II. Crack Initiation and Crack Growth in the Tooth Root –

Gerrit Hellenbrand, M.Sc (WZL)

Aviation gearboxes are used to increase the efficiency of aircraft engines. By decoupling the fan and engine stages, the fan can be enlarged and the bypass ratio increased. Aircraft gearboxes quickly reach very high load cycles during their lifetime. The predominant damage is tooth root fracture of the planetary gear under fully reversed bending load. To increase power density, steels with high material cleanliness and optimized surfaces by shot peening and superfinishing are used. According to literature, subsurface induced fractures occur in shot peened gears in the range of high load cycles, while non-peened gears have a crack origin at the surface. This cannot be explained by standard-based calculation approaches. In the field of fracture mechanics this can be demonstrated for standard specimens with the aid of crack growth tests using fracture mechanic equations for crack growth. At the WZL, a lifetime prediction model for the tooth root was developed on basis of NASGRO equation. Calculation studies showed that a precise determination of the fracture mechanical input variables is important. In contrast to standard samples, gears have a hardness and residual stress profile that changes over the depth due to case hardening and shot peening. To take these depth curves into account in the NASGRO equation, crack propagation tests are carried out with different hard specimens and dependencies of the fracture mechanical inputs on the hardness are established. The dependencies are integrated into the lifetime prediction model. Finally, validation tests are carried out on the pulsator to calculate the lifetime.

Crack Initiation and Crack Growth in the Tooth Root

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The Brazilian Gear Conference ITA-WZL 2025, August 13th / 14th 2025

Funding:

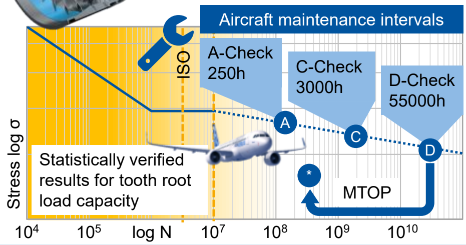
Agenda

1	**Introduction, Motivation, Aim and Approach**
2	Compact Tension Tests
3	Lifetime Prediction Model
4	Summary and Outlook

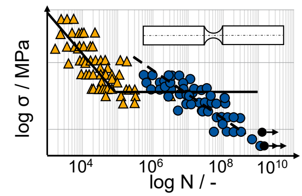
Introduction
High Number of Load Cycles in the Aerospace Sector

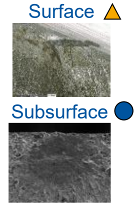
Pratt & Whitney PW1000G (A320neo)

- ▼ n_{Fan}
- ▲ d_{Fan}
- ▲ bypass ratio
- ▼ noice
- ▼ fuel
- ▼ CO_2



VHCF material behaviour (SAKAI)





Lebensdauerbetrachtung sinnvoller als Dauerfestigkeitsniveau?

- ▼ ISO 6336: Lebensdauerfaktor Y_{NT} bei N = 10^{10} von 0,85
- ▲ Gewichtseinsparung durch genauere Berechnung
- ▲ Besseres Verständnis der Schadensentwicklung

Introduction
High Number of Load Cycles in the Aerospace Sector

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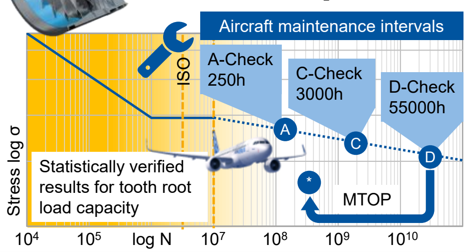

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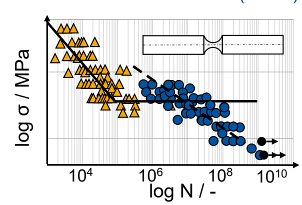
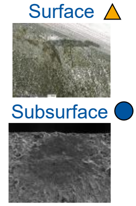
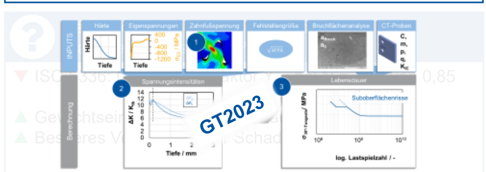
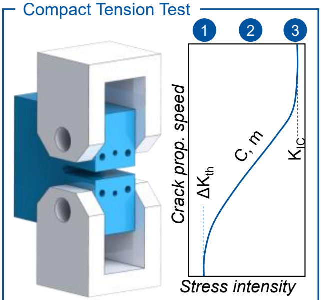






Introduction
Lifetime prediction via crack growth rate

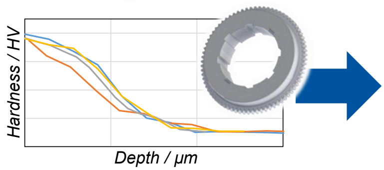
Compact Tension Test



ΔK_{th} = Threshold value
K_{IC} = Fracture toughness
C = PARIS constant
m = PARIS exponent

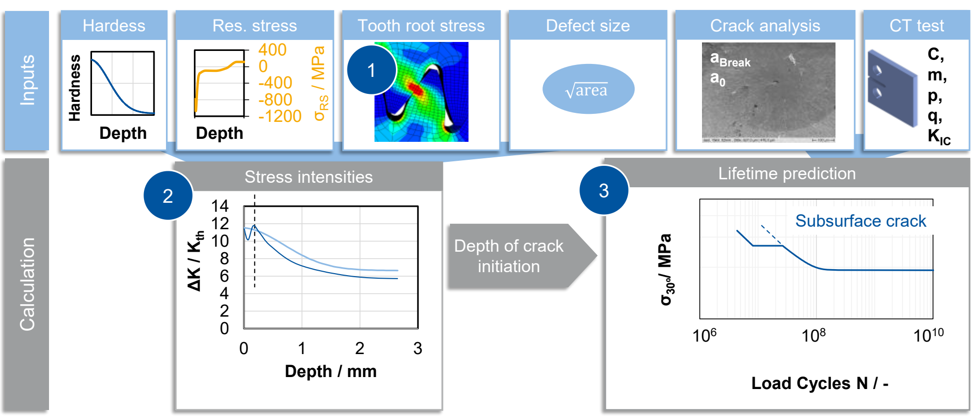
Equation	1	2	3	R = -1	√area	HV(x)	σ_{RS}(x)	Crack opening effect
PARIS	×	✓	×	×	×	×	×	×
FORMAN	×	✓	×	×	×	×	×	×
NEWMAN	×	✓	×	×	×	×	×	✓
NASGRO	✓	✓	✓	✓	×	×	×	✓
+MURAKAMI					✓	(✓)		
+loc. stress							✓	

GT2023



ΔK_{th} (HV) ?
K_{IC} (HV) ?
C (HV) ?
m (HV) ?

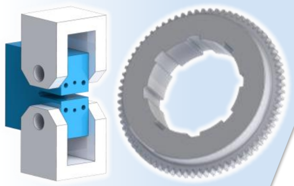
Introduction
Structure of the Lifetime Prediction Model for the Tooth Root



Aim and Approach

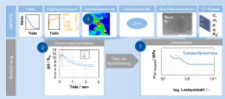
Extension of the lifetime prediction for the tooth root to include hardness-dependent fracture mechanics parameters

1 Investigation of the crack growth of gear steel

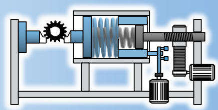


2 Extension of the tooth root lifetime prediction

K_{th} (HV
K_{IC} (HV)
C (HV)
m (HV)



3 Validation of the tooth root lifetime prediction through pulsator tests

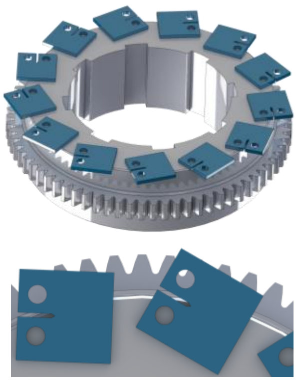


Agenda

1	Introduction, Motivation, Aim and Approach
2	**Compact Tension Tests**
3	Lifetime Prediction Model
4	Summary and Outlook

Compact Tension Tests
Specimen Extraction and Variants

Extraction of CT-specimens

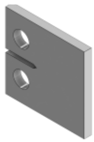


CT-specimen 25 mm

Carbon	Hardness
0.18 %	399 HV

Standard geometry for unhardened specimens ASTM E647

CT-specimen 3 mm



Carbon	Hardness
0.18 %	399 HV
0.35 %	571 HV
0.65 %	701 HV

Thinner due to carburization

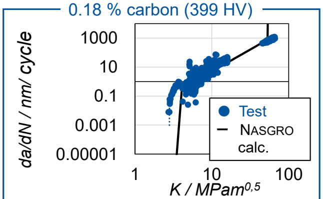
Test programm

		Stress ratio R			
		0.1	0.3	0.6	0.9
Carbon	0.18 %	x	x	x	x
	0.35 %	x	x	x	x
	0.65 %	x	x	x	x

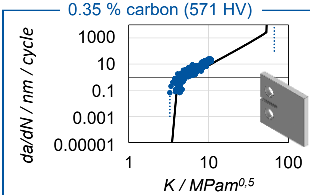
IWT
Leibniz-Institut für Werkstofforientierte Technologien

Compact Tension Tests
Evaluation of the Hardness Dependence at a Stress Ratio of R = 0.1

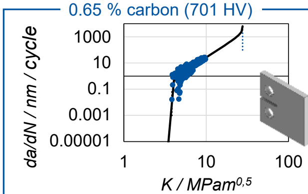
0.18 % carbon (399 HV)

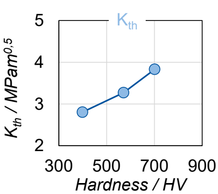


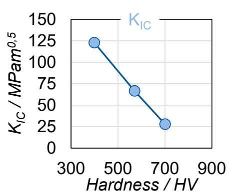
0.35 % carbon (571 HV)

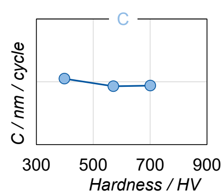


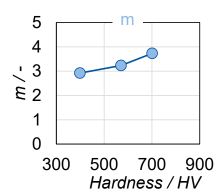
0.65 % carbon (701 HV)







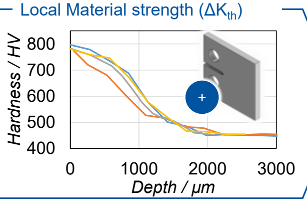




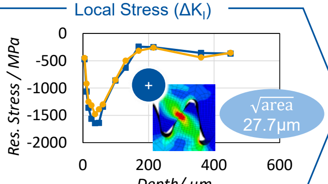
Agenda

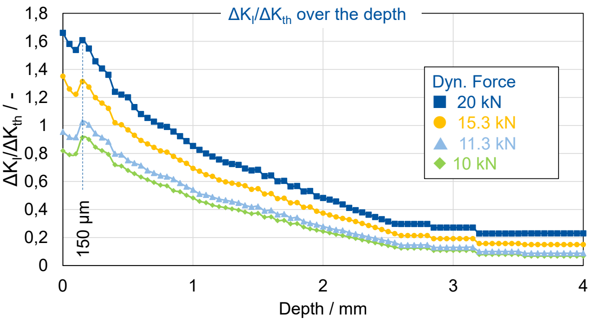
Lifetime Prediction Model
Calculation of the Crack Initiation Depth for R = 0.1

Local Material strength (ΔK_{th})



Local Stress (ΔK_I)





Conclusion for crack initiation

- For F_1 = 20 kN und F_2 = 15.3 kN Surface critical
- For F_3 = 11.3 kN t = 0.15 mm critical
- For F_4 = 10 kN no crack initiation

Lifetime Prediction Model
Lifetime Calculation with NASGRO Model

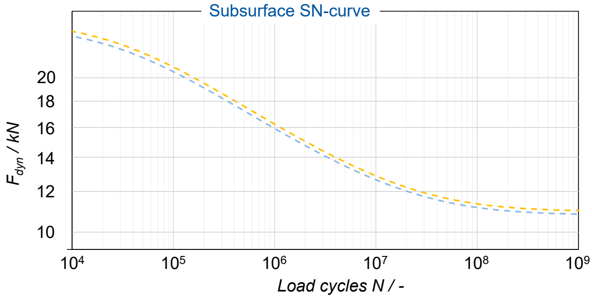
Calculation data

NASGRO Inputs

- R = 0.1
- C = Formel 4.7
- m = Formel 4.6
- p, q = 1
- K_{IC} = Formel 4.5
- K_{th} = Formel 4.3
- HV, σ_{ES} = Measured

Variation 1 : ------------------------
- RIT = 0.15 mm
- √area = 27,7 µm

Variation 2 : ------------------------
- RIT = 0.05 mm
- √area = 40 µm

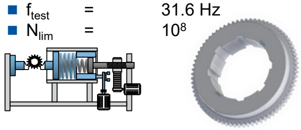


$$N = \frac{1}{C \cdot \left(\frac{1-f}{1-R}\right)^m} \cdot \int_{a_0}^{a} \frac{da \cdot \left(1 - \frac{\Delta K_{I,th}}{\Delta K_I}\right)^p}{\Delta K_I{}^m \cdot \left(1 - \frac{\Delta K_{I,max}}{K_{IC}}\right)^q}$$

Lifetime Prediction Model
Validation Tests on Pulsator Test Rig

Test data

- Test variant: 18CrNiMo7-6
- f_{test} = 31.6 Hz
- N_{lim} = 10^8

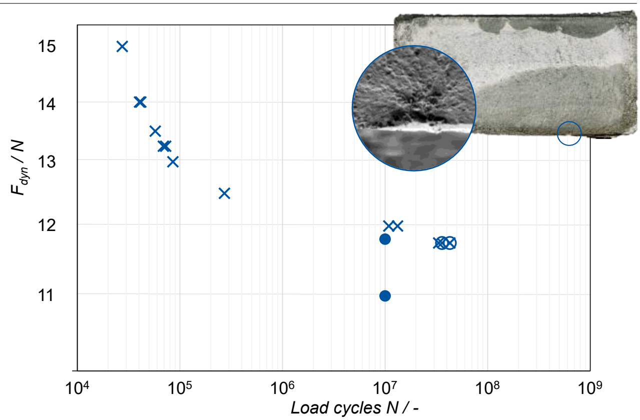


X Surface crack
⊗ Subsurface crack
● Run out
-- NASGRO calculation

Calculation data

Defect size and depth

- RIT = 50 µm
- √area = 40 µm



Lifetime Prediction Model
Validation Tests on Pulsator Test Rig

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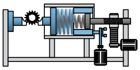

- X Surface crack
- ⊗ Subsurface crack
- ● Run out
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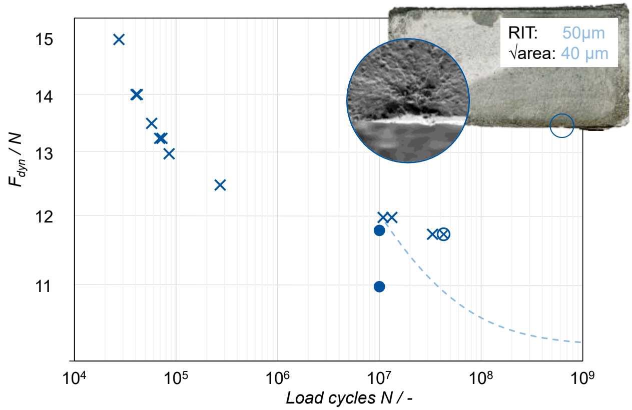

Agenda

Zusammenfassung und Ausblick
Summary and Outlook

Zusammenfassung Summary

- Risswachstumskurven zeigen Härteabhängigkeit
  Crack growth curves show hardness dependence
- Integration von Härteabhängigkeiten ins Lebensdauervorhersagemodel
  Integration of hardness dependencies into the fatigue life prediction model
- Rissausgangsort Suboberflächen konnte aufgrund hoher Laufzeiten bisher nicht erreicht werden
  Crack initiation site sub-surfaces could not be reached so far due to high lifetimes

Ausblick Outlook

- Weitere Pulsatorversuche mit $N > 3 \cdot 10^7$
  Further pulsator tests with $N > 3 \cdot 10^7$
- Inbetriebnahme des WZL-Hochdrehzahl-Verspannungsprüfstandes
  Commissioning of the WZL high-speed stress test rig
- Berechnung von Rissen, welche aus der Oberfläche starten
  Calculation of cracks that start from the surface