A time-dependent Proportional Hazard model for cutting tools Remaining Useful Life estimate under varying cutting parameters

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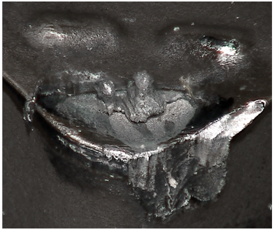

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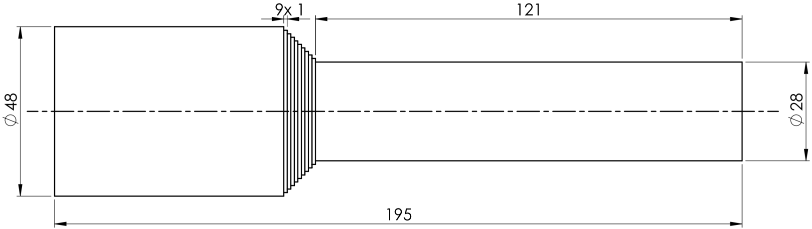
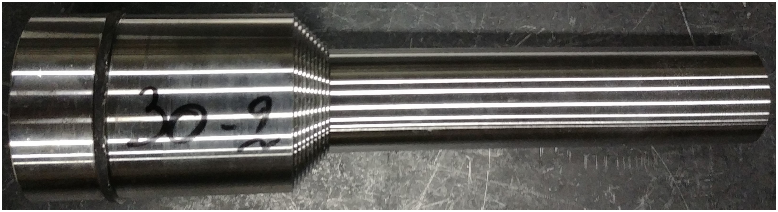
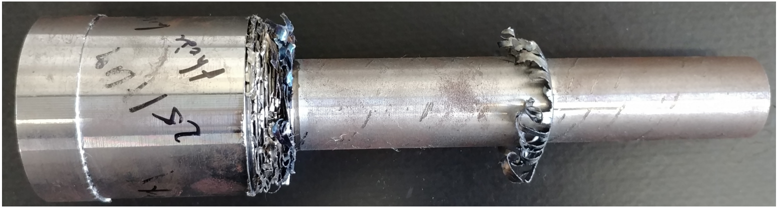

9x 1
121
ϕ48
ϕ28
195






DCLNR2020K12–M
SECO

Current procedures

Criteria for replacement:

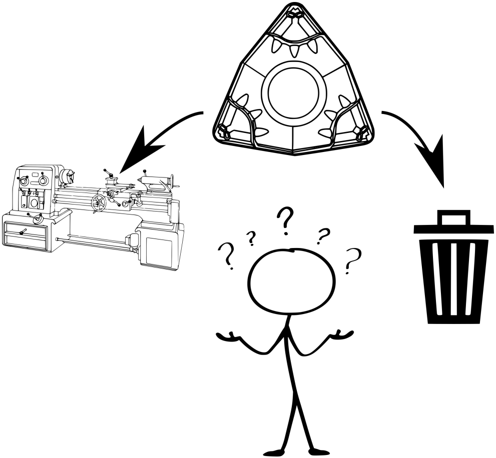
- Worker's experience (machine noise)
- Machining time (since last replacement)
- **Tool condition monitoring** (rarely)

ISO 3685 standard recommended value:

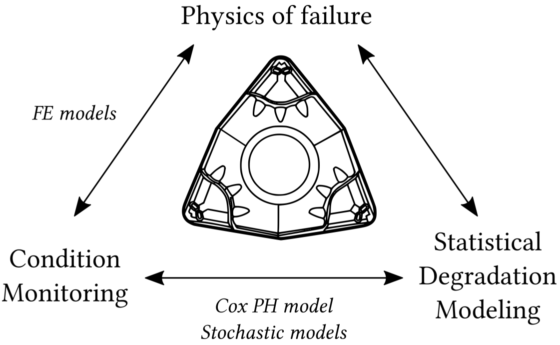
$$VB = 0.3 \text{ mm}$$

How to determine the RUL?

→ Remaining Useful Life



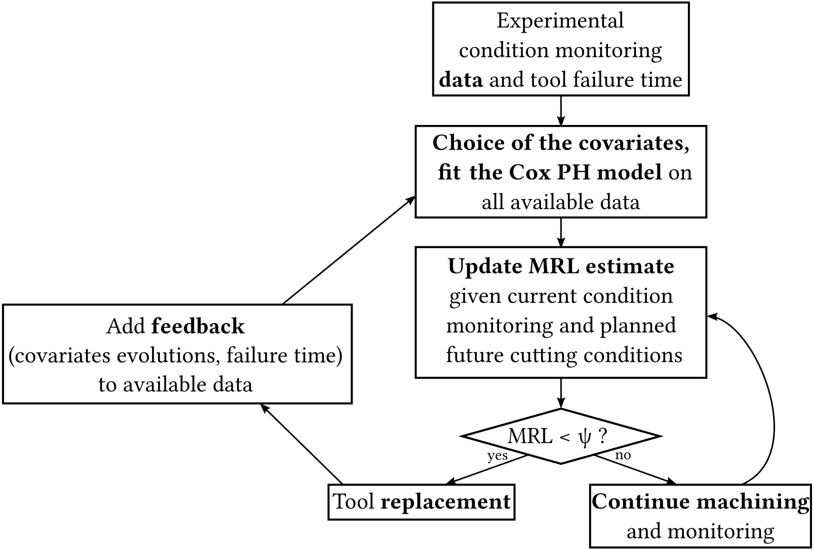
Tool RUL Estimate



- Physical degradation models
- Condition monitoring approaches[1]
- Statistical degradation/failure modeling

[1] A. Siddhpura and R. Paurobally, "A review of flank wear prediction methods for tool condition monitoring in a turning process," *The International Journal of Advanced Manufacturing Technology*, vol. 65, no. 1-4, pp. 371–393, 2013.

Extended Cox PH model



Cox Proportional Hazards Models

General expression: $h(t) = h_0(t) \cdot \exp(\Psi(\theta, \alpha))$

- $h_0(t)$ the baseline hazard (without influence of the covariates)
- Ψ a function of:
  - α the covariates (any variable related to the hazard rate ; may be time-dependent, but not colinear)
  - θ their weighting coefficients

Fitting through maximum likelihood (θ) and direct computation of non-parametric $h_0(t)$

Often expressed as: $h(t) = h_0(t) \cdot \exp\left(\sum_{i=1}^{p} \theta_i \alpha_i(t)\right)$

Cox Proportional Hazards Models (data transformation)

General expression: $h(t) = h_0(t) \cdot \exp\left(\sum_{i=1}^{p} \theta_i \alpha_i\right)$

(time-independent)

- Output: $h(t)$
- $\Rightarrow$ lifetime estimate: $MUT = \int_0^\infty R(t)\,\mathrm{d}t$
  (with the reliability $R(t) = \exp\left(-\int_0^t h(y)\,\mathrm{d}y\right)$)

… Should one normalize or transform the covariates?

- No variable normalization (weighting coefficients)
- Analytical developments → Variable transformation[2] in order to match Taylor's law → link between the covariate and the hazard rate

[2] L. Equeter *et al.*, "An Analytic Approach to the Cox Proportional Hazards Model for Estimating the Lifespan of Cutting Tools," *Journal of Manufacturing and Materials Processing*, 2020.

Time-Dependent Cox Proportional Hazards Models

General expression: $h(t) = h_0(t) \cdot \exp\left(\sum_{i=1}^{p} \theta_i \alpha_i(t)\right)$

(time-dependent)

- Update of RUL estimate through tool life
- Well adapted to condition monitoring
- Complexity: covariate values after the current time?
  $MUT = \int_0^{\infty} R(t)\,\mathrm{d}t$
  - Very practical for planned varying cutting conditions
  - Values of the covariates? → linear extrapolation of last values

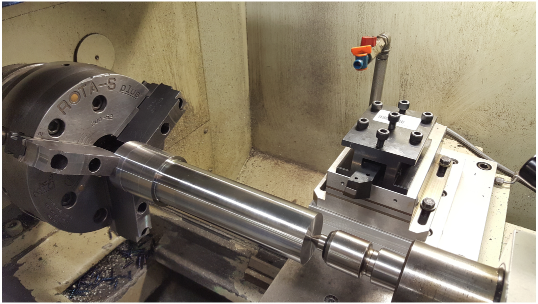
Experimental Work

Cutting edge number	Cutting speed ($m\,min^{-1}$)							
1–10	.... 260							
11–15	.... 250							
16	.... 240							
17–20	.... 265							
21	265	260	250	250	260	240	260	
22	260	240	250	250	260	240	260	
23	260	240	250	260	240	250	240	
24	260	250	260	240	250	260	240	
25	260	260	250	260	240	250	240	
26	260	240	250	260	240	250	240	
27	260	255	255	250	245	240	250	
28	260	255	255	250	245	240	240	250
29	240	260	240	255	240	250	250	250
30	240	260	240	255	240	250	250	260

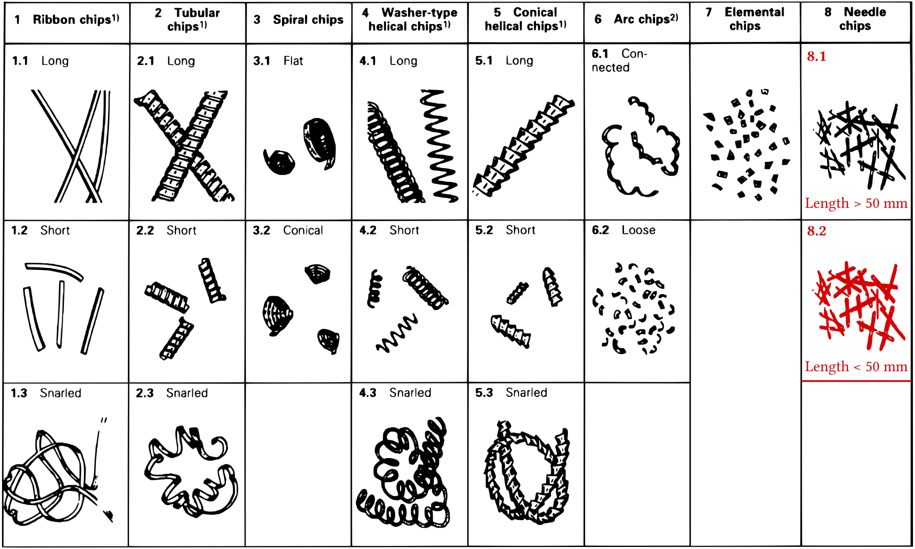
Experimental Work

30x CNMG120404-MF3 TP40; various cutting speeds ([240, 265] $\mathrm{m\,min^{-1}}$); 0.2 mm/rev; 1 mm

- Wear evolutions
- Cutting forces
- Electrical currents of 2 phases of the machine
- Workpiece roughness
- Chip samples (ISO 3685)



Experimental Work - chip sorting



Experimental Work

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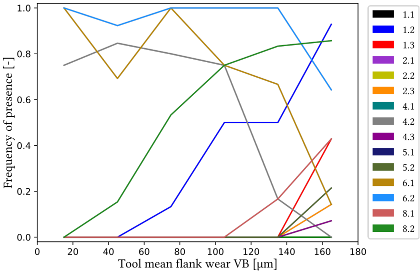

Cox PH model analysis

	Fitted value	95 % CI	p
F_f/F_c [-]	25.2	$[13.8, 37.6]$	<0.005
current [A]	12.5	$[1.1, 23.9]$	0.03
v_c [m/min]	-0.02	$[-0.03, -0.01]$	<0.005
chip 1.2	-0.7	$[-2.9, -1.5]$	0.53
chip 4.2	-2.1	$[-4.1, -0.1]$	0.04
chip 6.1	-1.9	$[-4.1, 0.2]$	0.08
chip 8.2	0.6	$[-1.2, 2.5]$	0.48
β	35	$[20, 51]$	0.01
η [min]	10.2	$[9.7, 11.5]$	0.01

Cox PH model result

	Fitted value	95 % CI	p
F_f/F_c [-]	24.8	[13.5, 36]	<0.005
β	36	[25, 46]	0.005
η [min]	10	[9.7, 10.6]	0.004

$$\Rightarrow h(t) = \frac{36}{10}\left(\frac{t}{10}\right)^{35} \cdot \exp\left(24.8 \cdot \frac{F_f}{F_c}\right)$$

Cox PH model

- Here based only on condition monitoring (force ratio F_f/F_c)
- **Overestimate the RUL** by $\sim$16% (in average)
- Possible correction through the parameter ψ
- $\rightarrow$ Case-specific optimization (costs, etc.)
- Complexity of the choice of covariates
- Possibility to use feedback to incrementally improve the model ("only" 30 inserts worn = 18 days of experiment)

Industrial implications

- What is a worn tool?
  - Focus on production quality first
  - Take into account the variability of the tool and material
- Determine an acceptable cost (or multi-criteria) optimization
- Equip the machines with **relevant** sensors and look for correlation with the end-of-life criterion
- Apply one of the presented methodologies
- Use the planned upcoming operations in the assessment

Conclusions and Outlook

- Extended PH model for cutting tools
- Extensive experimental work
  - Variable cutting parameters
  - Chip morphology as an indicator of tool wear

Outlook:

- Further experimental work
- Questions on the industrial tool replacement criteria
- Global process optimization on large data sets (industry 4.0)

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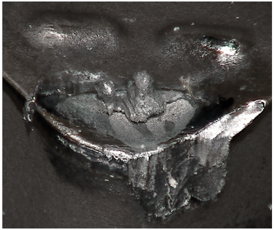

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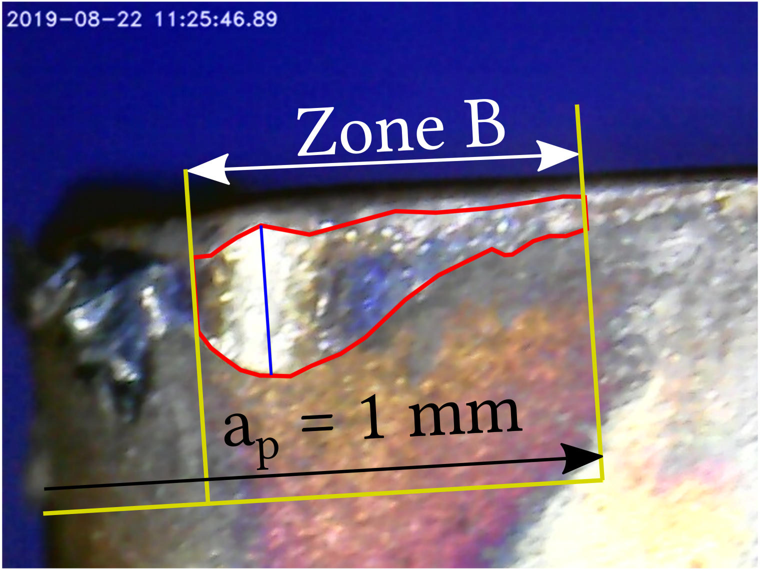
Wear Observations



Wear Observations

- Best correlation between flank wear and force ratio (+ feed and cutting forces)
- Regression: linear or logarithmic
- Other variables: electrical current, workpiece roughness, **chip morphology**