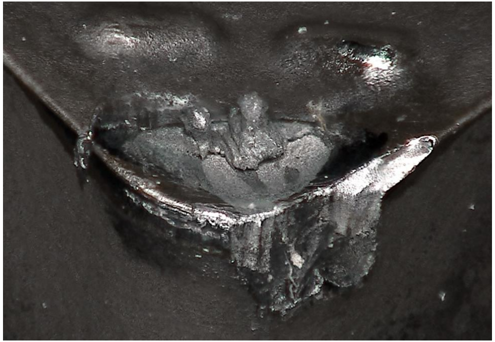
Cutting Inserts Wear Monitoring in AISI 1045 Dry Longitudinal Turning through Cutting Forces: a Case Study



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Industrial Context

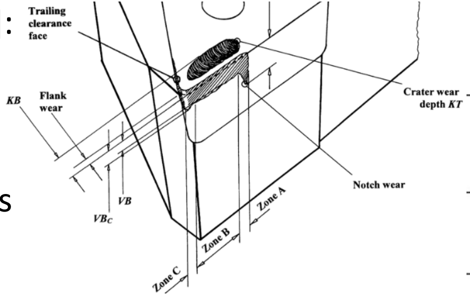
- High industrial financial stakes
- Example: Oil industry pipe threading
  - 100 000€/month cutting inserts for one machine-tool
  - Cutting insert end-of-life:
    - Operator's hearing
    - (Unaided) visual cutting insert observation
    - Mirror finish of the thread
    - Tolerance: 5-10 µm
  - 1-2 % scrap

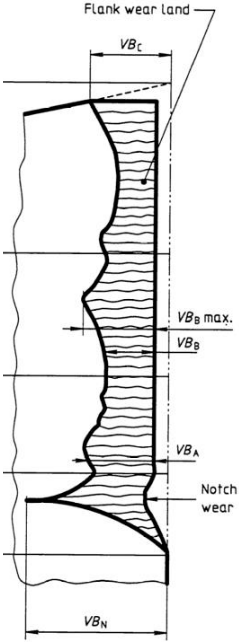
Empirical (Operator's hearing; (Unaided) visual cutting insert observation; Mirror finish of the thread)

- Is it possible to save on cutting inserts without worsening the scrap rate?

Cutting tools degradation

- Flank wear
  - Most predictable [1, 2]
  - Most advisable [1, 2]
  - Mainly due to abrasion [1, 2]
    - End-of-life criterion [3]:
      - VB=0.3 mm (mean)
      - VB=0.6 mm (max)
    - Specific to life-testing
    - Industrial practice differs

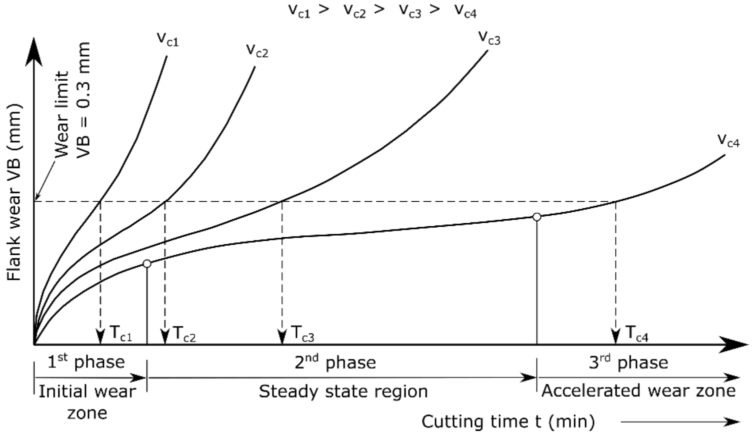




[1] Sandvik Coromant, Training Handbook - Metal Cutting Technology. AB Sandvik Coromant, 2017.
[2] Seco Tools, Turning catalog and technical guide, 2nd ed. SECO TOOLS AB, 2018.
[3] "ISO 3685:1993 - Tool-life testing with single-point turning tools."

Cutting tools degradation

- Degradation modeling
  - Tool life models (Taylor's model) [1]
  - Description of degradation trajectory [2]
  - Degradation models
    - Archard [3]
    - Takeyama and Murata [4]
    - Usui [5]



→ **Arrhenius laws**

[1] V. P. Astakhov and J. P. Davim, "Tools (Geometry and Material) and Tool Wear," in *Machining - Fundamentals and Recent Advances*, Springer-V., J. P. Davim, Ed. London: Springer London, 2008, pp. 29–57.
[2] Y. Altintas, *Manufacturing automation*. Cambridge University Press, 2012.
[3] J. F. Archard, "Contact and Rubbing of Flat Surfaces," *J. Appl. Phys.*, vol. 24, no. 8, pp. 981–988, 1953.
[4] H. Takeyama and R. Murata, "Basic Investigation of Tool Wear," *J. Eng. Ind.*, vol. 85, no. 1, p. 33, 1963.
[5] E. Usui, T. Shirakashi, and T. Kitagawa, "Analytical prediction of cutting tool wear," *Wear*, vol. 100, no. 1–3, pp. 129–151, 1984.

Degradation monitoring

- Condition monitoring
  - Vibratory frequential contents below 10 kHz (~~RMS~~) [1]
  - Noise (change in pitch) [2]
  - Cutting forces (RMS, $\frac{F_f}{F_c}$ ratio) [3]
  - Tool temperature [4]
  - Quality (roughness, dimensional deviation) [5]

[1] D. R. Salgado and F. J. Alonso, "Tool wear detection in turning operations using singular spectrum analysis," *J. Mater. Process. Technol.*, vol. 171, no. 3, pp. 451–458, 2006.
[2] M.-C. Lu and E. Kannatey-Asibu, "Analysis of Sound Signal Generation Due to Flank Wear in Turning," *J. Manuf. Sci. Eng.*, vol. 124, no. 4, p. 799, 2002.
[3] A. Attanasio, E. Ceretti, A. Fiorentino, C. Cappellini, and C. Giardini, "Investigation and FEM-based simulation of tool wear in turning operations with uncoated carbide tools," *Wear*, vol. 269, no. 5–6, pp. 344–350, 2010.
[4] L.-J. Xie, J. Schmidt, C. Schmidt, and F. Biesinger, "2D FEM estimate of tool wear in turning operation," *Wear*, vol. 258, no. 10, pp. 1479–1490, 2005.
[5] L. Equeter, R. Devlamincq, F. Ducobu, C. Dutoit and P. Dehombreux, "Use of Longitudinal Roughness Measurements as Tool End-of-Life Indicator in AISI 1045 Dry Longitudinal Turning," *Material Science Forum*, in press (2019)

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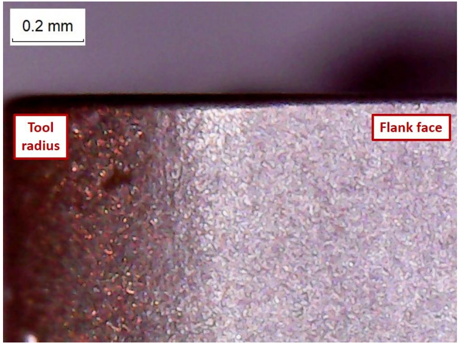
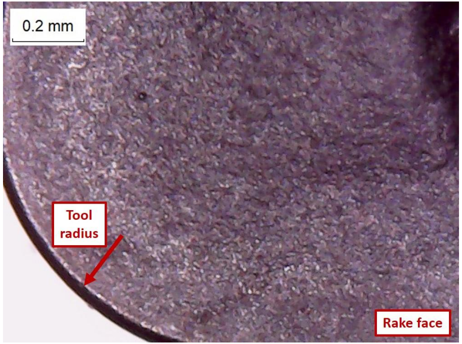
Experimental Setting

- Workpiece: cylindrical bars
  - AISI 1045 (154 HV_{30})
  - 250 mm length, 58 mm diameter, 10 passes with a_p = 0.7 mm
  - Wear, Forces and roughness measurements every 10 passes

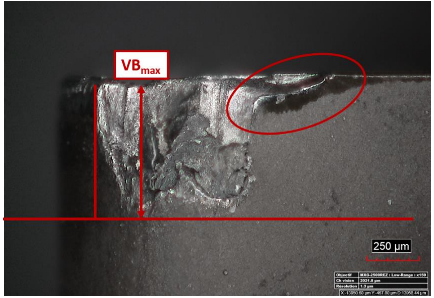
Tool Wear

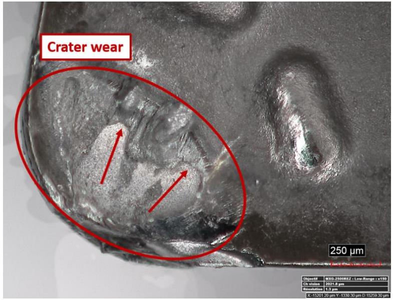
Before



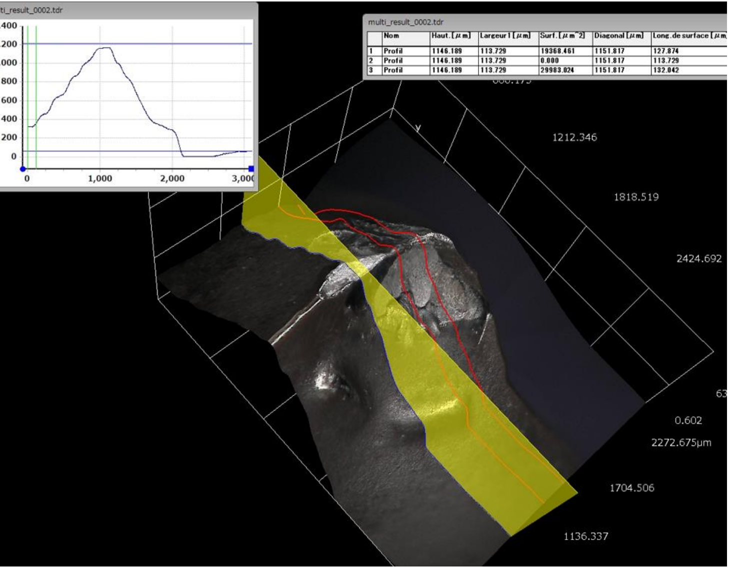


30 min
dry turning

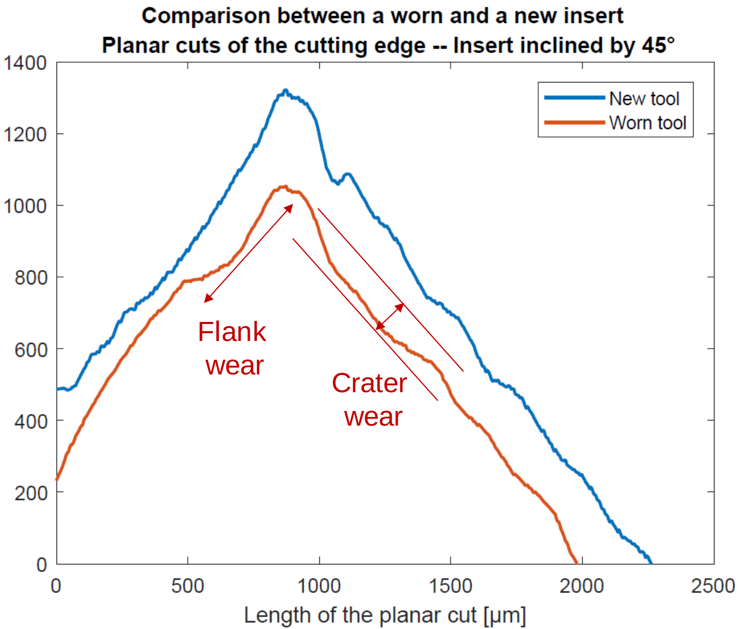




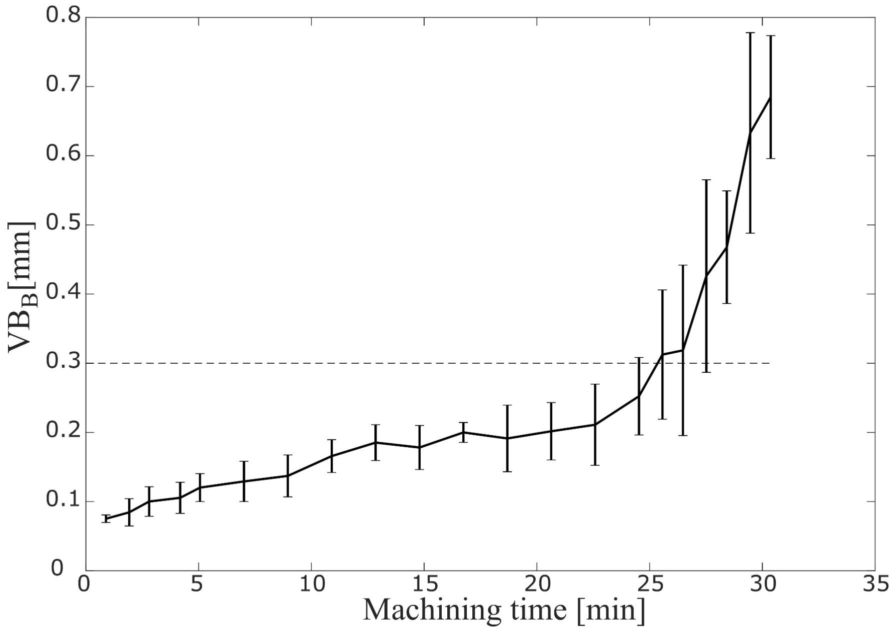
Tool Wear



	Nom	Haut.[µm]	Largeur1[µm]	Surf.[µm^2]	Diagonal[µm]	Long.de surface[µm]
1	Profil	1146.189	113.729	19368.461	1151.817	127.874
2	Profil	1146.189	113.729	0.000	1151.817	113.729
3	Profil	1146.189	113.729	29983.024	1151.817	132.042



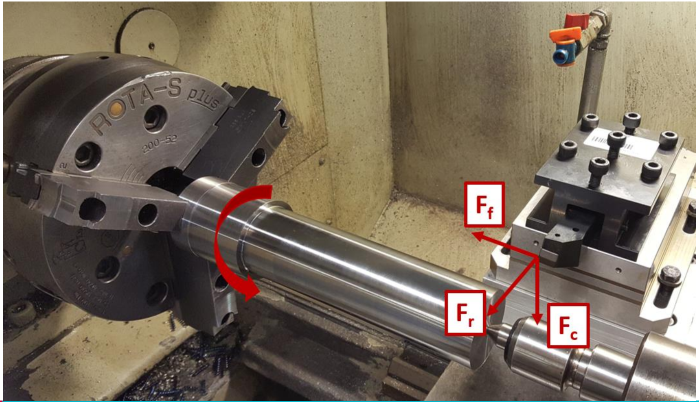
Tool wear



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
VB_B[mm]
0
5
10
15
20
25
30
35
Machining time [min]

Cutting Forces Measurement

- Cutting, feed and radial force
  - Triaxial Kistler 9257B force sensor
  - Sensitivity: -7.5 pC/N (F_f and F_r); -3.7 pC/N (F_c)
  - RMS values over the pass



Cutting Forces and Tool Wear

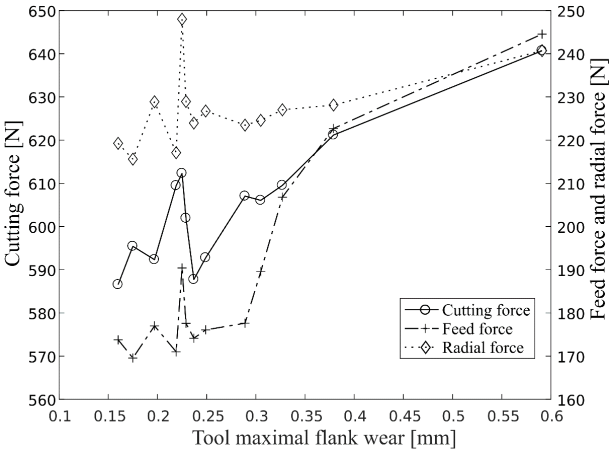
- Cutting, **Feed** and Radial Force
  - Increases of resp. 9%, **40%** and 10%
  - Locally important increase prior to tool end-of-life

Correlation vs. $VB_{B,mean}$

	Pearson correlation coefficient	95 % confidence interval	*p*-value
$VB_{B,mean}$ vs F_c	0.81	[0.47, 0.94]	< 0.001
$VB_{B,mean}$ vs F_f	0.87	[0.63, 0.96]	< 0.001
$VB_{B,mean}$ vs F_r	0.51	[-0.05, 0.83]	0.07

Correlation vs. $VB_{B,max}$

	Pearson correlation coefficient	95 % confidence interval	*p*-value
$VB_{B,max}$ vs F_c	0.88	[0.63, 0.96]	< 0.001
$VB_{B,max}$ vs F_f	0.93	[0.78, 0.98]	< 0.001
$VB_{B,max}$ vs F_r	0.48	[-0.10, 0.81]	0.10

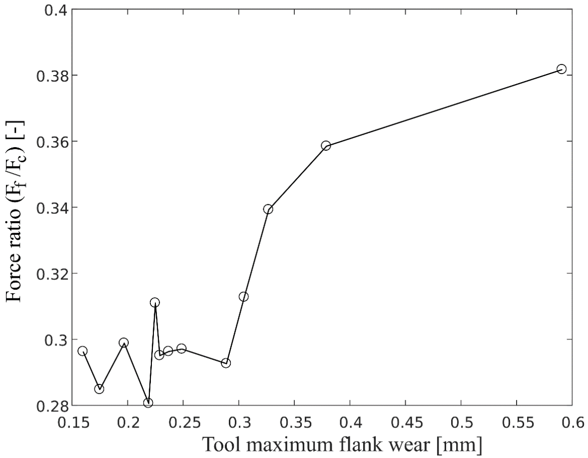


Force ratio $\frac{F_f}{F_c}$ and Tool Wear

- Major indicator of tool wear in literature
  - 29% increase
  - Locally important increase prior to tool end-of-life

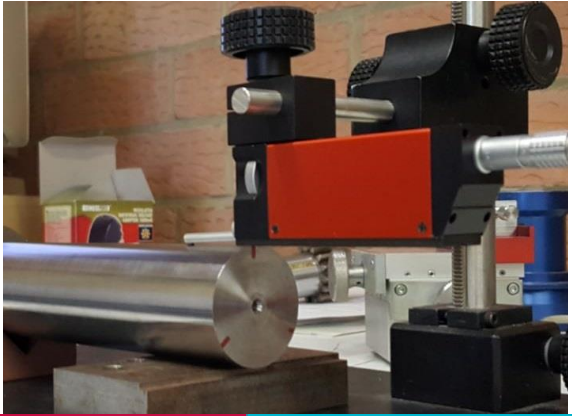
Correlation vs. $VB_{B,mean}$ and $VB_{B,max}$

	Pearson correlation coefficient	95 % confidence interval	*p*-value
$VB_{B,mean}$ vs F_f/F_c	0.86	[0.59, 0.96]	< 0.001
$VB_{B,max}$ vs F_f/F_f	0.90	[0.69, 0.97]	< 0.001



Roughness Measurement

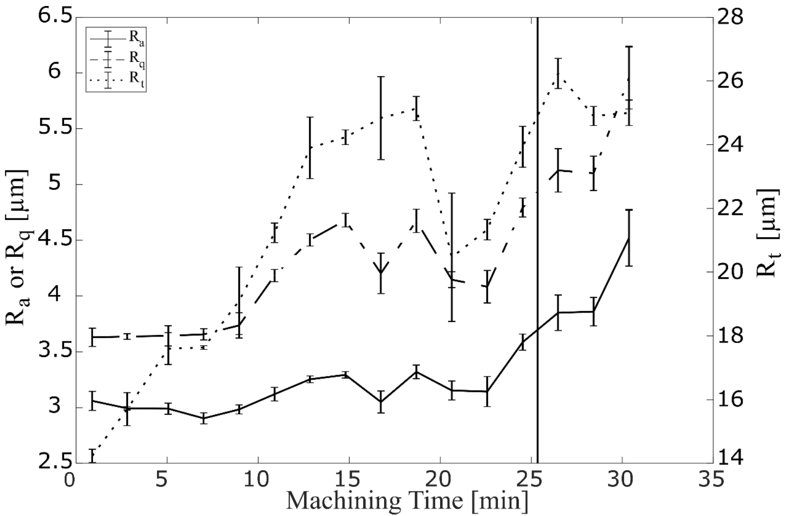
- Total, arithmetic and quadratic roughness
  - Rt = total height of the profile
  - Ra = arithmetic average roughness
  - Rq = quadratic average roughness



- Diavite DH-6 roughometer
- 3 longitudinal measurements on each bar, separated by 120°
- Gaussian filter in accordance with ISO 16610

Roughness and Tool Wear

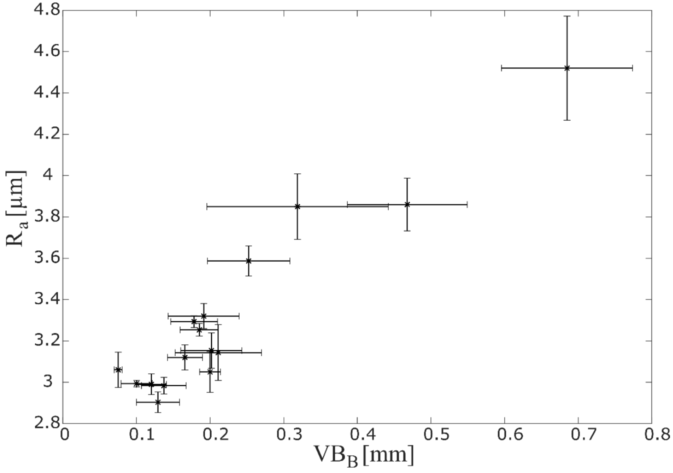
- Total, arithmetic and quadratic roughness
  - Increases of resp. 75, 47 and 64 %
  - Indicator may be considered
    - Not monotonous evolution
    - Not on-line measurement
  - Locally important increase at tool end-of-life



Roughness and Tool Wear

- Arithmetic roughness as an indicator of tool wear
  - ρ=0.95, CI95 is [0.86, 0.98] → very strong correlation
  - p<.001 → significant

	Pearson Correlation coefficient	95 % confidence interval	*p*-value
VB_B vs R_a	0.95	[0.86, 0.98]	< 0.001
VB_B vs R_t	0.62	[0.17, 0.85]	0.011
VB_B vs R_q	0.90	[0.72, 0.96]	< 0.001



Conclusions

Cutting forces indicators may be extremely relevant

- On-line condition monitoring
- RMS value is sufficient to gain valuable knowledge

But…

- Image of tool wear rather than production quality

Roughness indicators may be extremely relevant

- Focus on production quality hence value
- Relevance of standard-recommended indicator questioned
  - Flank wear → wear on nose radius and trailing edge

But…

- No account of other quality indicators
  - Residual stresses, dimensional accuracy, etc.
- Based on sampled quality control
- Complex for on-line use

Thank you for your attention!