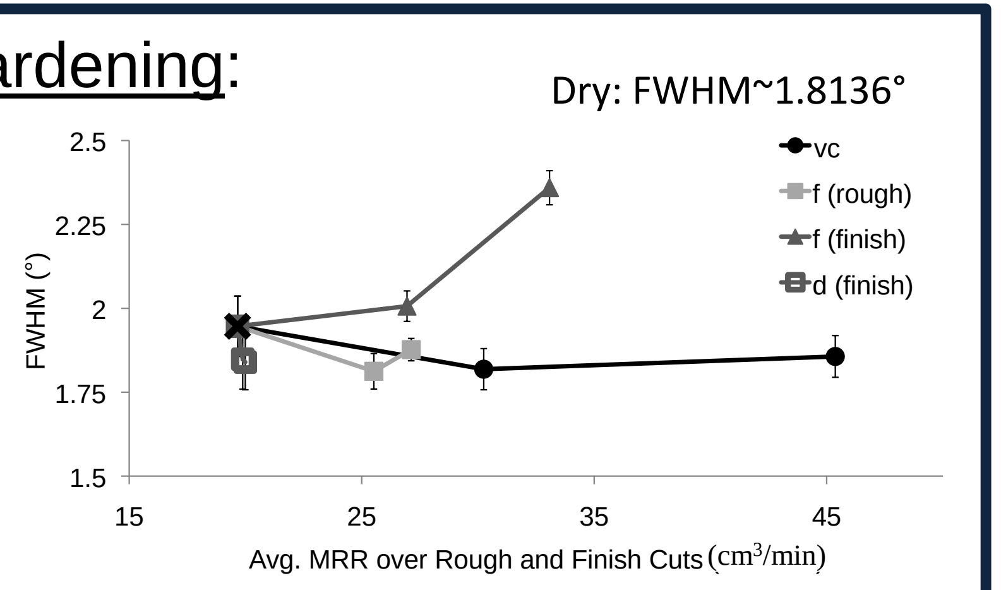
### Surface roughness:



- Primarily driven by feed marks
- Final roughness strongly influenced by finish cut

### Local strain hardening:

Dry: FWHM~1.8136°



- Feed rate had highest influence
  - ↑ elastic-plastic deformation in shear zone
  - ↑ tool wear and surface roughness
- FWHM strongly influenced by finish cut

## Conclusions

| | Electrical Energy | Tool Wear | Service Costs | Surface Roughness | Local Strain Hardening |
|---|---|---|---|---|---|
| ↑ $v_c$ | ↓ | ↑ | ↓ | - | - |
| ↑ *f* | ↓ | ↑ | ↓ | ↑ | ↑ |
| ↑ *d* | ↓ | - | Variable | - | - |
| Dry | ↓ | ↑ | - | - | - |

- Process time reduction has far reaching impacts
- Part functionality plays critical role in total costs
  - Dictates tool life and subsequent costs
  - Allows for trade-offs between manufacturing and use to decrease overall life cycle impacts
- None of the strategies may be viable for titanium
  - Great financial risks associated with unexpected breakdowns
  - Tooling of great concern
    - Maximum electrical energy saved is ~500 kJ but each cutting edge requires ~1 MJ of embodied energy
  - Potential impact on surface integrity can reduce operational efficiency of part

## Future Work

- Limitations of current analysis:
  - Simple test piece made of difficult-to-cut material
  - Non-industrial setting
  - Only focused on electrical energy
  - Only investigated flank wear
  - Variability in service costs caused by unexpected breakdowns
- Future work:
  - Determine appropriate case study part to investigate part functionality effects
  - Determine optimal process parameters that maximize resource efficiency over life cycle
  - Incorporate other tool wear metrics
    - Rake face measurements?
  - Incorporate other surface quality metrics
    - Geometrical accuracy
    - Residual stress
  - Develop run charts to aid process planning

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