Intelligent Testing

Mechanical Property Characterization of Coatings and Surfaces within the Nano- and Micro-Scale

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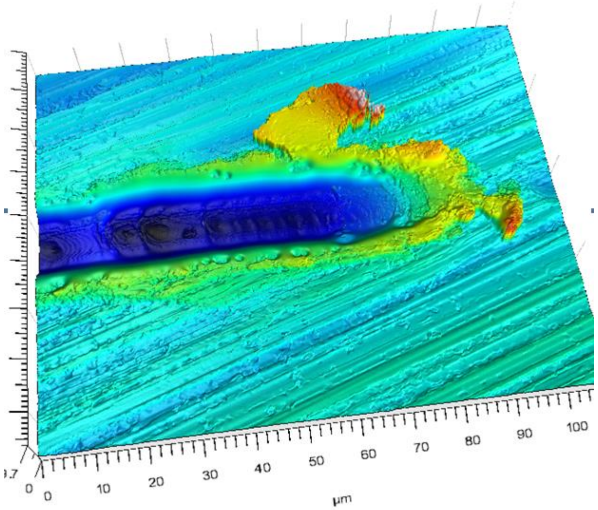

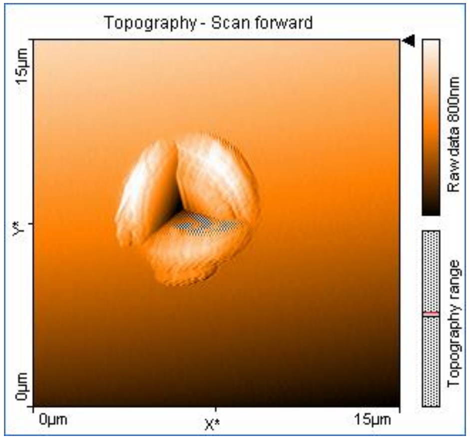

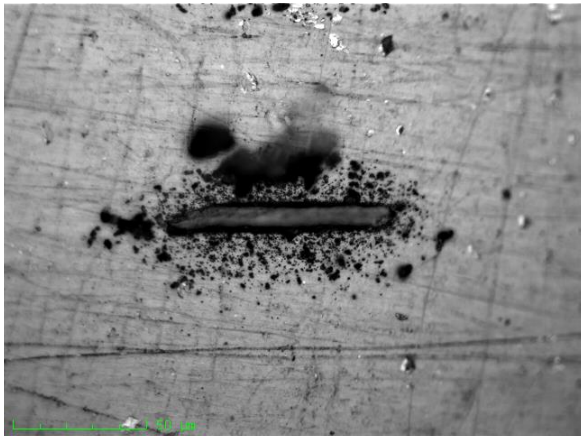

This talk contains contributions from

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Content

1) Motivation for mechanical testing

2) Mechanical material parameters

3) Comparison of test methods – the difficulty of quantification

4) Conclusions

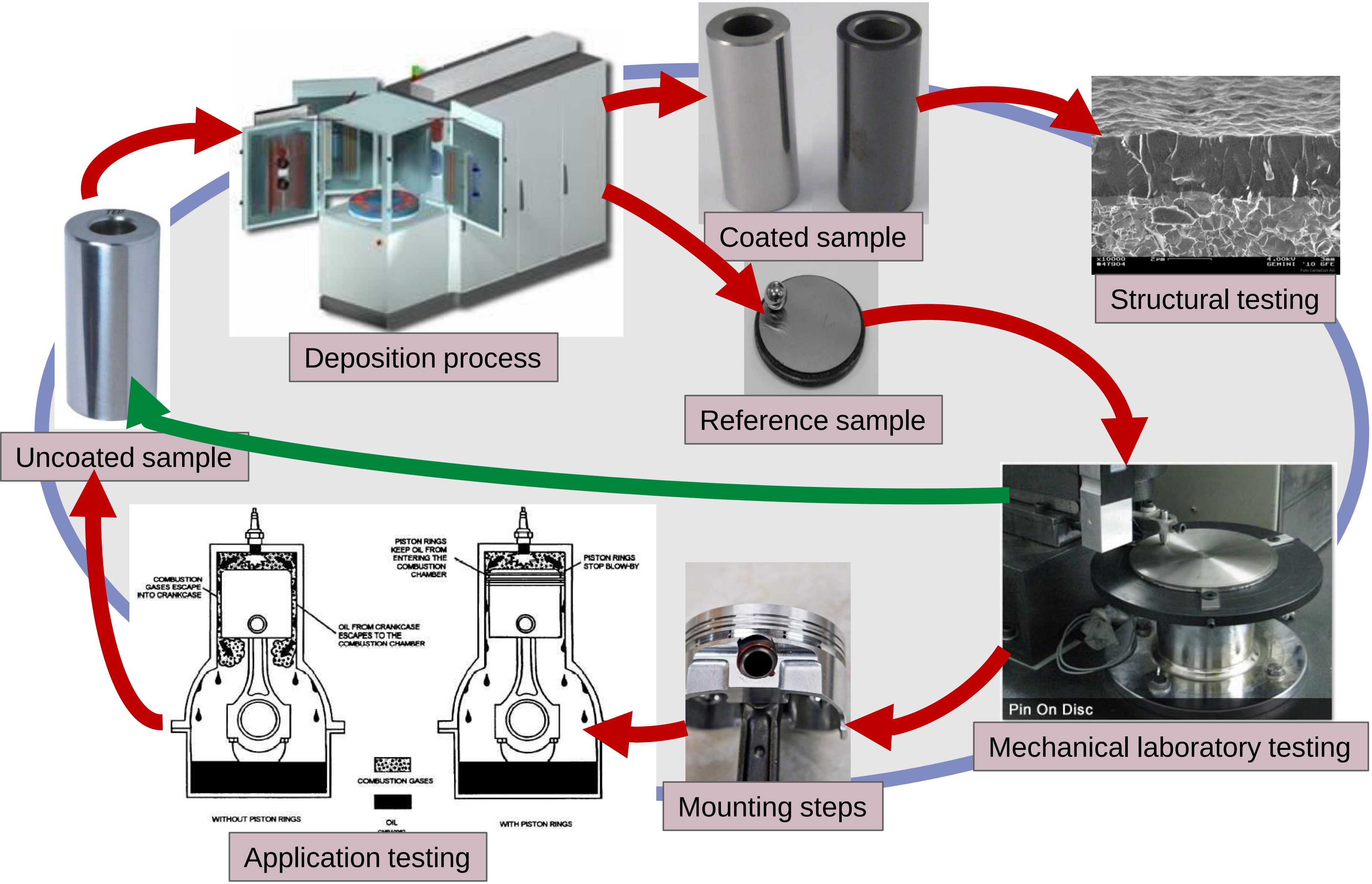
Mechanical surface tests are used for:

1) Development → Finding an optimum surface/coating for a certain application

2) Failure analysis → Finding out why certain surfaces/coatings fail

3) Quality control → Guarantee stable surface/coating properties over time

Iterative development process



Trial and error development process in a multi parameter space

Example: Double layer coating

Testing of:

- 10 materials for each single layer (10 x 10)
- 10 process parameters per material
- 10 film thickness combinations

= 10 x 10 x 10 x 10 combinations

= **10000** samples

Problems of surface mechanics for coated systems

The search for the optimum coating material is
time consuming and expensive.

Mechanical parameters of thin coatings and small structures are
difficult to measure.

Laboratory measurements and simulations often
differ from the conditions in a real application.

Core messages at the beginning:

It is hard to get accurate data!

You need a higher level of modelling and calculations!

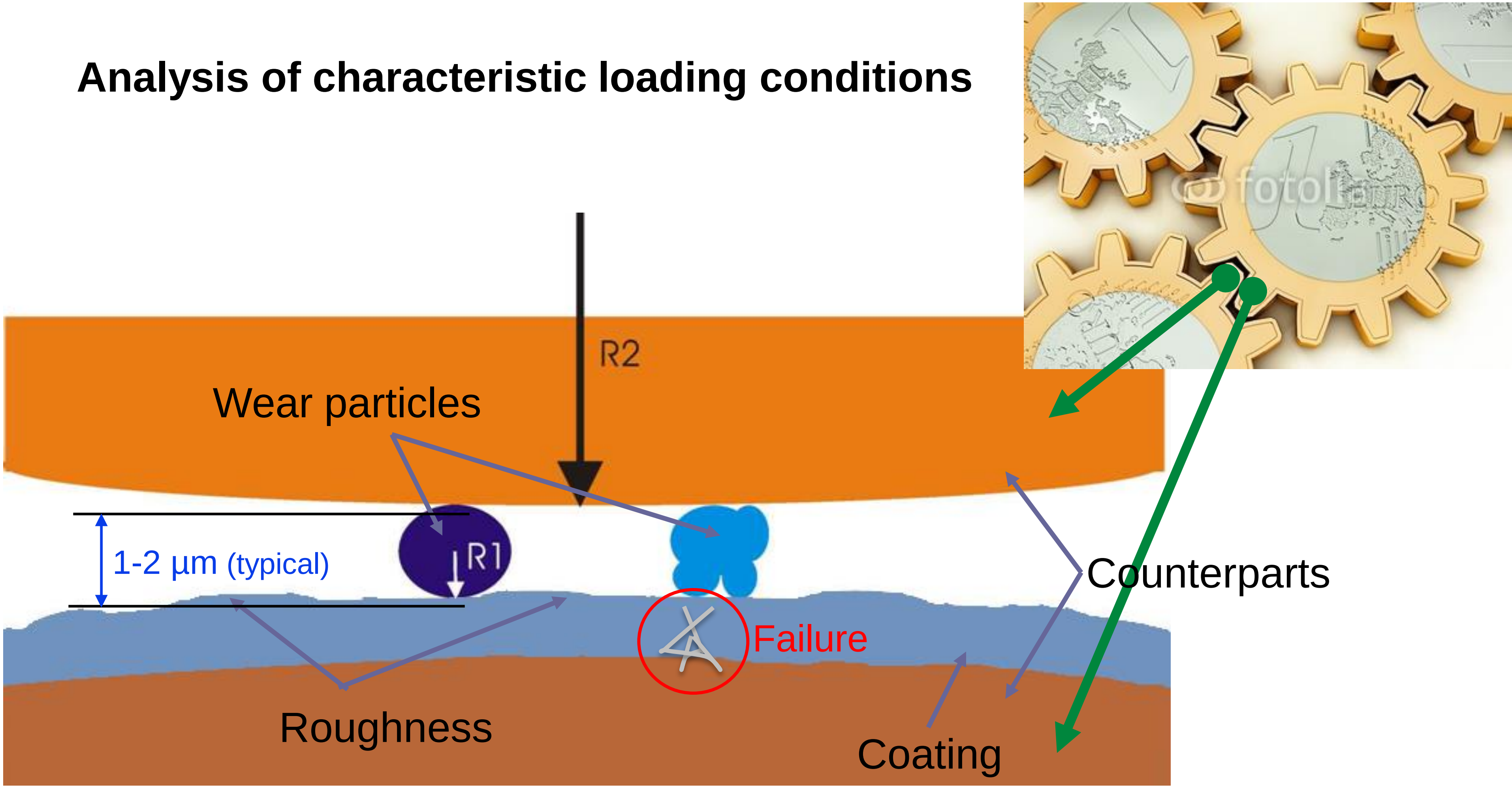
Steps for a reduction of the development effort

Identify the most critical conditions in the application, which cause failures

Identify the most critical mechanical (physical) material parameters

Combine tests with a higher level of modelling and calculations

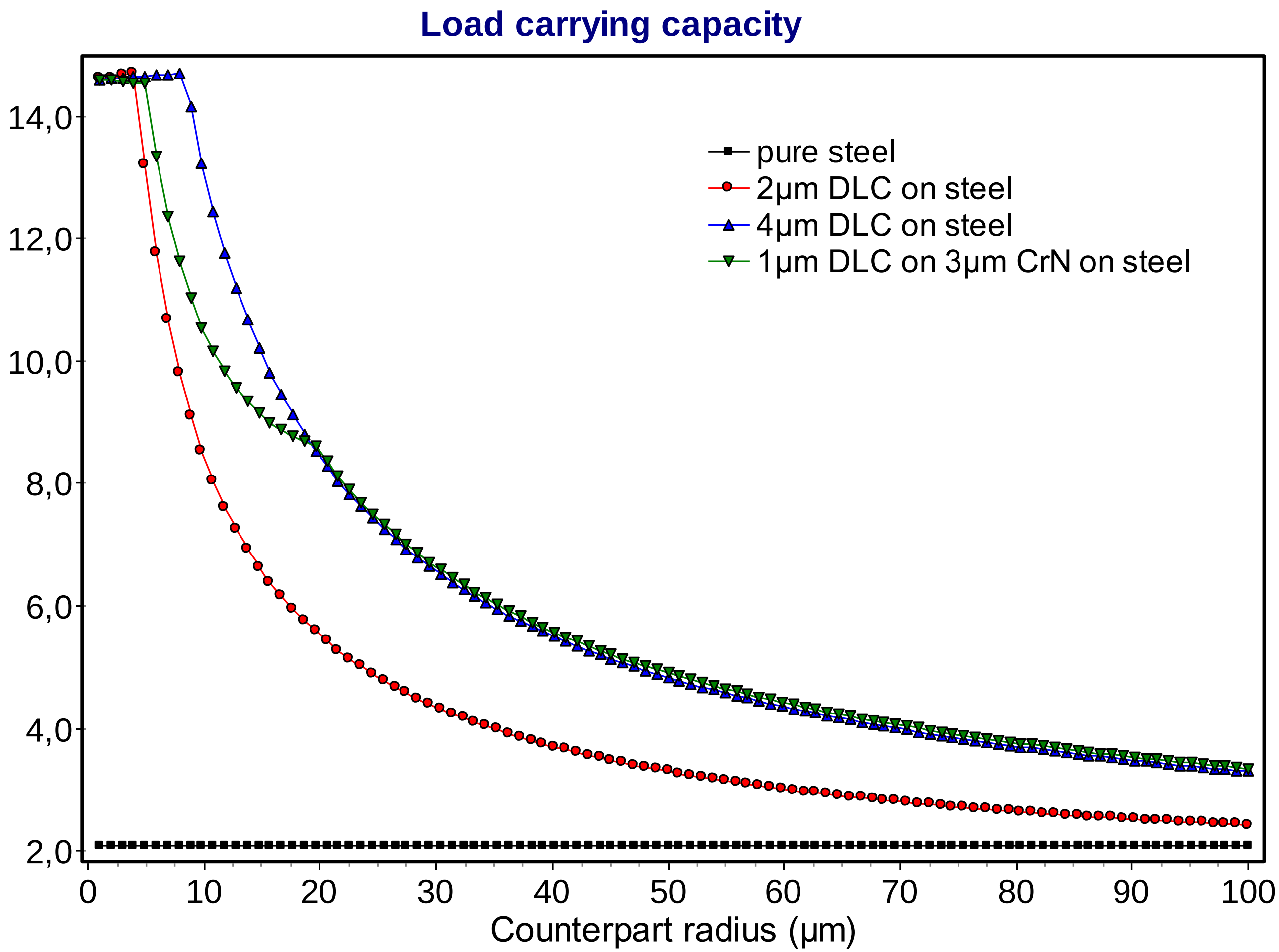
Analysis of characteristic loading conditions



To understand the failure reasons one has to go down to the dimension of roughness and wear particles → This requires high resolution.

Example for modelling

Load carrying capacity of different coating systems on steel



Input parameter required:
E – Young's modulus
v – Poisson's ratio
Y – Yield strength
(T – Tensile strength)

	Steel	DLC	CrN	
E	200	270	300	GPa
v	0.3	0.2	0.25	
Y	2	15	8	GPa

2) Mechanical material parameters

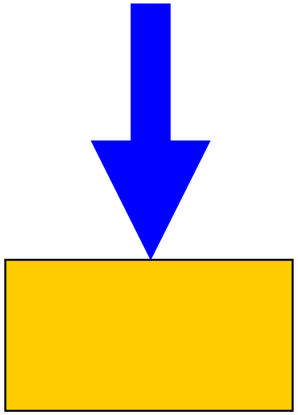
Mechanical behavior	Parameter	Test methods for coatings
Elastic behavior	Young's modulus, Poisson's ratio	Nanoindentation+LFU, ultrasonic surface waves, AFAM, impulse excitation technique
Plastic behavior	Hardness, Yield strength, Stress-strain-curve, hardening exponent	Nanoindentation+LFU
Brittle behavior	Fracture toughness, tensile strength	Nanoindentation+LFU, 4-point bending
Time dependent behavior	Creep, fatigue resistance, strain rate dependence	creep test, impact test, cavitation test, fatigue test (cyclic contact loading)
Frictional and wear behavior	Friction coefficient (not intrinsic) Wear coefficient (not intrinsic) Stribeck curve (not intrinsic)	Friction test, wear test, nanoindentation+LFU
Adhesion	Adhesive strength Scratch resistance (not intrinsic)	Scratch test (LFU), peel test, centrifuge test, cavitation test, Rockwell test

For all parameter it also has to be considered:

- Internal stress
- Dependency on temperature
- Dependency on sample homogeneity: failure density, gradients, thickness constancy, roughness

LFU = Lateral Force Unit

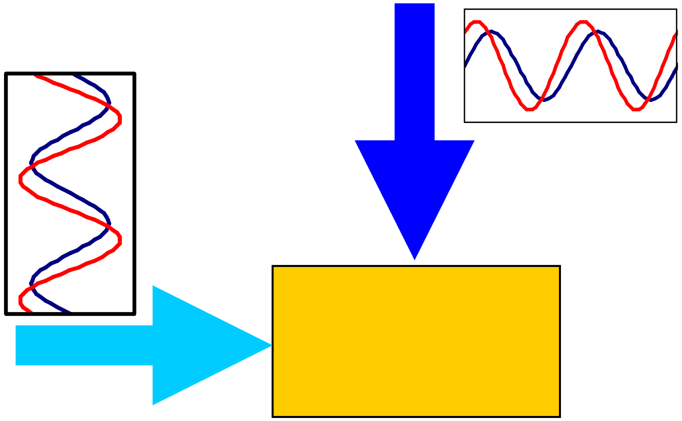
Default Nanoindenter



1 degree of freedom:

- Normal load-displacement-curve

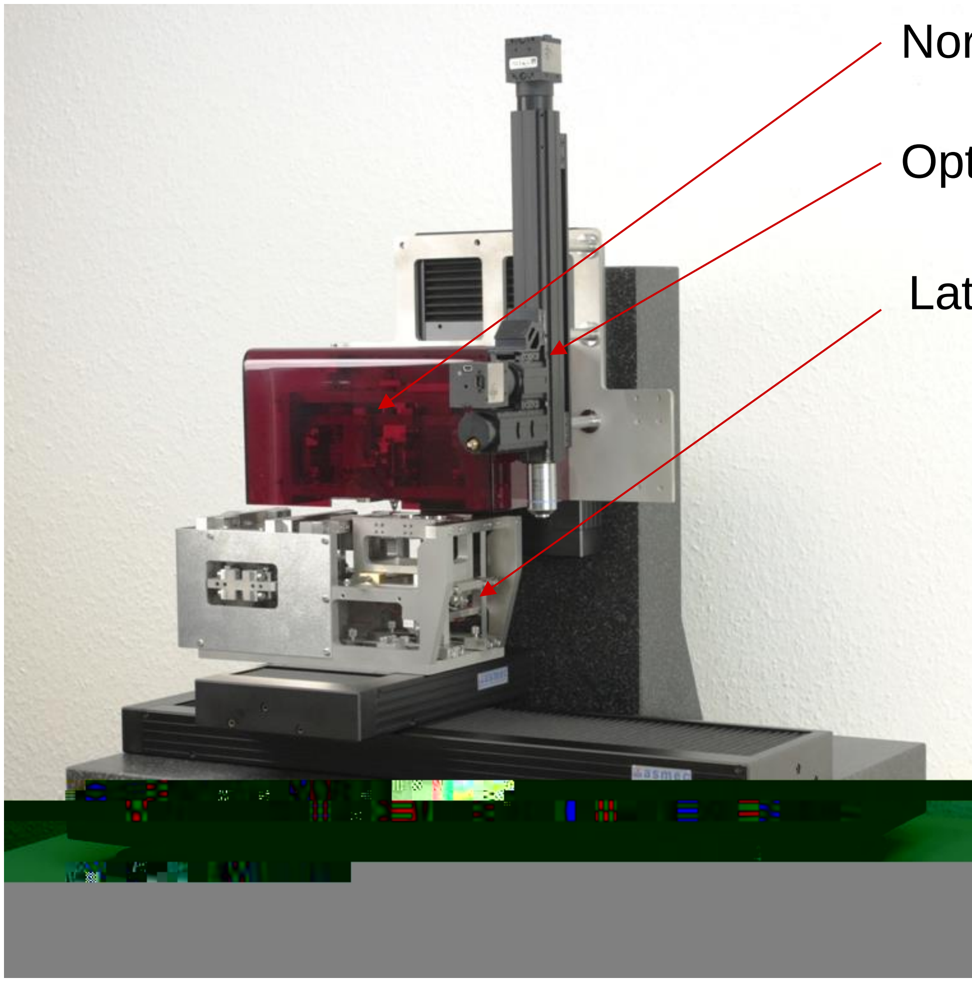
Universal nanomechanical tester



4 degrees of freedom:

- Normal load-displacement-curve
- Lateral load-displacement-curve
- Oscillation normal (dynamic mode)
- Oscillation lateral (dynamic mode)

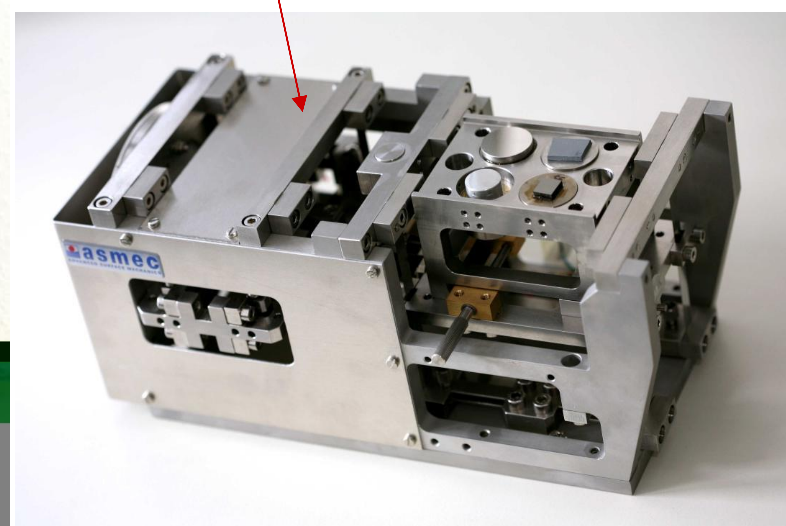
UNAT – Universal Nanomechanical Tester



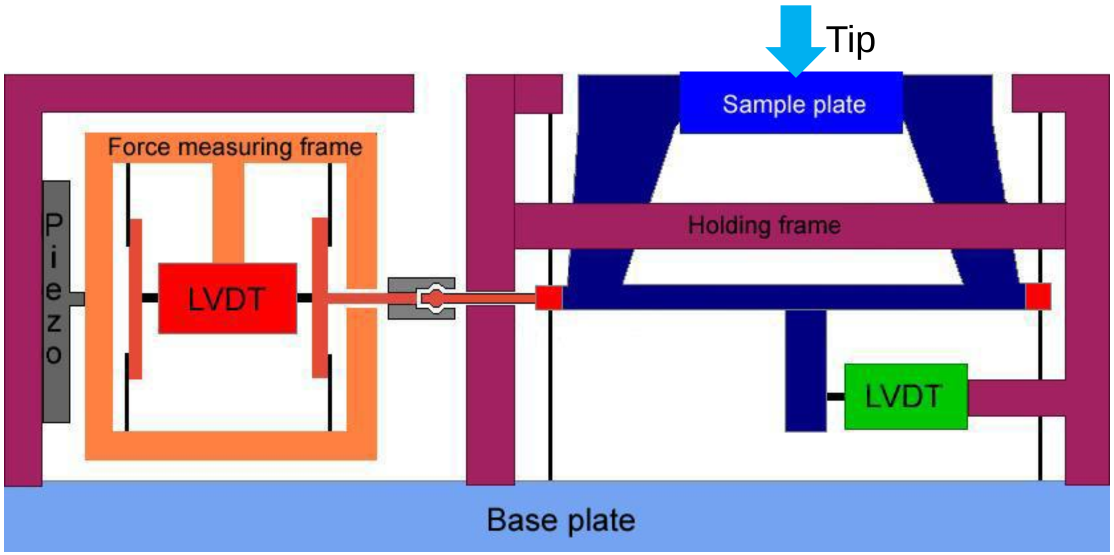
Normal force unit NFU

Optics

Lateral force unit LFU



Lateral force head – the new component



- Nanometer resolution like in normal direction
- The sample is moved laterally (not the tip)
- High stiffness in normal direction
- No height change during lateral movement
- Force generation independent on movement

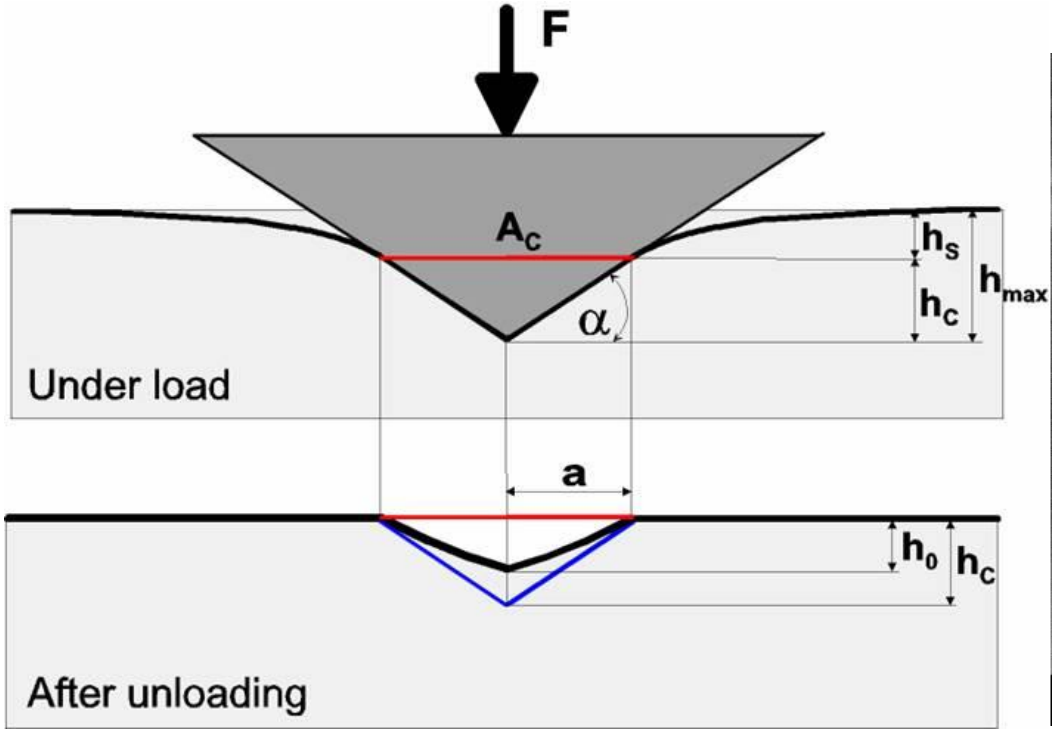
- A force can be applied and measured without any movement of tip or sample
- No rolling motion of the tip due to bending of the indenter shaft
- Transition sticking- sliding friction highly resolved

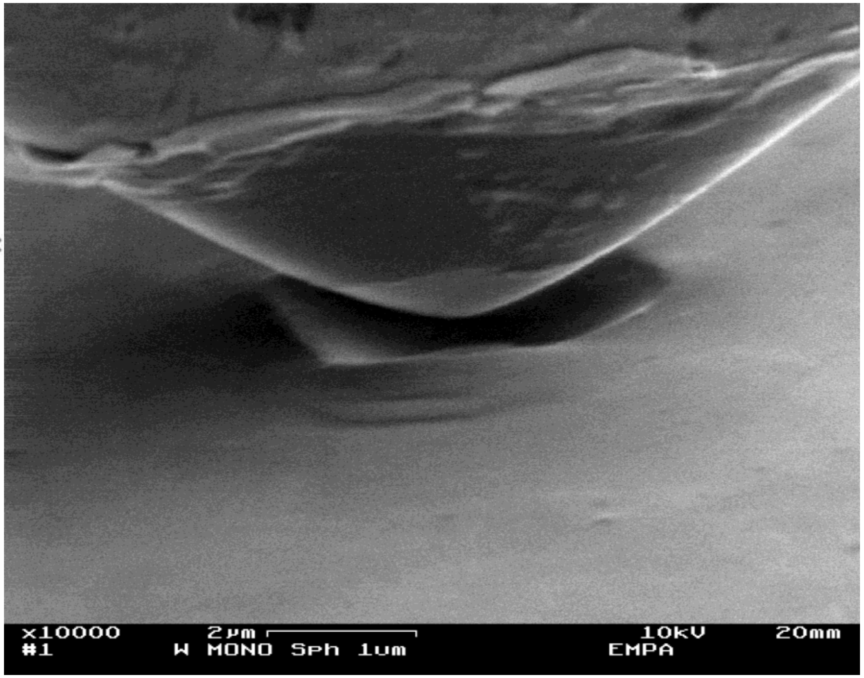
Elastic behavior

Young's modulus
Poisson's ratio

Nanoindentation
ISO 14577

Quantitative: Yes
Local





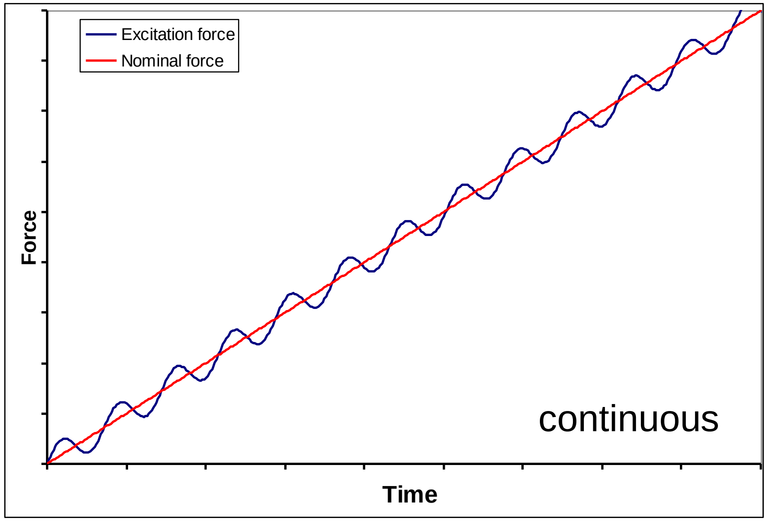
Determination of Hardness and Modulus

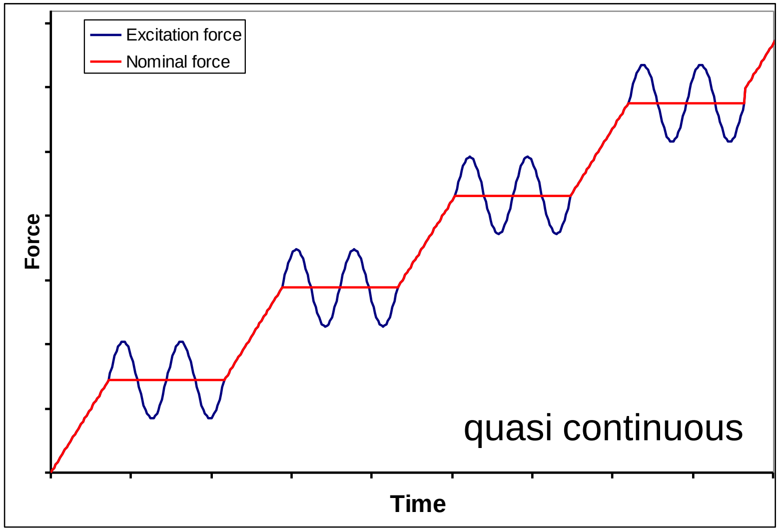
Only normal forces

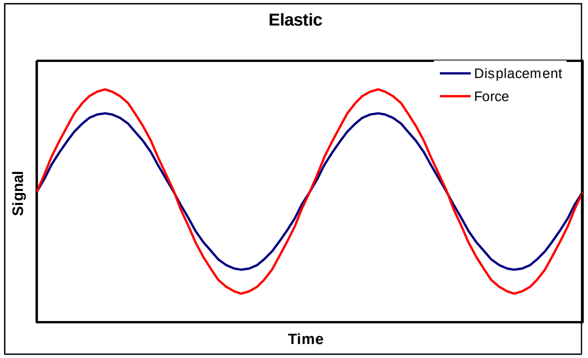
Counterpart always diamond

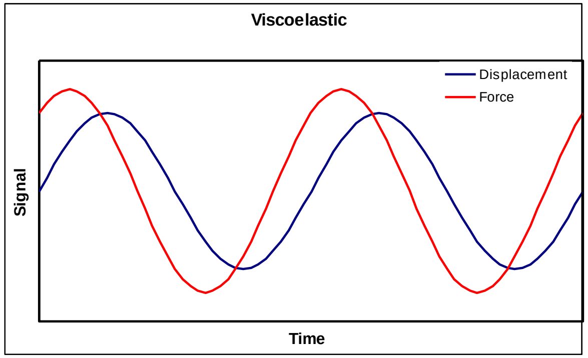
QCSM – Quasi Continuous Stiffness Measurement

A sinusoidal oscillation is superposed to the force signal.
Force/Displacement amplitude ratio ~ contact stiffness S



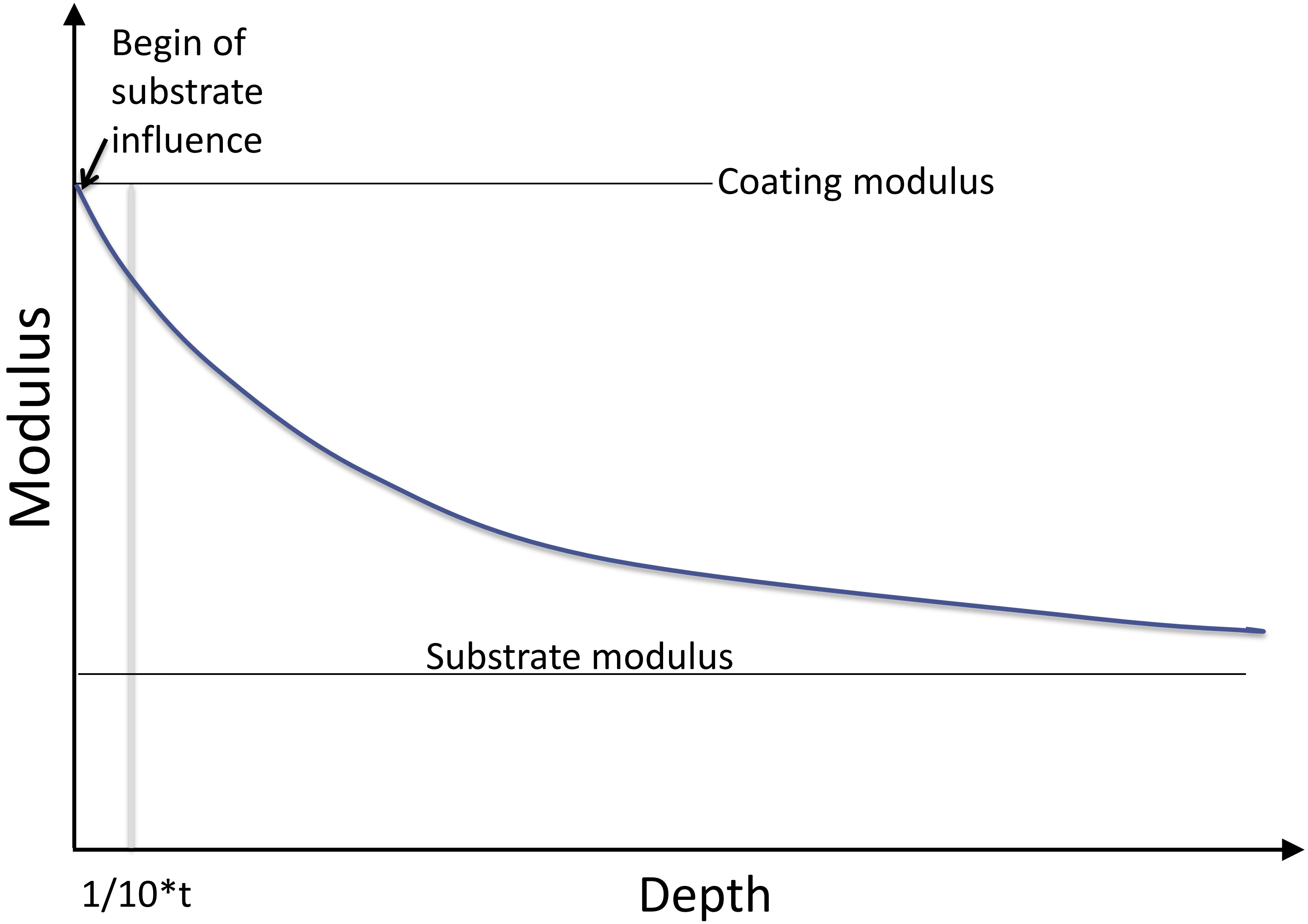






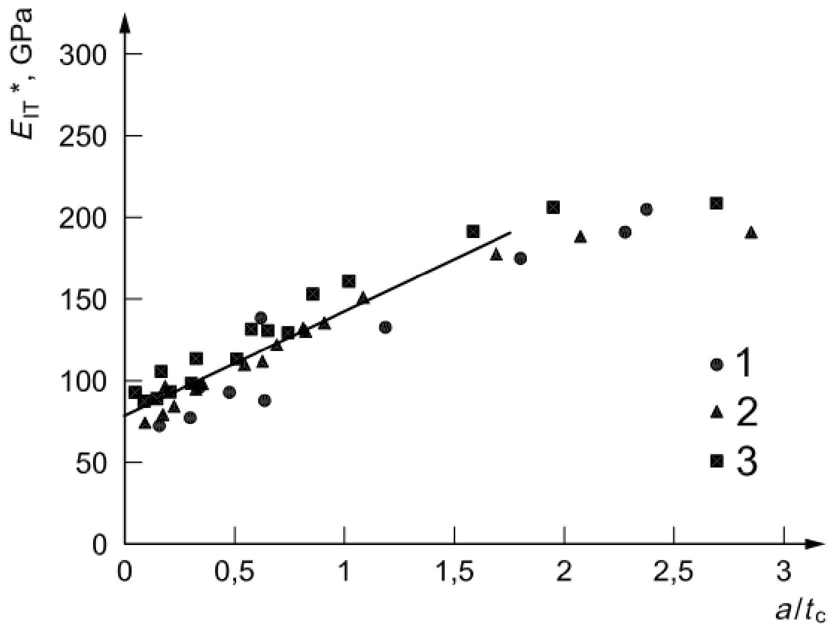
Viscoelastic behavior results in a phase shift between force and displacement.

Substrate influence on modulus



ISO 14577 Part 4

In the case of soft/ductile coatings, indentation force or displacement and indenter geometry shall be chosen such that data shall be obtained in the region where $a/t_c < 1,5$. The plane strain indentation modulus of the coating E_c* is obtained by taking a series of measurements at different indentation depths and extrapolating a linear fit to plane strain indentation modulus vs. a/t_c to zero, see Figure 4.



Key

1 spherical indenter

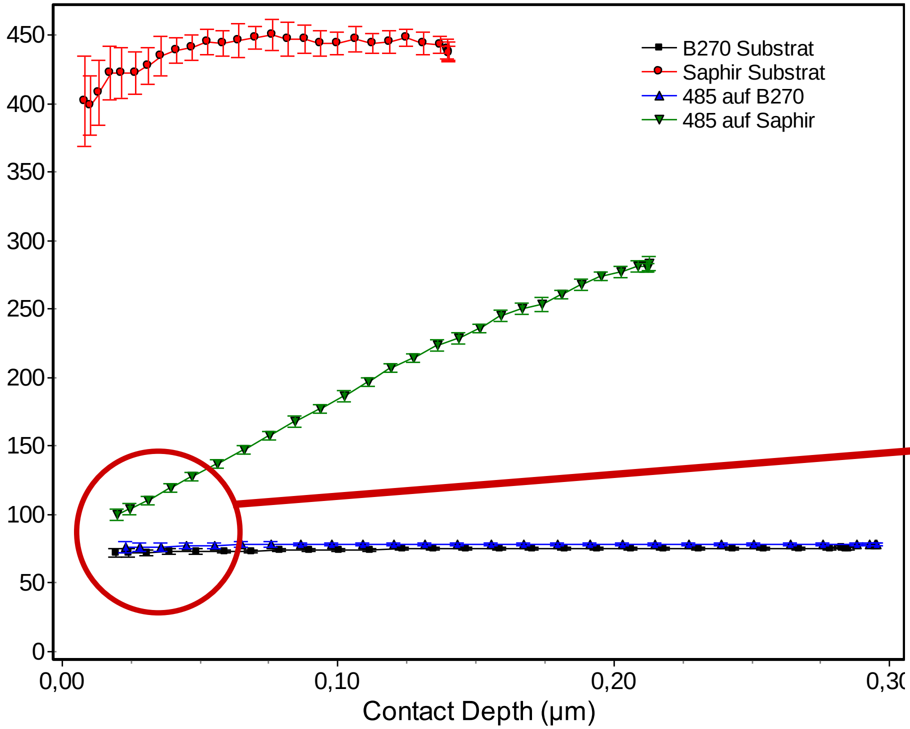
2 Berkovich indenter

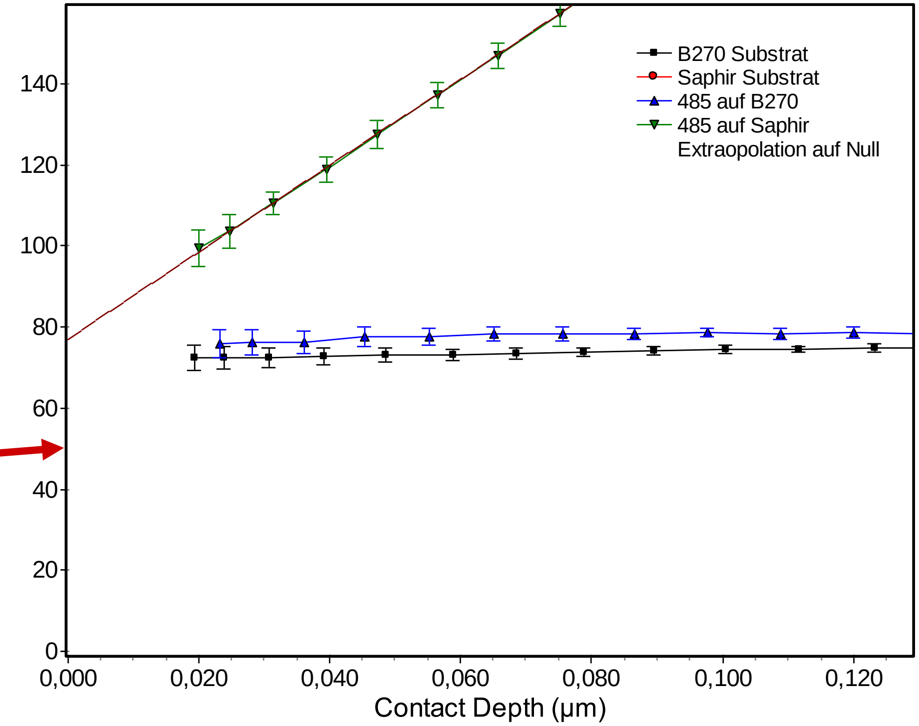
3 Vickers indenter

Zwick / Roell

asmec ADVANCED SURFACE MECHANICS

Example: **260nm SiO_2** coatings on glass and sapphire

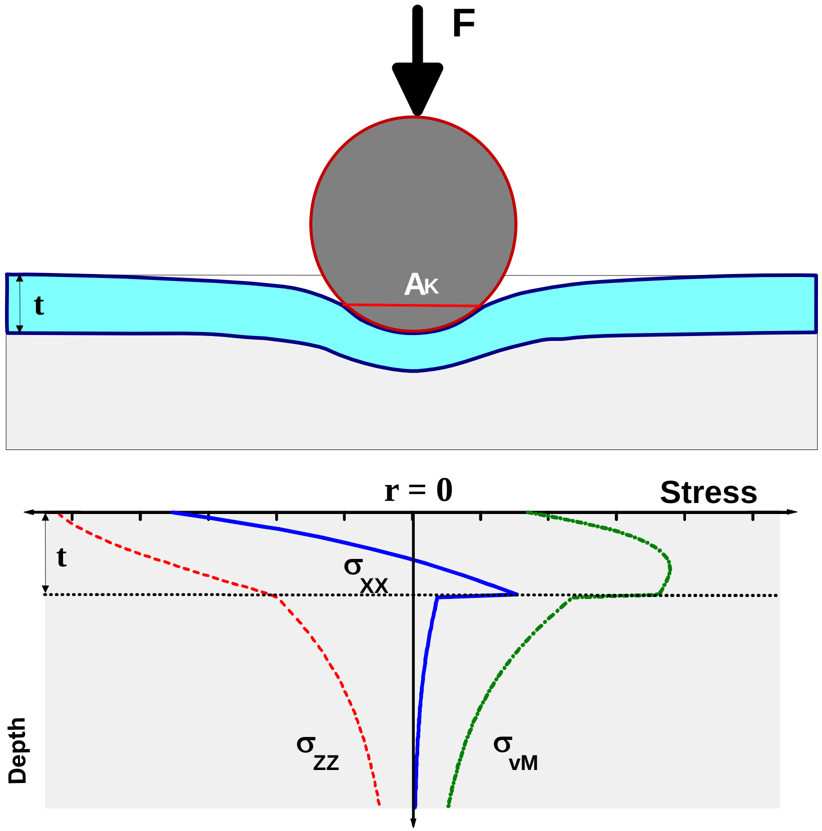




Maximum tip radius for hardness measurements: 120nm

Maximum force for all measurements: 18mN, first point at (20 nm; 0,24 mN).

Elastic indentation with spherical indenter



Requirements

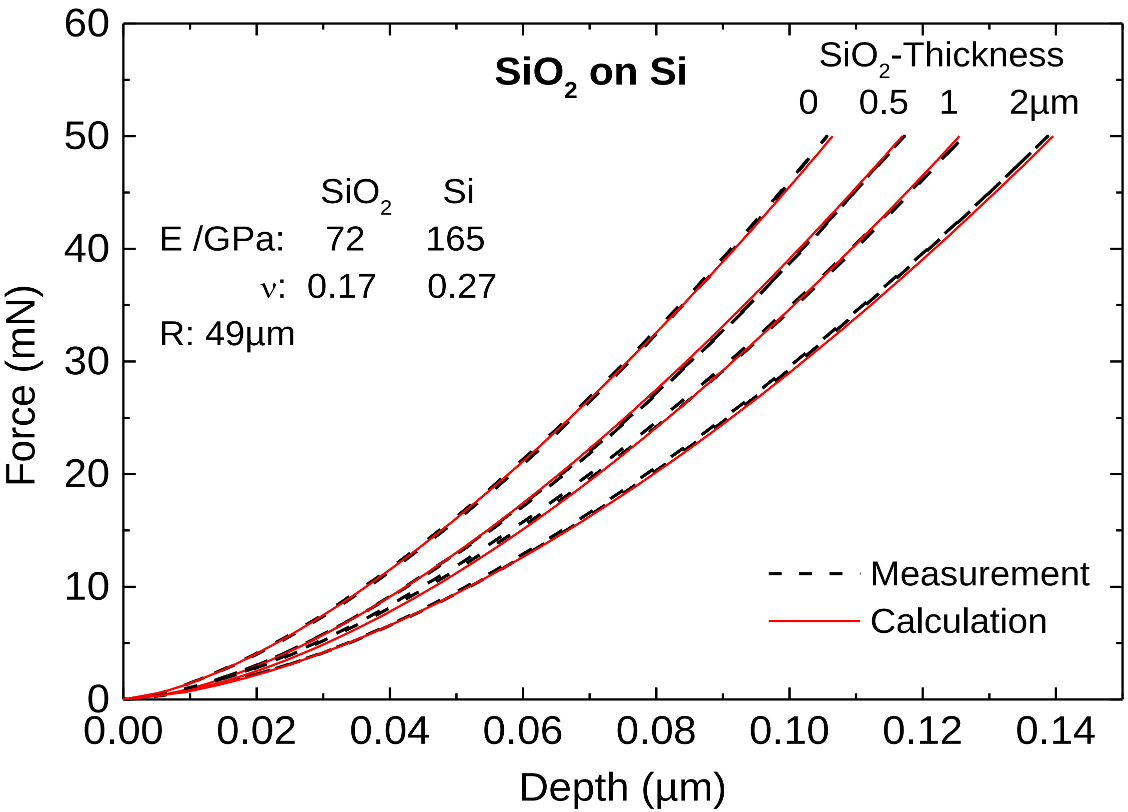
Wholly elastic indents

High accurate measurements with resolution < 1 nm

Accurate knowledge of tip radius and frame compliance

Combination with elastic modelling

Elastic calculation of Hertzian pressure profile for coated systems



T. Chudoba, N. Schwarzer, F. Richter
Surf. Coat. Tech. 127 (2002) 9-17

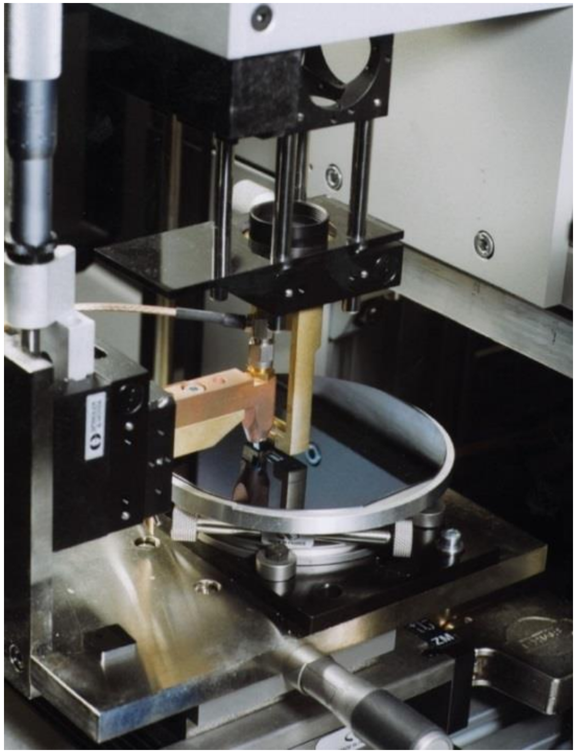
Fit of the measurement data with a theoretical load-displacement curve.

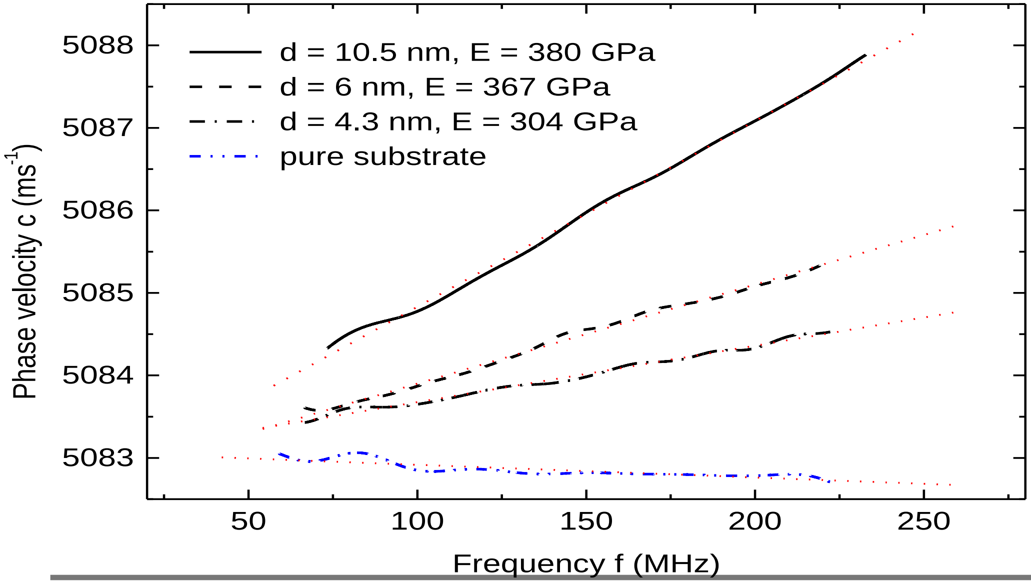
Known substrate properties; fit parameter: film modulus

Useable software ELASTICA, FilmDoctor

Acoustic surface waves
DIN 50992-1

Quantitative: **Yes**
Integral



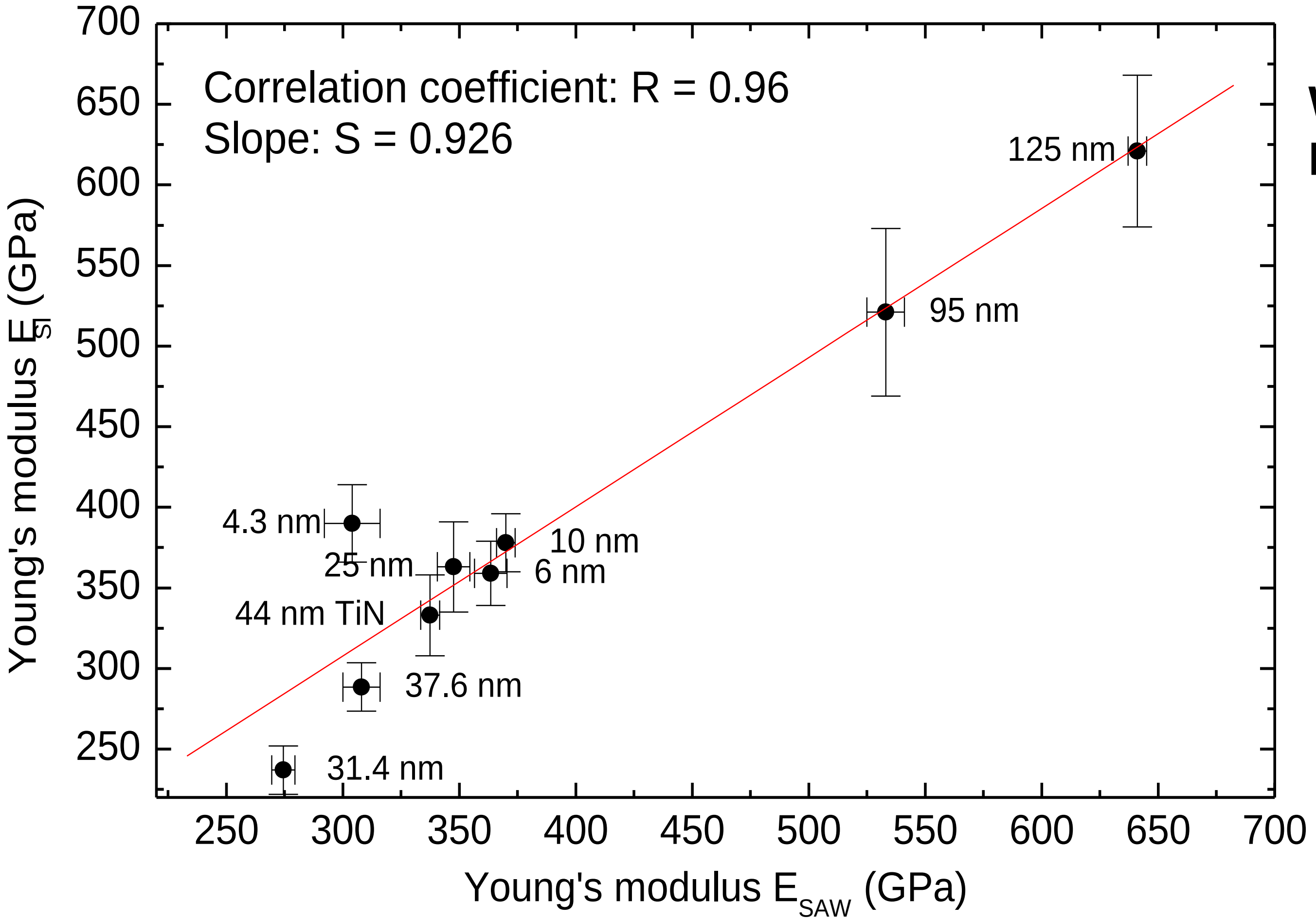


LA*wave*

Comparison SAW - Nanoindentation

	SAW (IWS)	SAW (BAM)	Sphere (75 nm)	Sphere (3 µm)
Thickness	E (GPa)	E (GPa)	E (GPa)	E (GPa)
4.3 nm	304	246 ± 6	Not elastic	390 ± 24
6 nm	367	360 ± 5	Not elastic	359 ± 20
10 nm	380	360 ± 4	Not elastic	378 ± 18
25 nm	370	325 ± 6	367 ± 81	359 ± 28
31.4 nm	272	277 ± 2	236 ± 42	238 ± 15
37.6 nm	315	301 ± 5	291 ± 37	286 ± 15
44 nm TiN	339	336 ± 1	Not elastic	333 ± 25
95 nm	533	530 ± 12	521 ± 52	**Not measured**
125 nm	641	638 ± 6	621 ± 47	**Not measured**

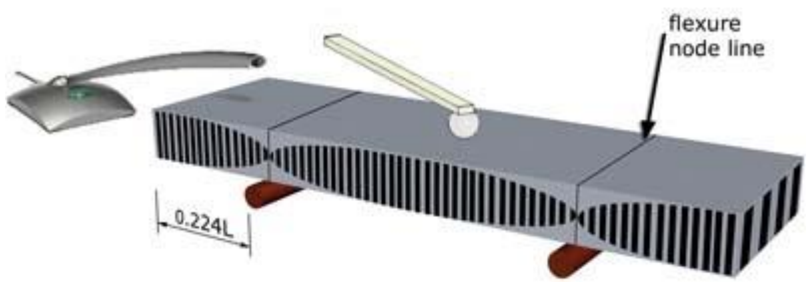
Comparison SAW - Nanoindentation

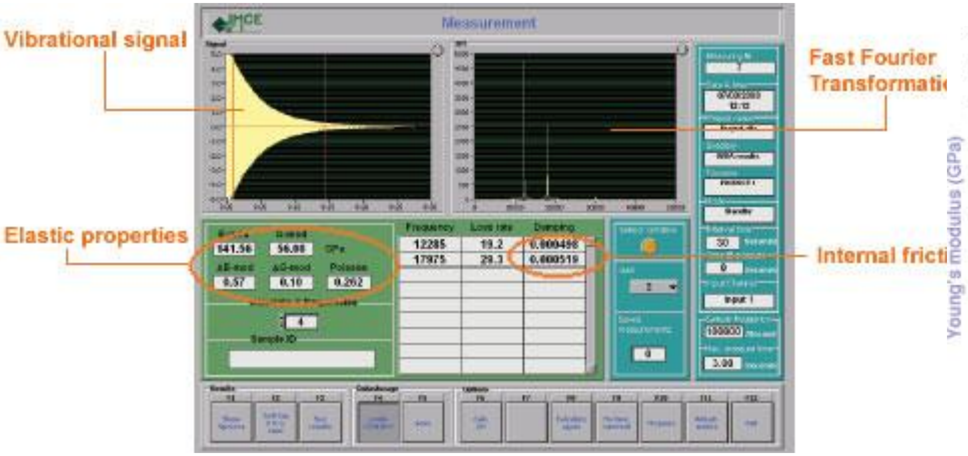


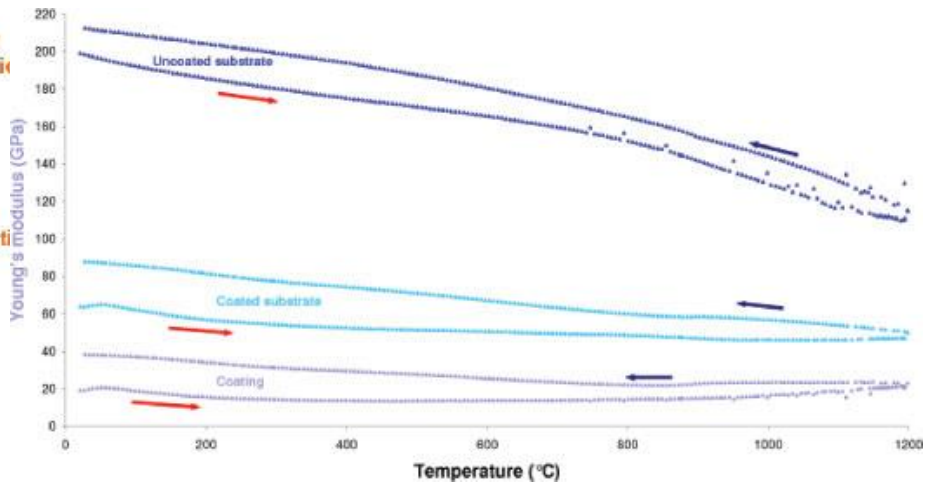
Without 4.3 nm:
R = 99.1; S = 0.993

Impulse excitation technique
ASTM E1876

Quantitative: Yes
Integral





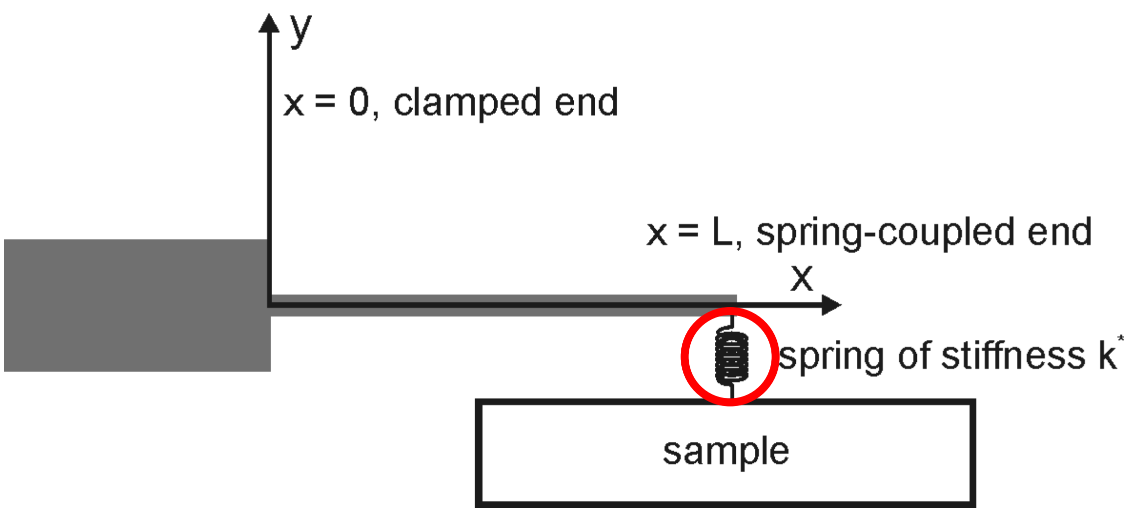


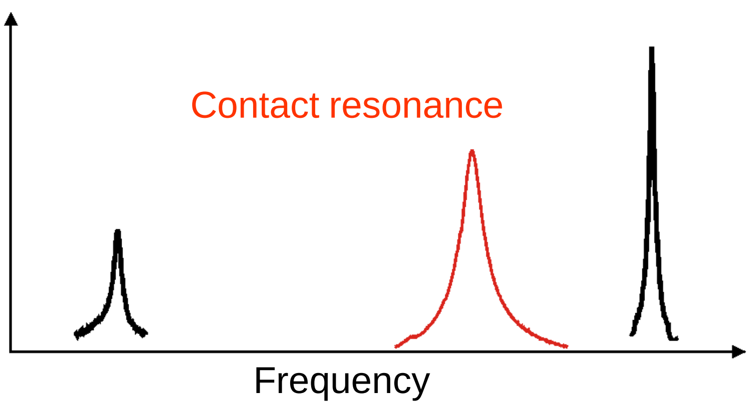
from IMCE, Belgium

Atomic force acoustic microscopy
AFAM

Quantitative: partially
Local

Contact resonance frequencies of an AFM cantilever





contact mechanics

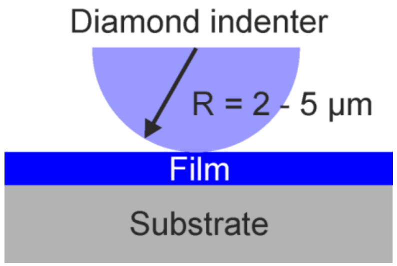
dynamic behavior of the cantilever

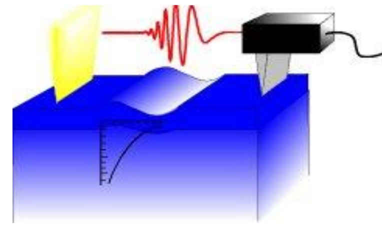
tip-sample contact stiffness

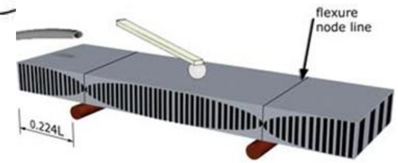
$$k^* = 2aE^*$$

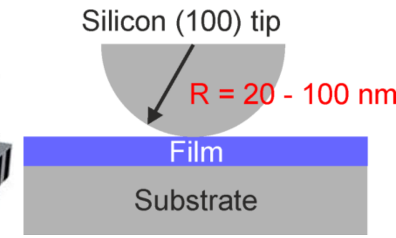
$$f_n = F_i(k^*, k_c, L_1, L) \longleftarrow k^* \longrightarrow \frac{1}{E^*} = \frac{1}{M_{tip}} + \frac{1}{M_{sam}}$$

Source: Kopycinska-Müller, Fraunhofer IzfP, Dresden





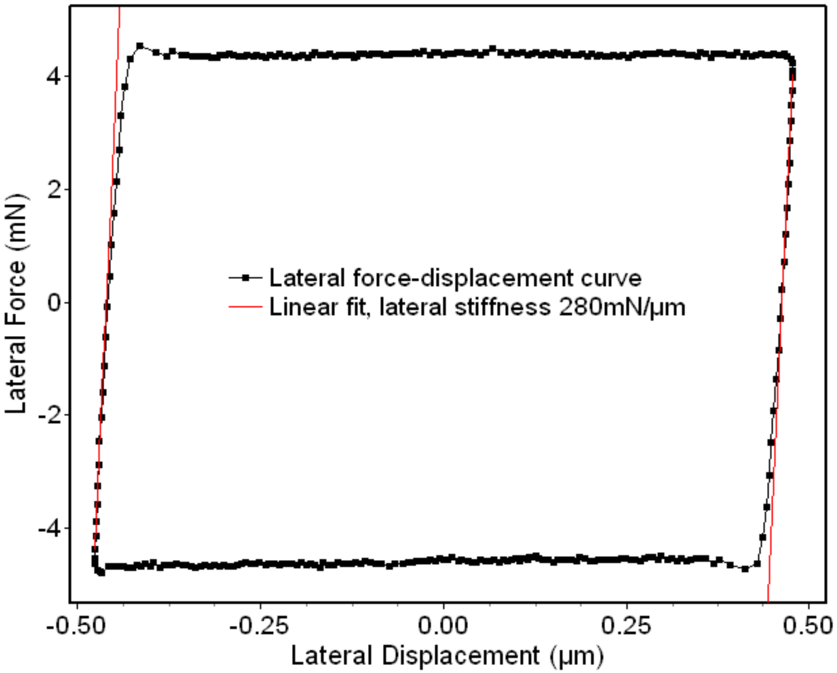




Method	Nanoindentation	Surface acoustic wafes	Impulse excitation technique	Atomic force acoustic microscopy
Locality type	Local	Integral	integral	Local (high)
Knowledge required	Tip and substrate properties, Poisson's ratio	Substrate properties, density, (Poisson's ratio)	Substrate properties	Tip properties
Surface requirements	Very smooth, Hard (elastic indents)	Light absorbing, low damping	No special	smooth
Deviating conditions	High pressure	none	none	High pressure
High tempera-ture testing	Up to 700°C (1000°C)	no	Up to 1600°C	no

Poisson’s ratio measurement
by nanomechanical testing

Measurement of **lateral** contact stiffness (lateral instrument stiffness corrected)



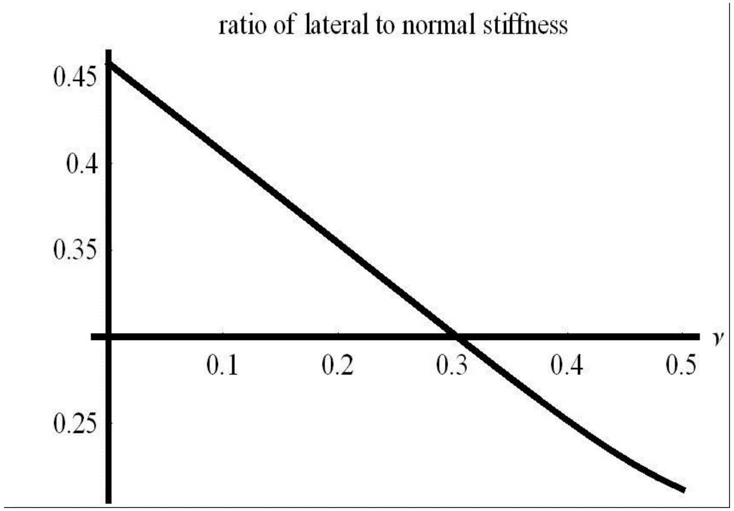
Poisson‘s ratio can be determined → Contact model required

Two unknown Parameters:

- Young‘s modulus E
- Poisson‘s ratio ν

Two measured parameters (same position)

- Normal stiffness S_N
- Lateral stiffness S_L

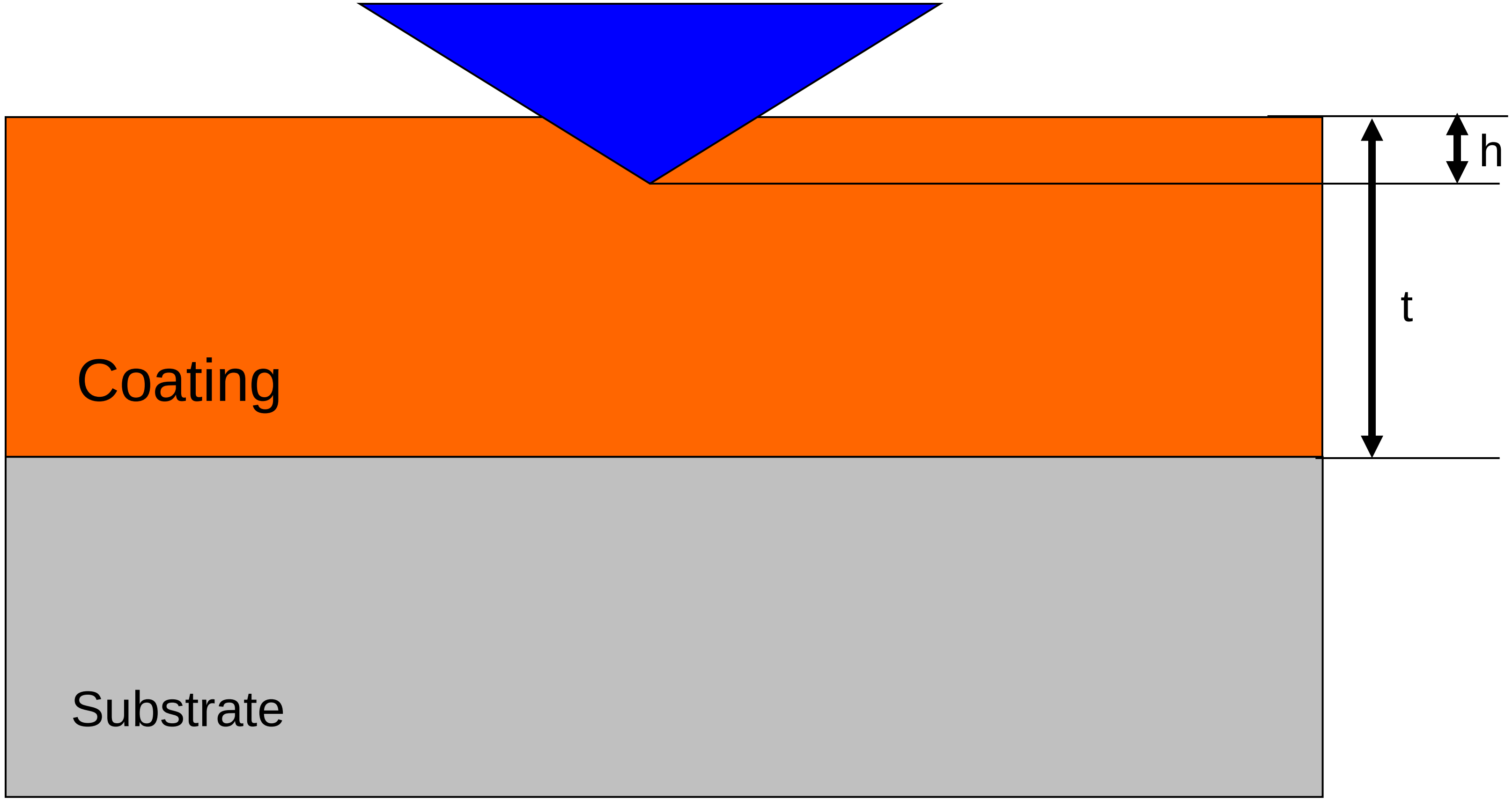


Plastic behavior

Hardness
Yield strength
Stress-strain curve
Hardening exponent

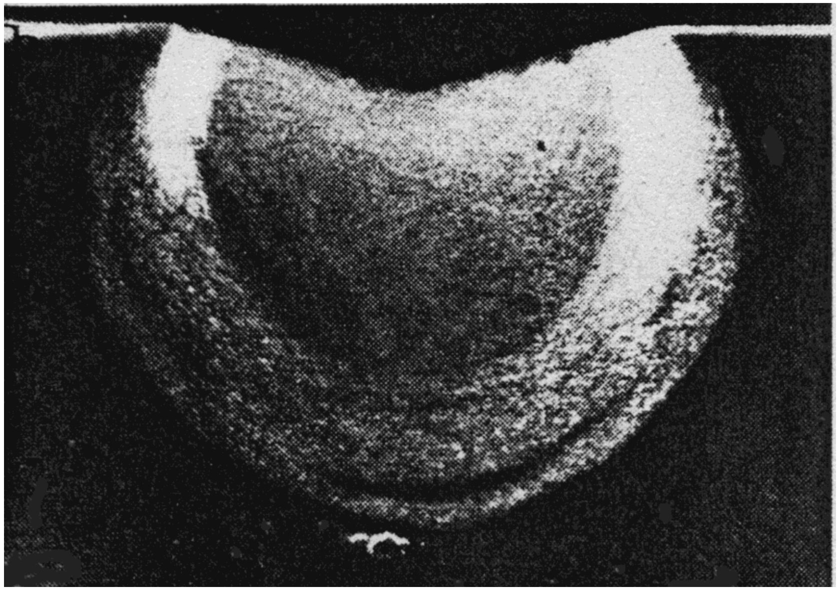
Depth limit for coating hardness tests

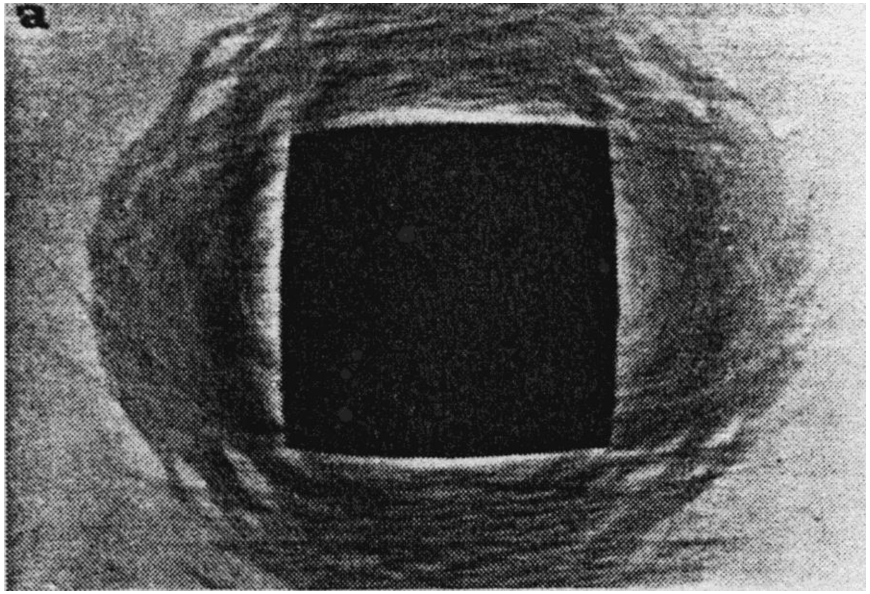
One tenth rule $h < \frac{t}{10}$



Reason for depth limit

The plastic zone is much larger and deeper than the indent.
Therefore the information in the load-displacement curve comes from a depth of up to10 times the indentation depth.





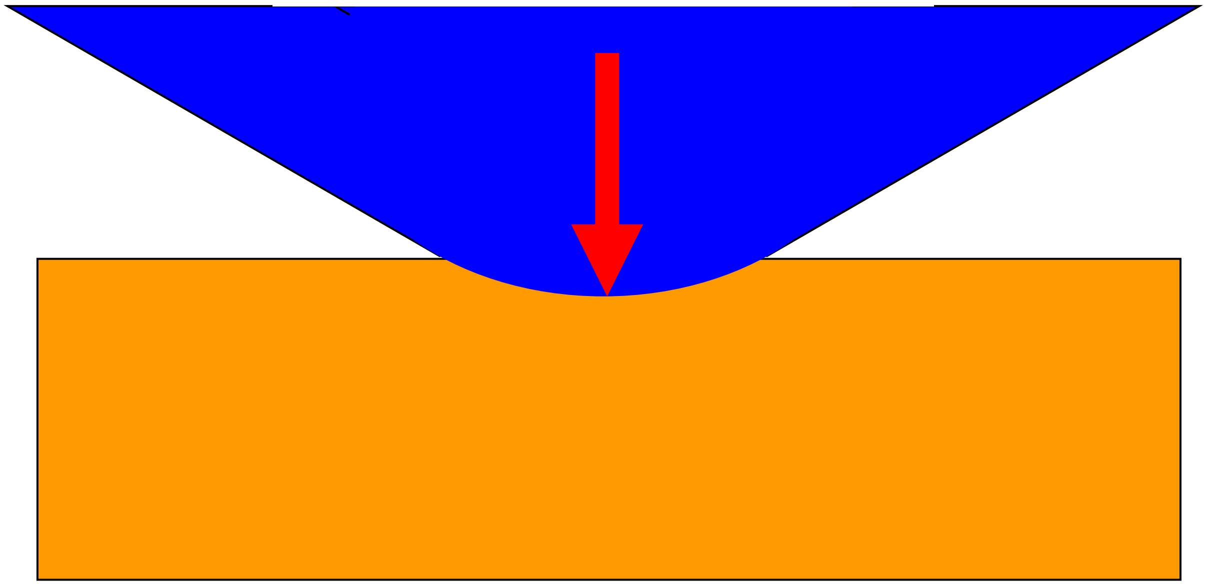
Presentation of the plastic zone in steel using a special etching technique

Limited resolution due to tip rounding

Area function with high accuracy needed

Minimum indentation depth for comparable hardness results:
20% of tip radius

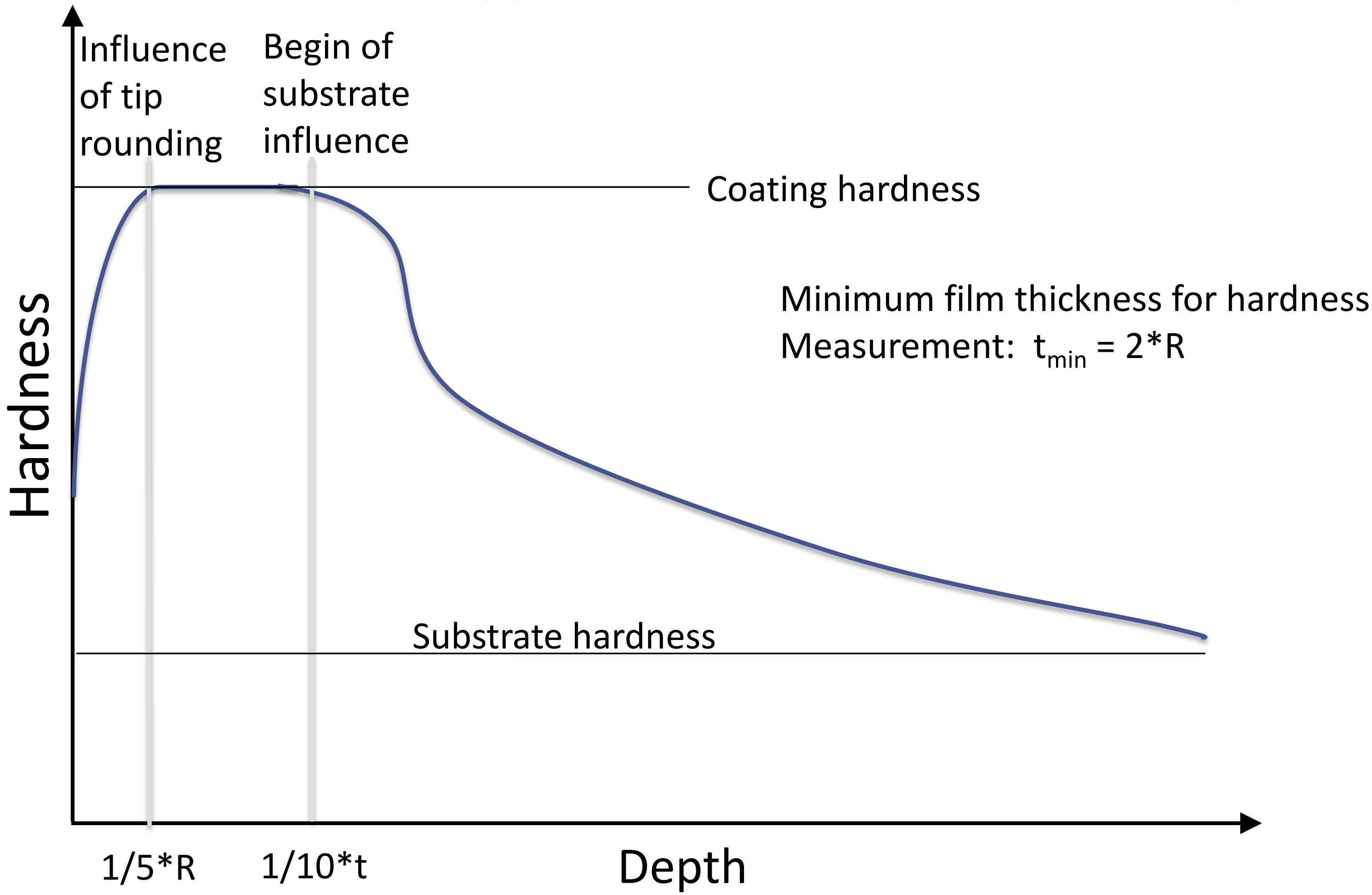
A Berkovich tip has a typical tip radius between 100 – 300 nm



Minimum depth for hardness tests:

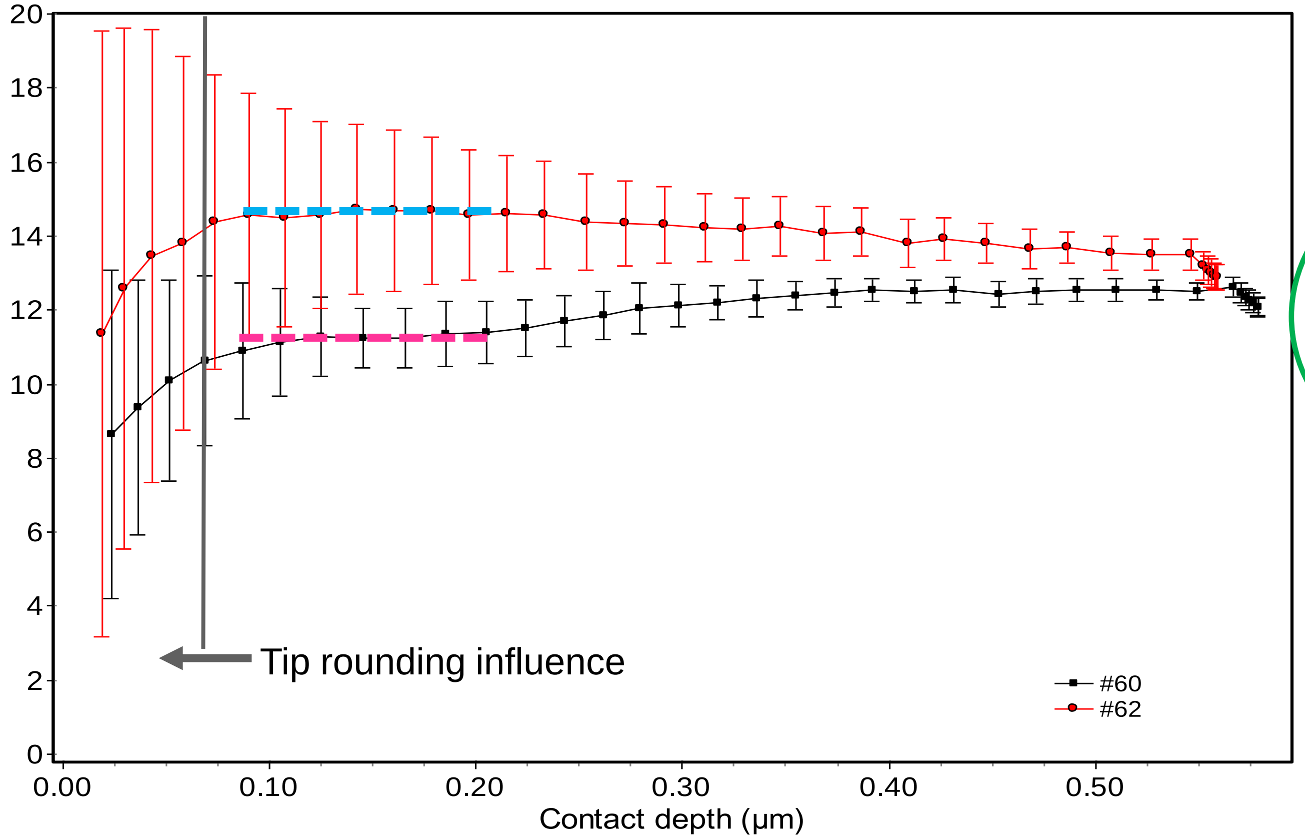
$h_{min} = 0.2*R$

Substrate influence on hardness



Minimum film thickness for **hardness** measurements in dependence on tip radius (not for modulus)

Tip radius (nm)	**Minimum film thickness (nm)**
50	100
75	150
100	200
150	300
200	400
250	500
300	600

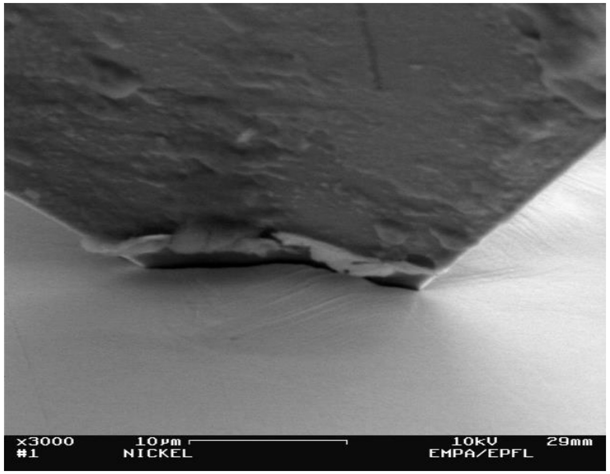


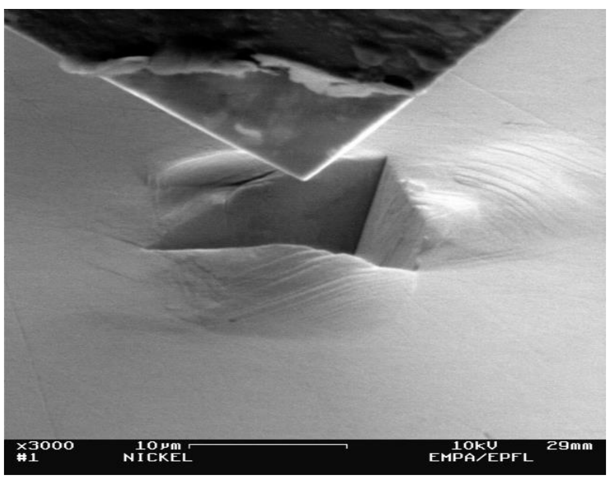
H (#60) < H (#62)

11.3 GPa 14.8 GPa

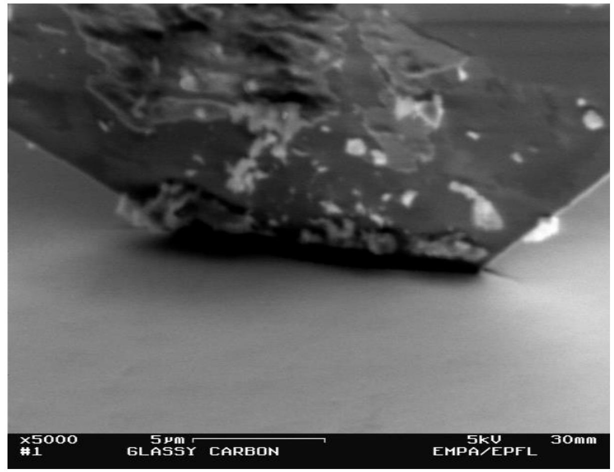
Indentation hardness of two different **a:C:H:W** coatings (DLC) as function of depth, measured with dynamic QCSM method

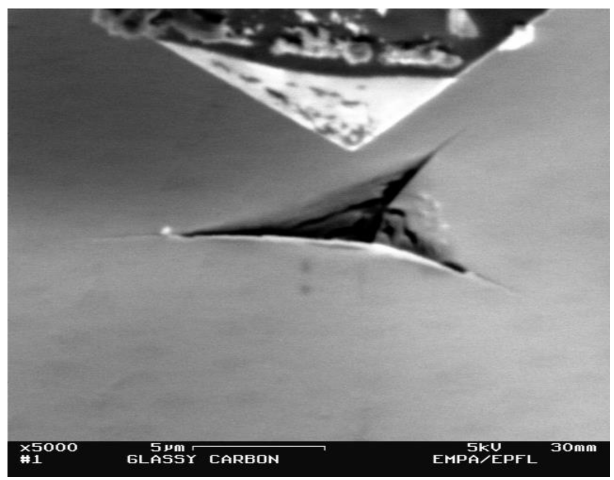
SEM images from indents with Cube Corner indenter



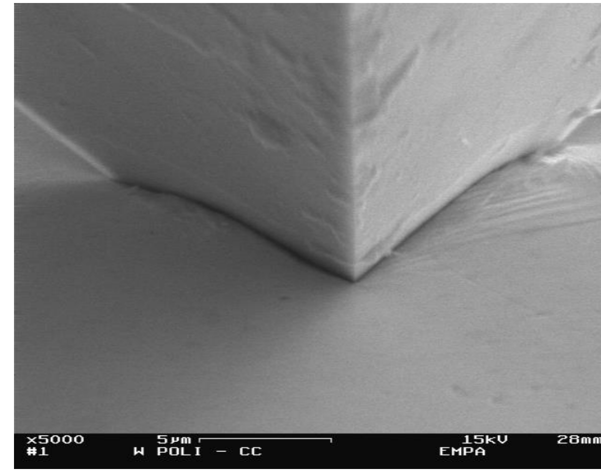


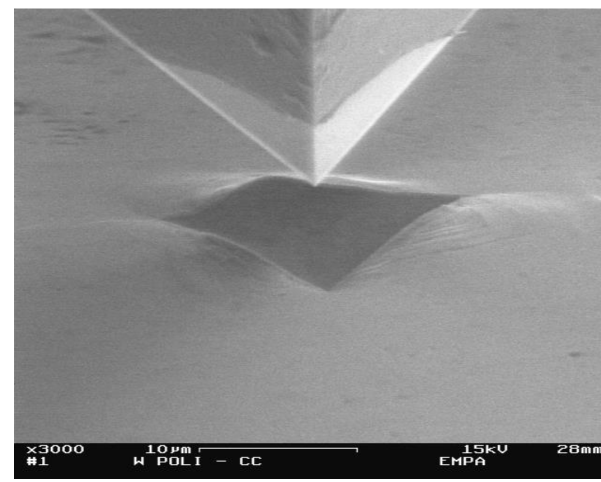
Nickel





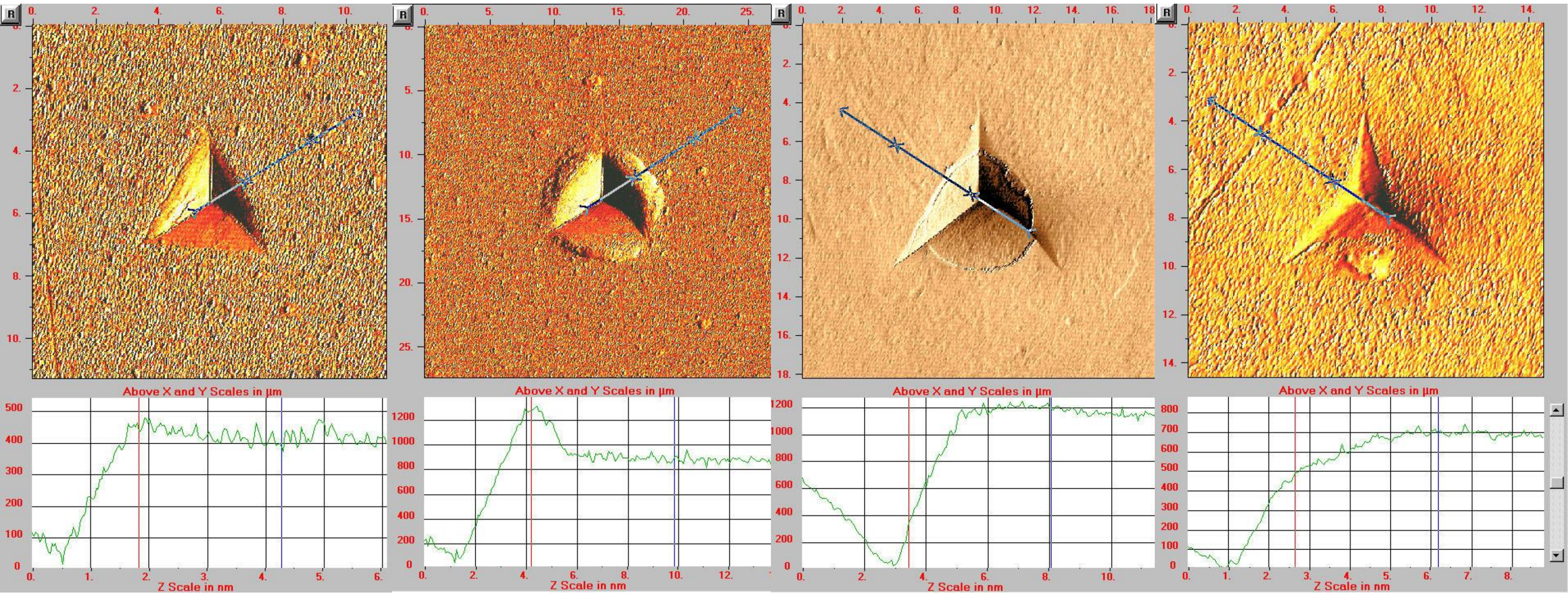
Glassy carbon





Tungsten

Source: EMPA, Switzerland

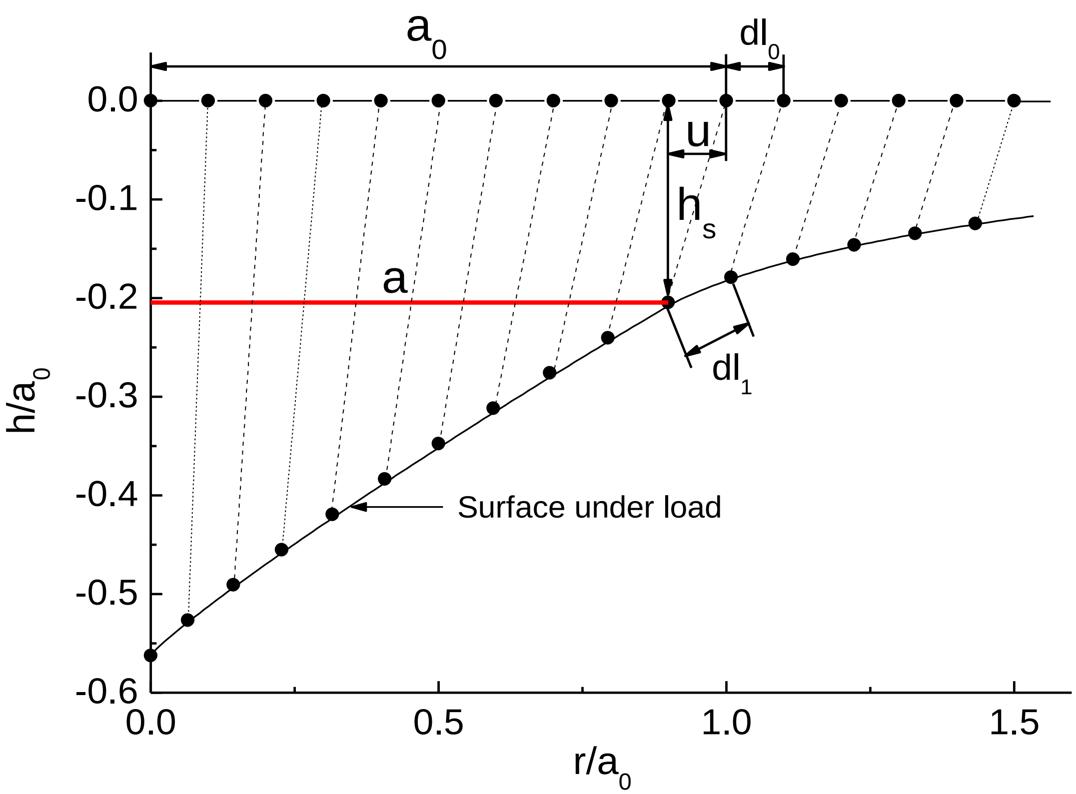


normal	pile-up	cracks	sink-in
Al on BK7 glass	Al on BK7 glass	Al_2O_3 on Nickel	Al_2O_3 on Nickel
0,4 µm / 1,1 µm	0,9 µm / 1,1 µm	1,2 µm / 0,9 µm	0,7 µm / 2 µm
Load: 10 mN	50 mN	100 mN	100 mN

green = depth / film thickness

Additional correction: radial displacement correction

Included in the new revision of the standard ISO 14577



Example for influence:

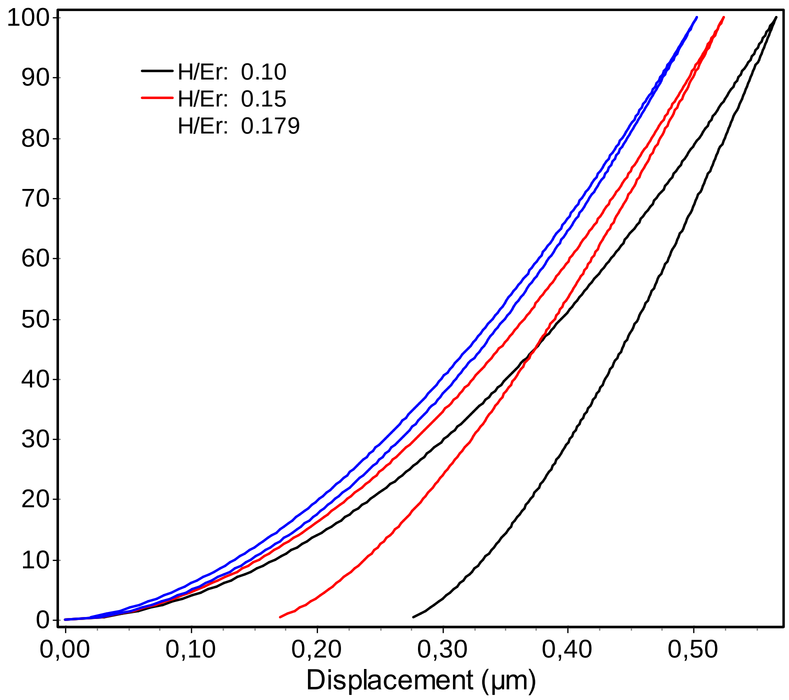
	with	without correction
H:	30 GPa	→ 31,5 GPa
E:	400 GPa	→ 413 GPa

$$u_r = \frac{(1-2\nu)(1+\nu)}{2}\frac{F}{E \cdot a^2}\cos(\arctan(\frac{h_0}{a}))$$

T. Chudoba, N. M. Jennett, Higher accuracy analysis of instrumented indentation data obtained with pointed indenters, J. Phys. D: Appl. Phys. 41 (2008)

Theoretical limit for plastic deformation with pyramidal/conical indenter: $\frac{H}{E_r} = \frac{\tan\alpha}{2}$

With α = 19.7° follows $\frac{H}{E_r} \leq 0.179$ for Berkovich and Vickers



Examples: Fused silica: $H/E_r = 0.14$

DLC $H/E_r = 0.10$

CrN $H/E_r = 0.07$

Steel $H/E_r = 0.01 .. 0.05$

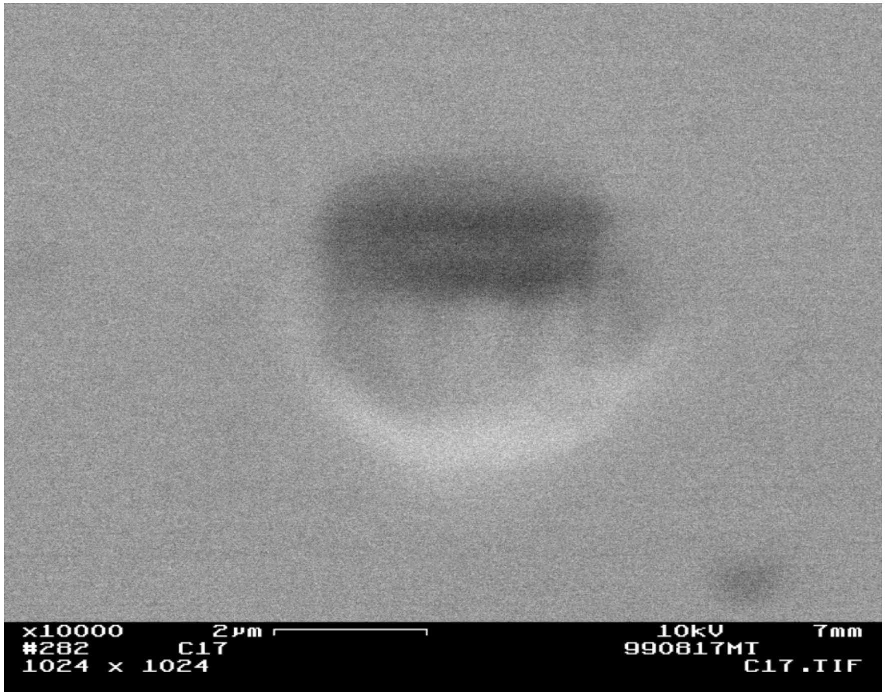
Seen in this conference: H = 50 GPa / E = 300 GPa → $H/E_r = 0.197$ ($E_r = 254$ GPa)

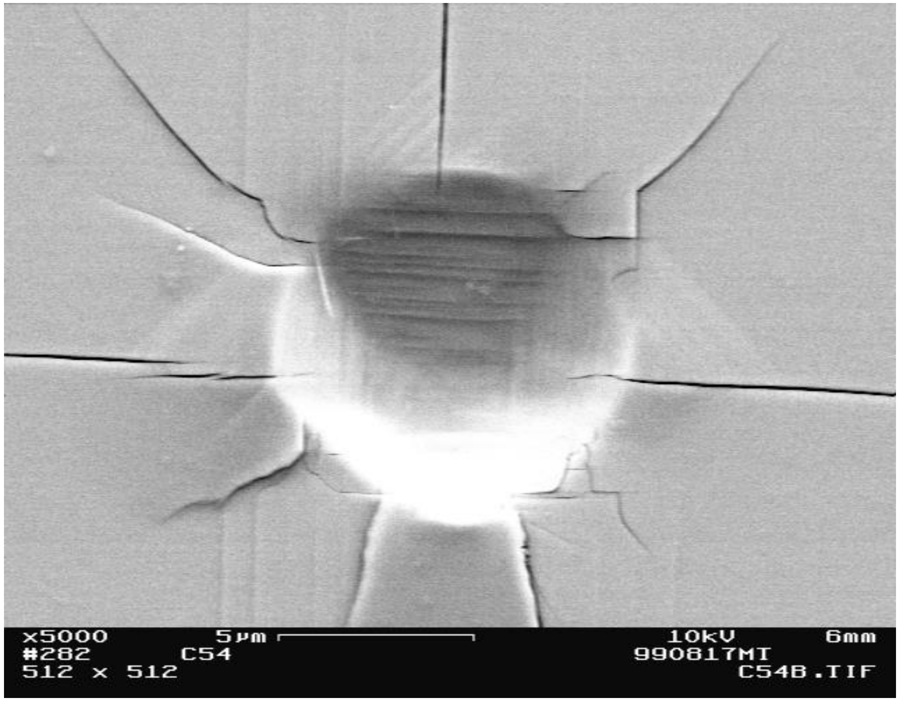
→ Not possible

Yield strength

Can we measure the yield strength of hard and brittle materials?

Yes, it is a question of dimension!





small load

higher load

4µm radius indenter in GaAs

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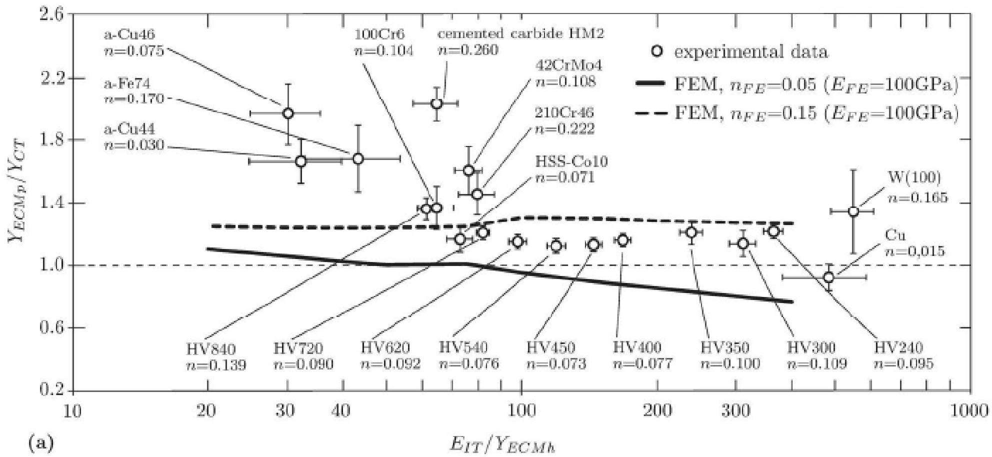
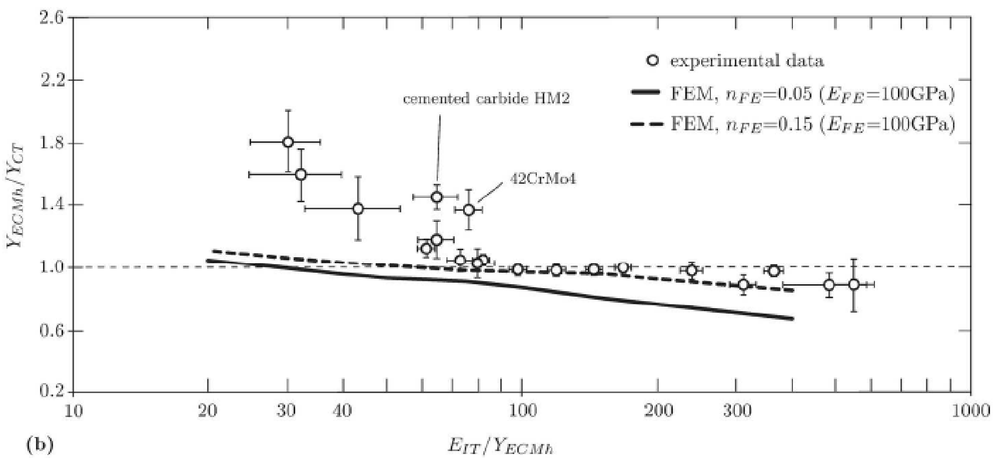
Yield strength determination

Quantitative: Yes local





Clausner, Richter, JMR 2014, accepted for publication

Tabor relation for metals

[D. Tabor, The hardness of metals, Oxford University Press (1951)]

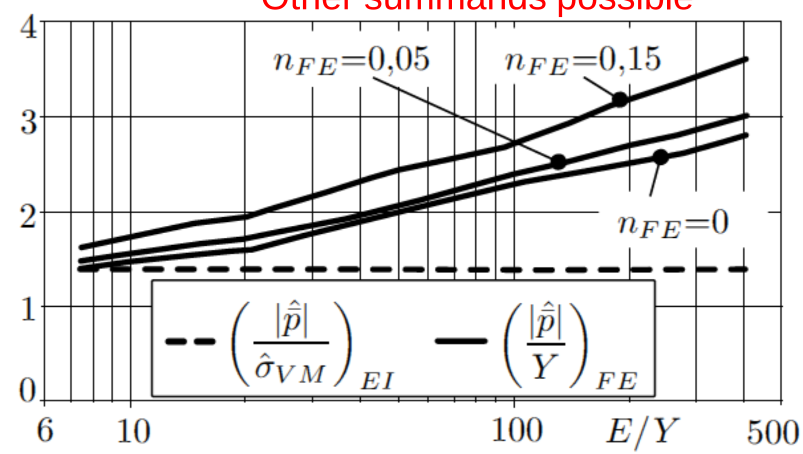
$$H = 3Y$$

Expanding cavity model of Marsh

[D. M. Marsh, Proc. Roy. Soc. A279 (1964) 420]

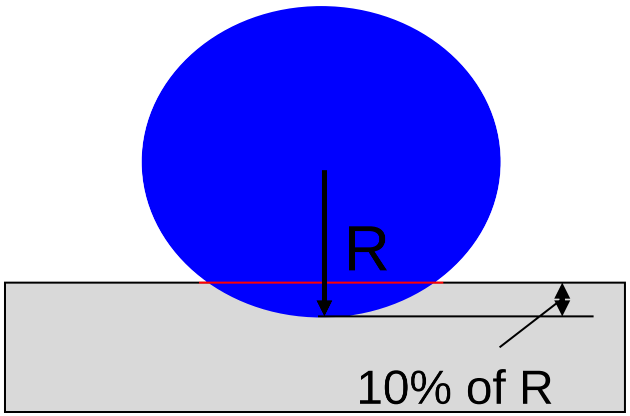
$$\frac{H}{Y} = 1.25 + \frac{2}{3}\ln\left(\frac{1}{3}\frac{E}{Y}\tan\beta\right)$$

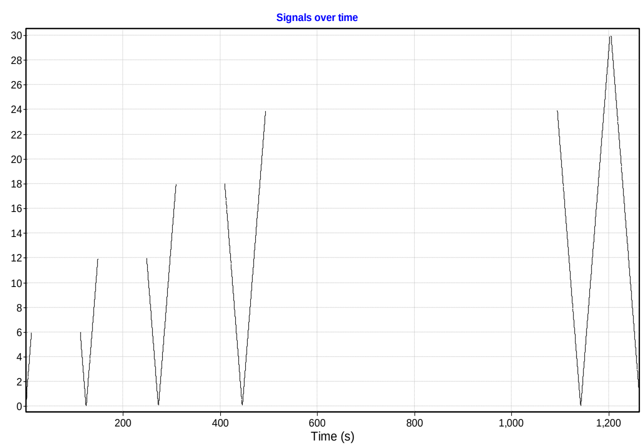
Other summands possible

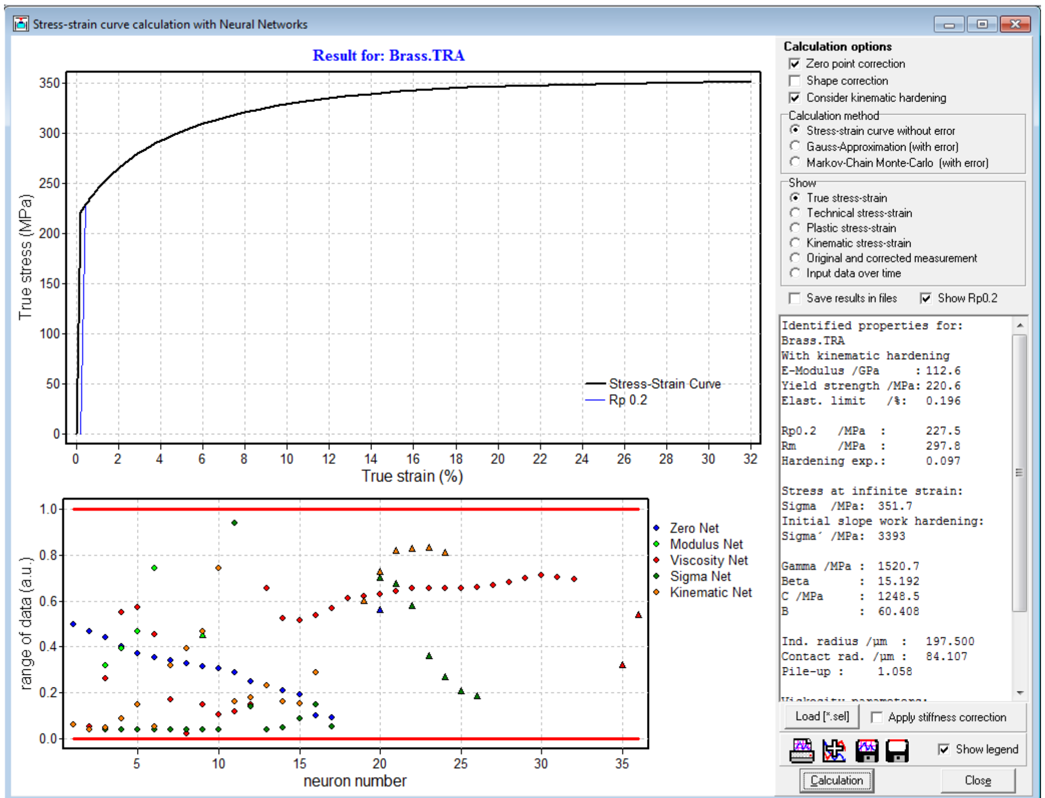


Stress strain curve determination
with spherical indenter and neural network

Quantitative: Yes
local







$$\sigma(\varepsilon_p) = k_0 + \frac{\gamma}{\beta}\left(1 - e^{-\beta\varepsilon_p}\right) + \frac{3}{2}\frac{c}{b}\left(1 - e^{-b\varepsilon_p}\right)$$

In the model the stress consists of 3 terms.

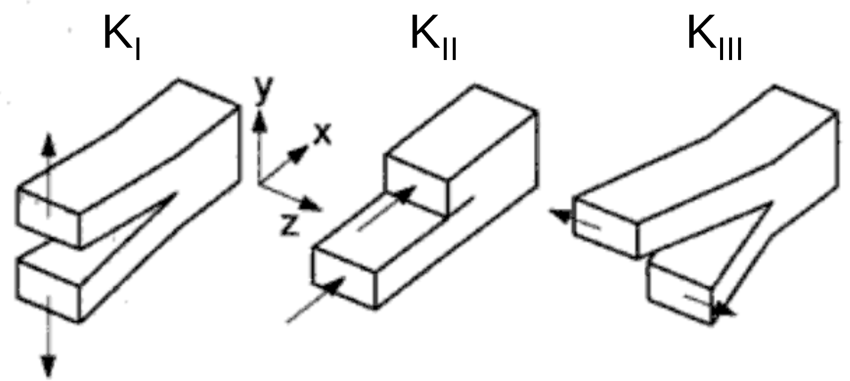
first term k_0 is the yield stress
second term the isotropic hardening
third term the kinematic hardening

Brittle behavior

Fracture toughness

Tensile strength

Fracture toughness estimation from indentation tests



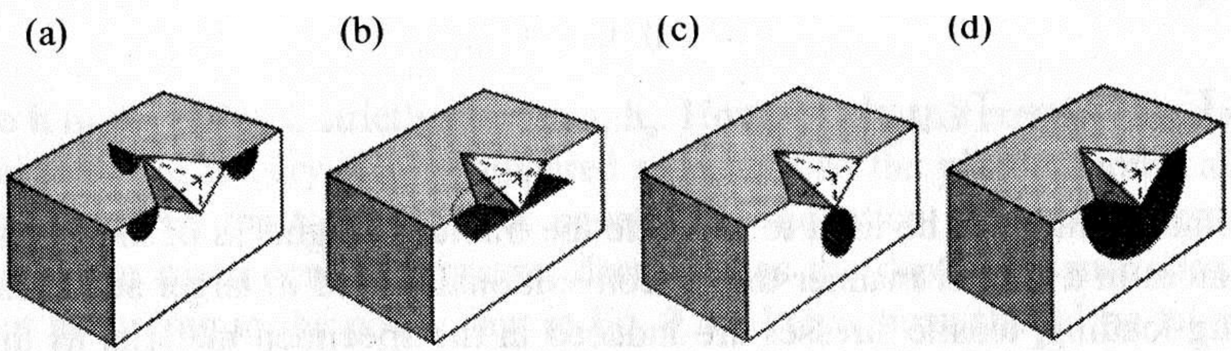
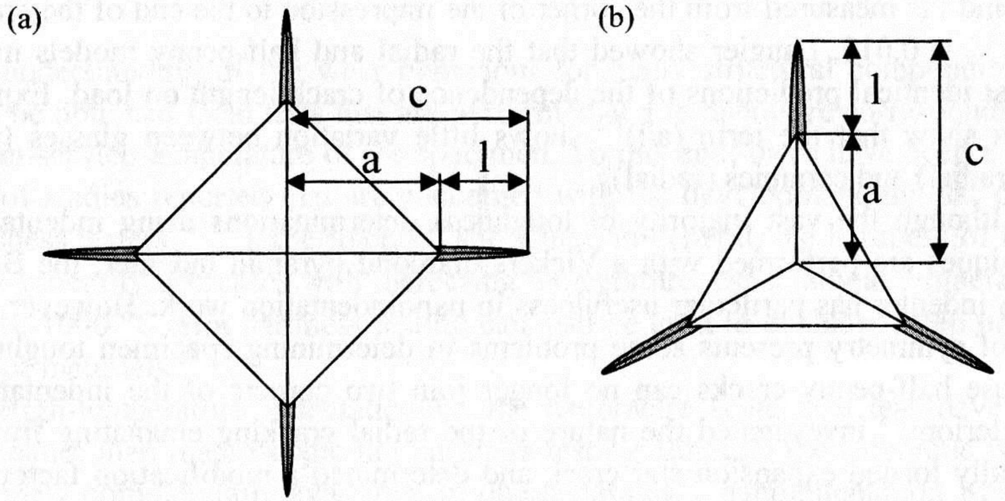


Fig. 9.2 Crack systems for Vickers indenter: (a) radial cracks, (b) lateral cracks, (c) median cracks, (d) half-penny cracks (after reference 13).

(a) Also known as Palmquist cracks
Image from: A.C. Fischer-Cripps, Nanoindentation, Springer



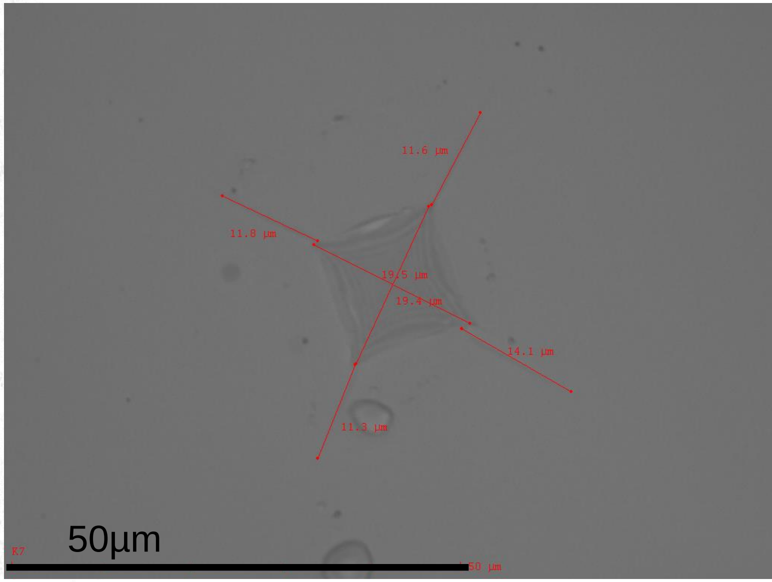


Fig. 9.3 Crack parameters for Vickers and Berkovich indenters. Crack length c is measured from the center of contact to end of crack at the specimen surface (After reference 13).

Image from: A.C. Fischer-Cripps, Nanoindentation, Springer

For c/a > 2.5 Median crack shall form

Median $$K_C = 0.016 \cdot \left(\frac{E}{H}\right)^{0.5} \cdot \frac{F}{c^{1.5}} \qquad c = a + l$$

Median $$K_C = 0.015 \cdot \left(\frac{a}{l}\right)^{0.5} \cdot \left(\frac{E}{H}\right)^{2/3} \cdot \frac{F}{c^{1.5}}$$

F - Force

Factor	Vickers	Cube corner
	0.016	0.032
	0.015	0.016

Palmquist crack: $l \propto F$
Median crack: $c \propto F^{2/3}$

Fracture toughness from indentation using sharp tips

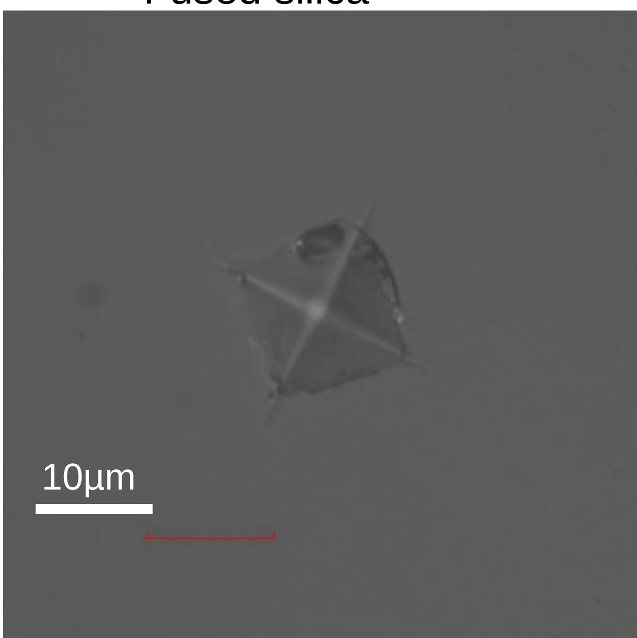
Quantitative: partially
Local

$$K_C = 0.087 \cdot \left(\frac{E}{H}\right)^{2/3} \cdot (\cot\phi)^{2/3} \cdot \frac{F}{c^{2/3}}$$

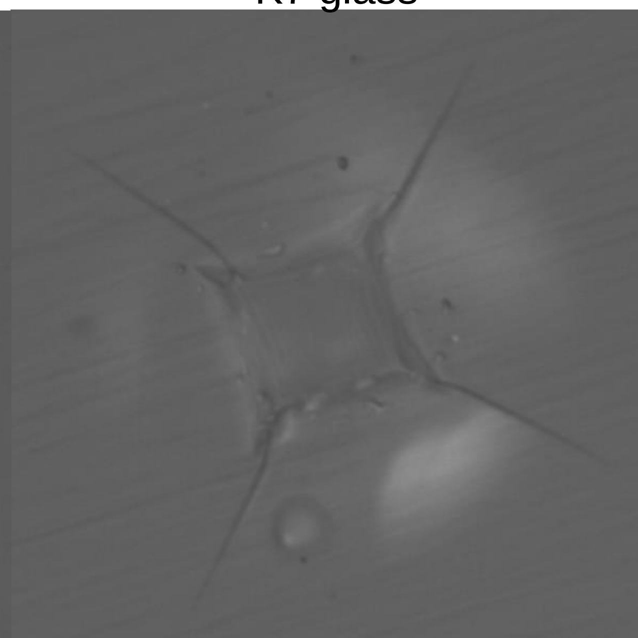
Half opening angle Vickers: 68° Cube Coner: 35°

1.5 N indents with Vickers indenter into:

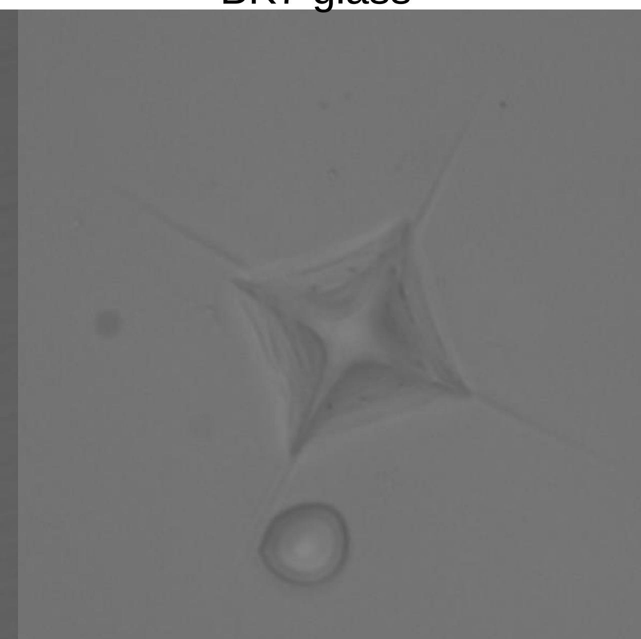
Fused silica



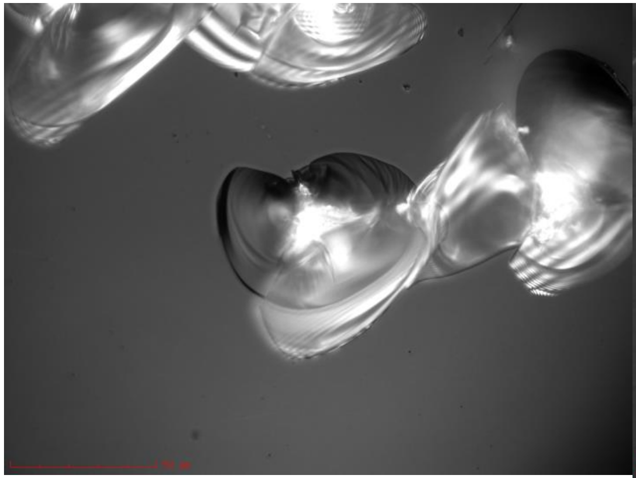
K7 glass

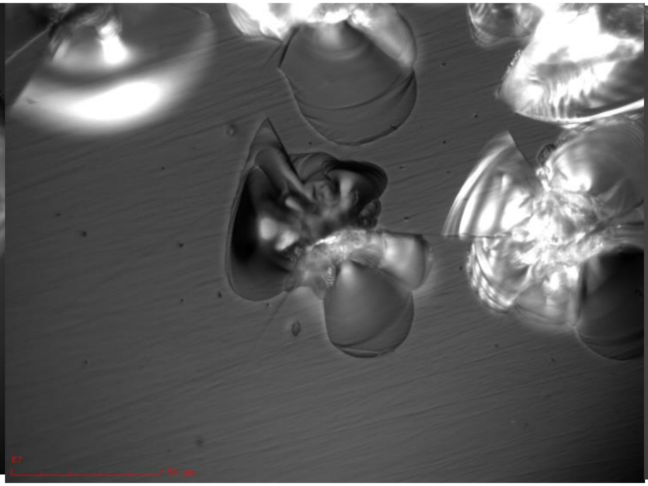


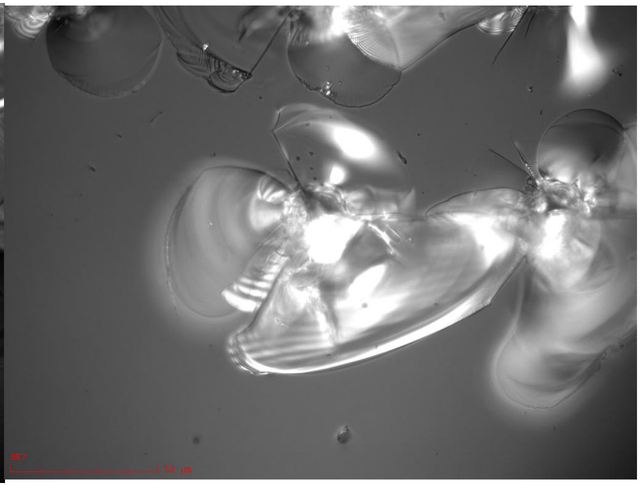
BK7 glass



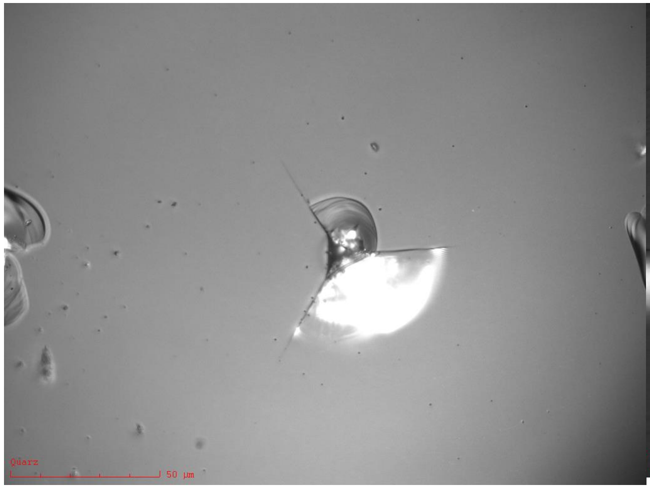
Cube corner 1.5N: Silica K7 BK7







Cube corner 1.0N: Silica K7 BK7



Parameter	FS	K7	BK7
H / GPa	9.3	5.7	7.4
E / GPa	72	69	82
Poisson's ratio	0.17	0.214	0.206
KIc Literature	**0.75**	**0.95**	**0.82**
Fracture toughness MPa*m$^{1/2}$			
Kc (Eq. 1) Vickers	**1.4**	0.60	0.84
Kc (Eq. 1) Berkovich	0.71	0.56	0.95
Kc (Eq. 2) Vickers	**2.0**	0.6	0.8
Kc (Eq. 2) Berkovich	0.4	0.4	0.9
Kc (Eq. 3) Vickers	**4.6**	0.8	1.1
Kc (Eq. 3) Berkovich	0.4	0.4	0.9
Kc (Eq. 4) Vickers	0.6	0.4	0.5
Kc (Eq. 4) Berkovich	0.4	0.5	0.7
Mean	**0.50**	**0.56**	**0.84**

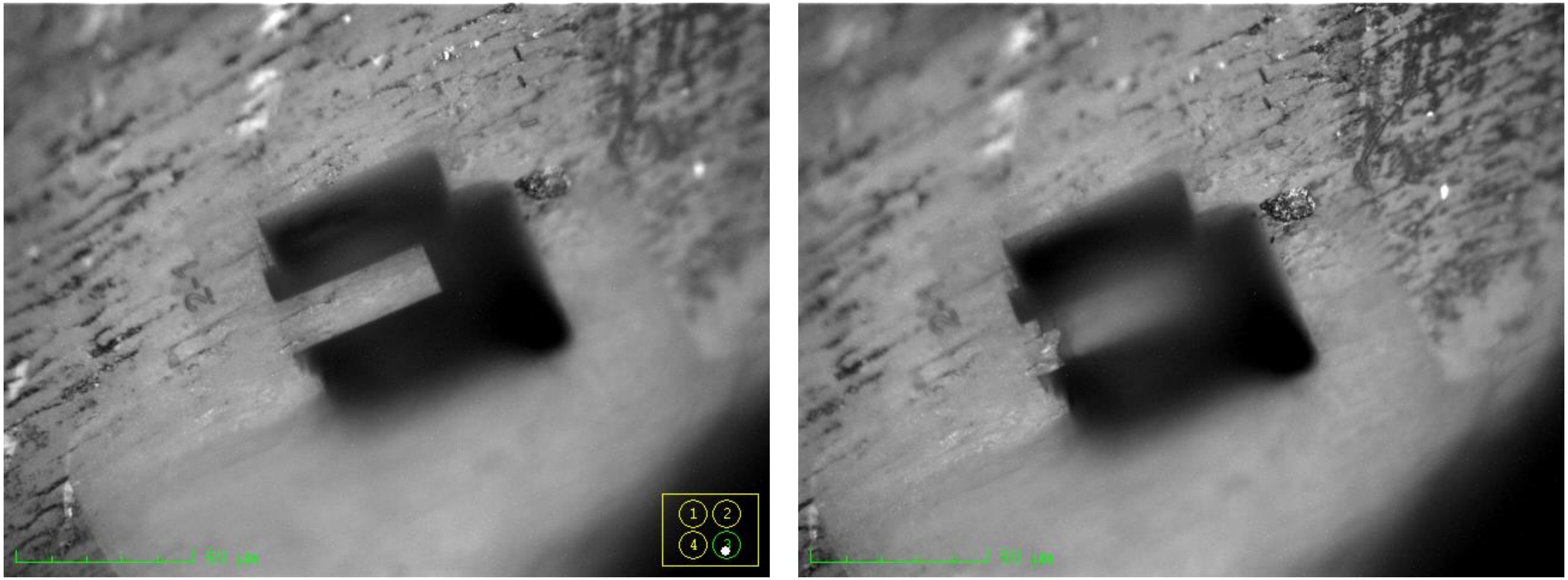
Mean without blue numbers

- It is possible to determine fracture toughness data from Vickers or cube corner indentations in the micro range
- Results depend on indenter type
- Accuracy decreases with decreasing indent size
- High load indents with cube corner indenter result in severe crack formation.
- For thin coatings the substrate influence has to be considered → quantitative results only in combination with FE modelling

Tensile strength from beam bending experiments
in combination with FE calculations

Quantitative: partially
Integral

Quantitative results for coatings only possible in combination with FE modelling

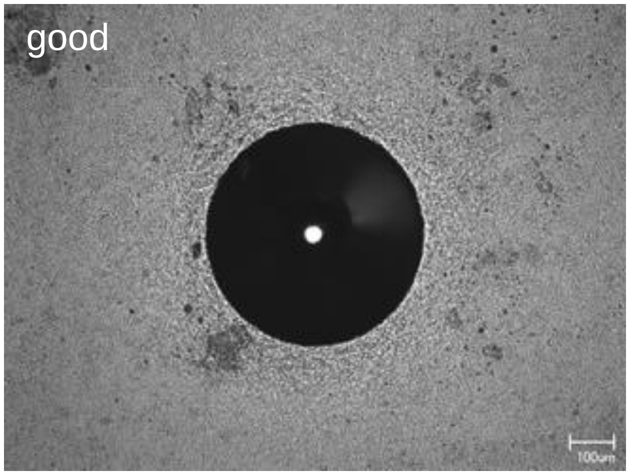


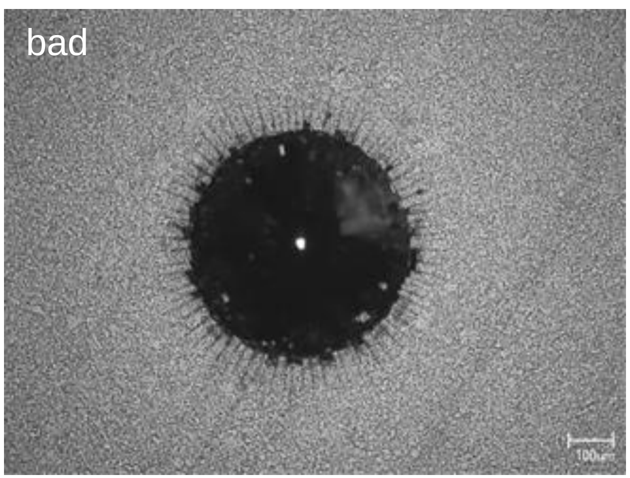
Example: micro beam bending experiment on tooth material

Adhesion

Rockwell adhesion test
VDI guideline 3198

Quantitative: No
Local





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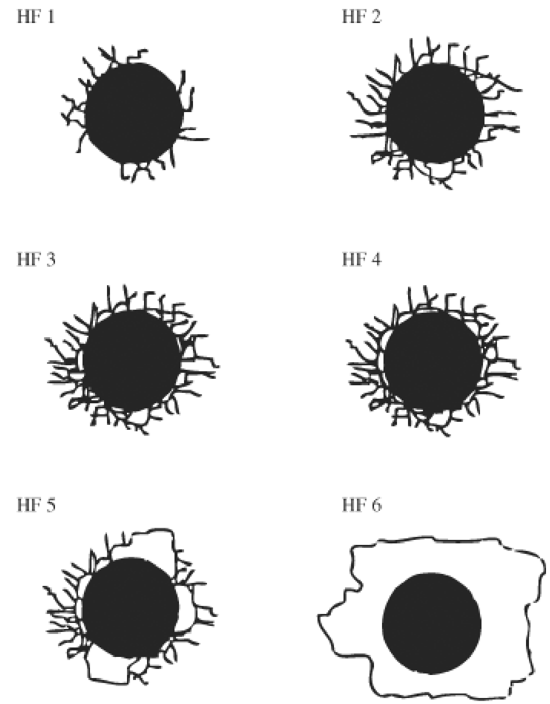
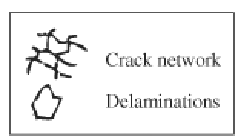




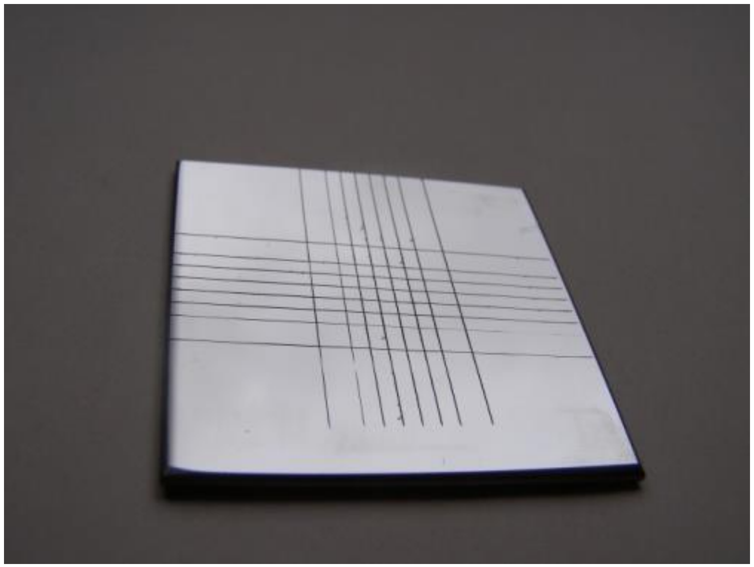
VDI guideline 3198

Figure 5. Adhesion strength quality HF 1 to HF 6[26].

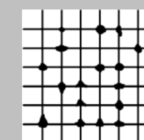
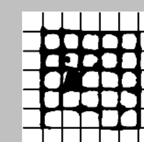
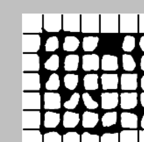
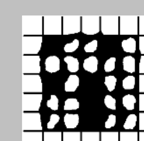
Mat. Res. vol.10 no.3 São Carlos July/Sept. 2007

Cross-cut test
ISO 2409 (paints and varnishes)
ISO 9211-4 (optical coatings)

Quantitative: No
Integral



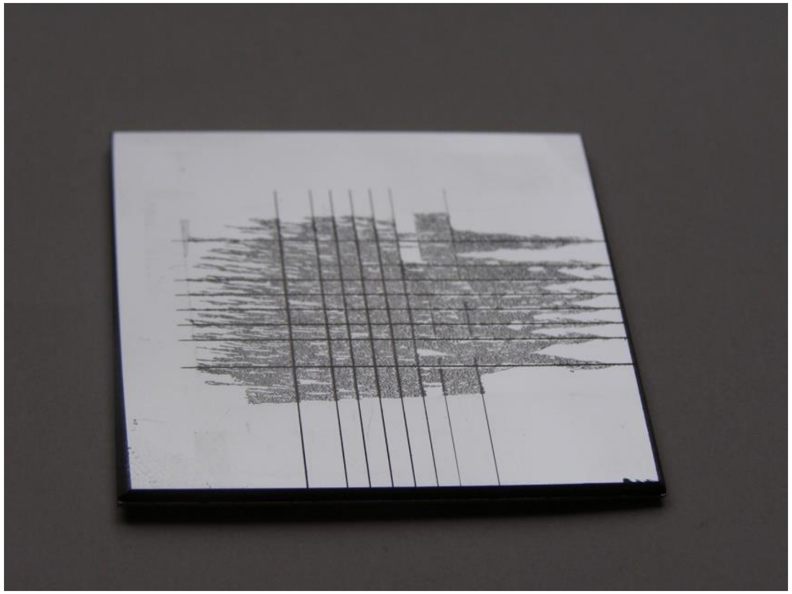
100 nm Cr on PC – passed (class 0)

class	description	pattern
0	no delaminated square, no visible defects	-
1	no delaminated square, small defects at cut-crossings, delaminated area less than 5%	
2	defects at cut-crossings and -lines, delaminated area between 5% and 15%	
3	additional areal defects and/or delaminated squares, delaminated area in between 15 % and 35 %	
4	additional areal defects and/or delaminated squares, delaminated area in between 35 % and 65 %	
5	beyond class 4	-

Courtesy Beck, BAM

Peel test
EN 28510

Quantitative: No
Integral



100 nm Cr on PC

Cross-cut: passed
Peel test: failed

Peel test for flex-rigid bonded composites (according to ISO 8510-1)

Peel width: (25 ± 0.5) mm

Testing length: 150 mm

T-sized substrate, 5 samples

90° pull direction for peel vs. 60° pull direction for cross-cut tests

Testing velocity: (50 ± 5) mm/min

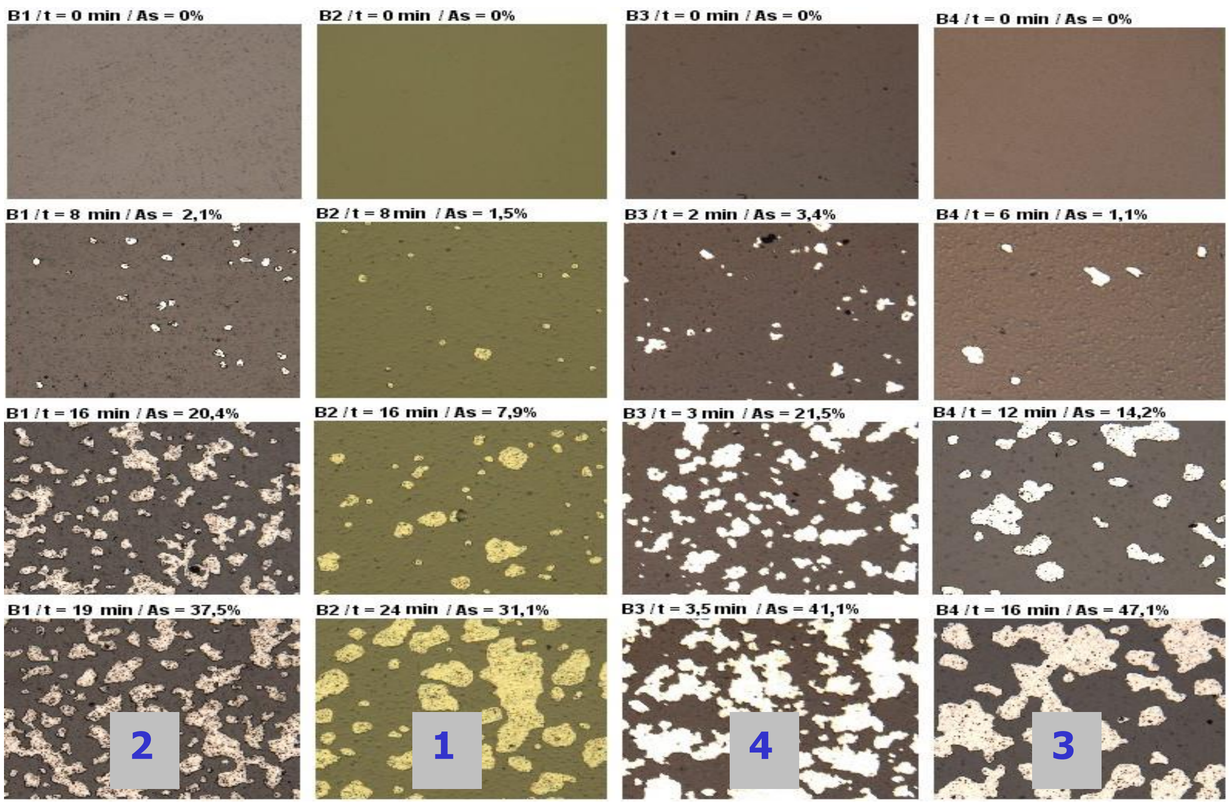
Peel force: N/m

Courtesy Beck, BAM

Cavitation test
ASTM G32

Quantitative: No
Integral

DLC – coatings, different pre-deposition treatment



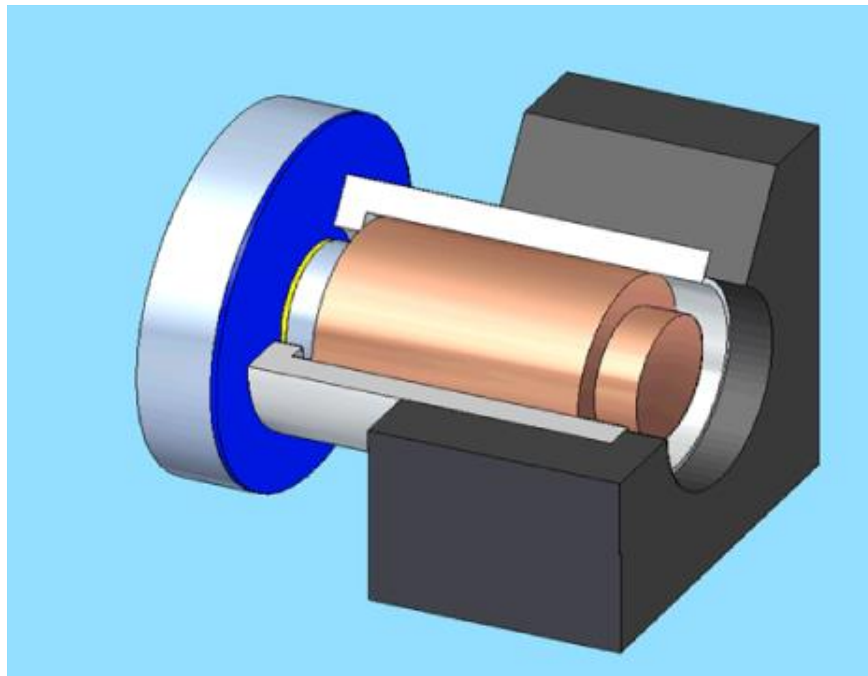
s = 1 cm, f = 20 kHz

The cavitation resistance is measured in **s** to reach a distinct degree of coverage (DoC).

Courtesy Beck, BAM

Centrifuge test

Quantitative: Yes
Integral
Up to 100MPa, 6.5kN

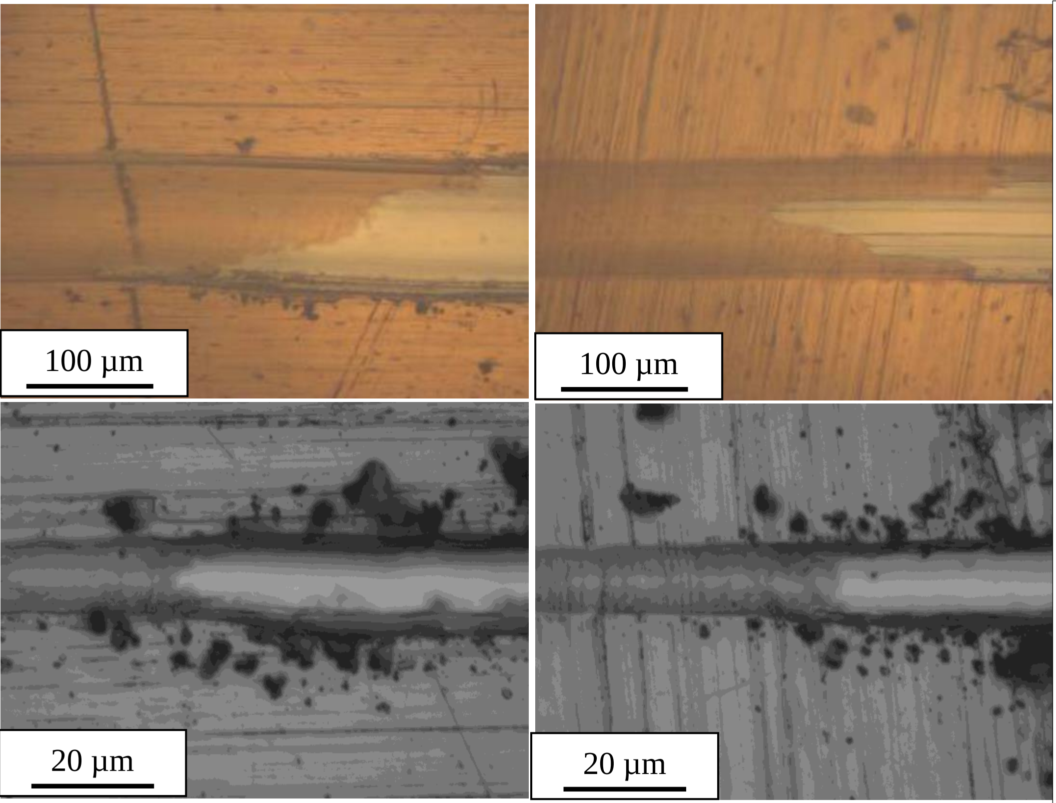


Courtesy Beck, BAM

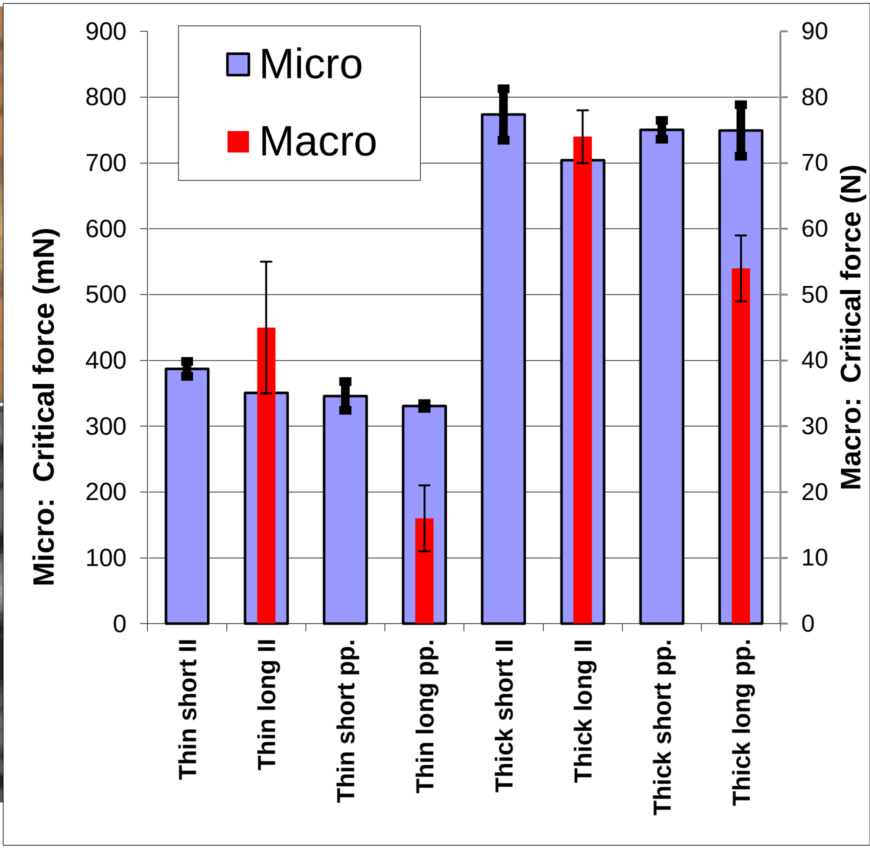
substrate/coating – adhesive – adherend – test stamp – guiding sleeve – testing unit

Scratch test --- Micro scratch test
EN 1071 none

Quantitative: **partially**
Integral

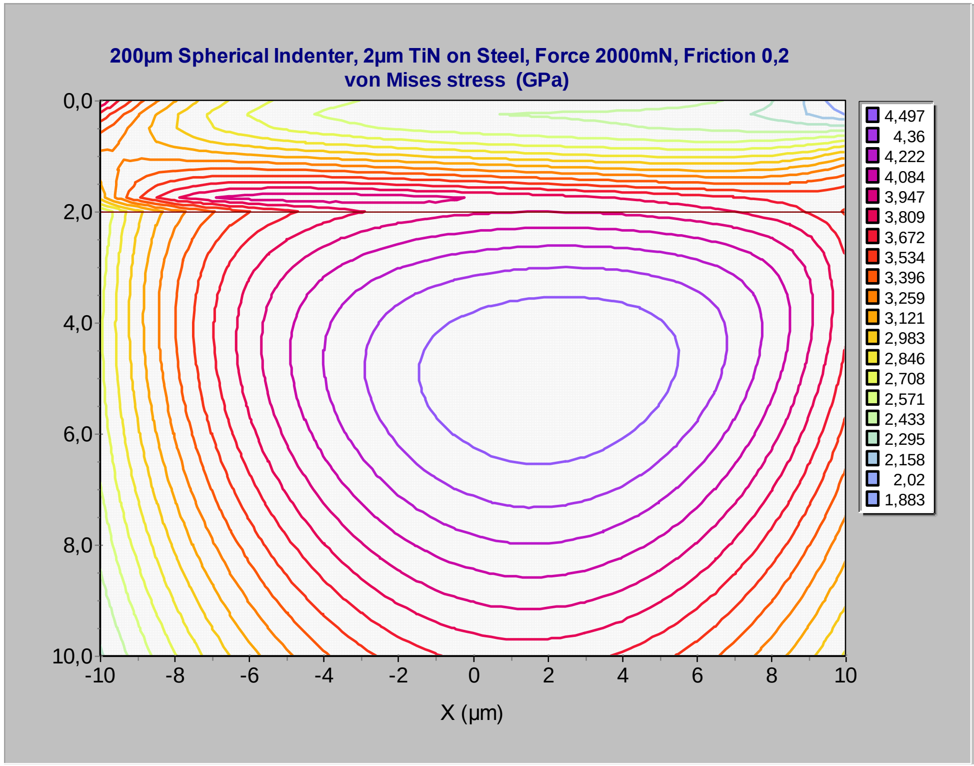


550 nm TiN on steel

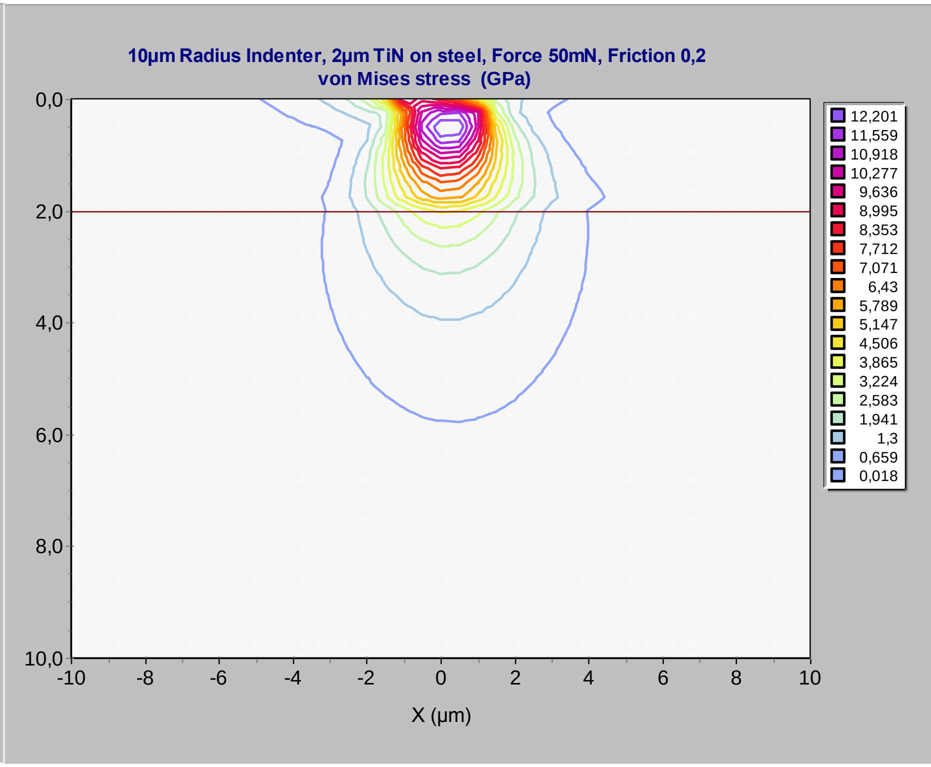


Thin = 550 nm TiN
Thick = 1500 nm TiN

Von Mises stress field in the surface of a 2µm thick hard coating on steel for a scratch test with tips of different radius.



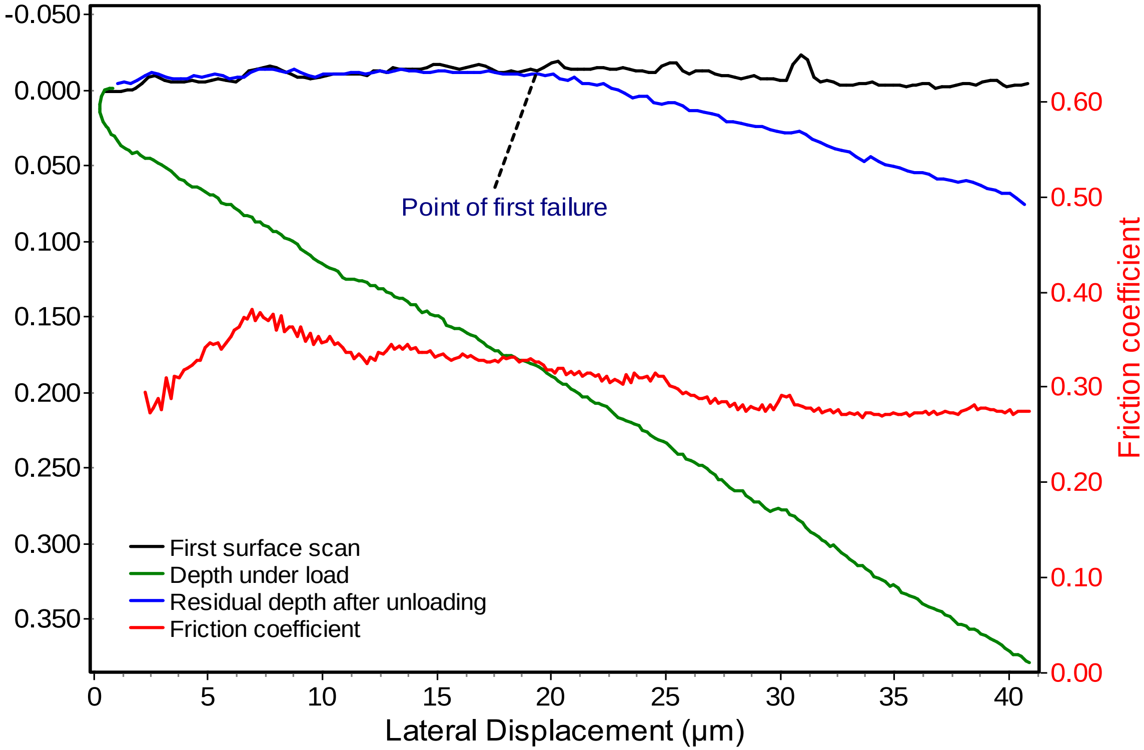
200µm radius

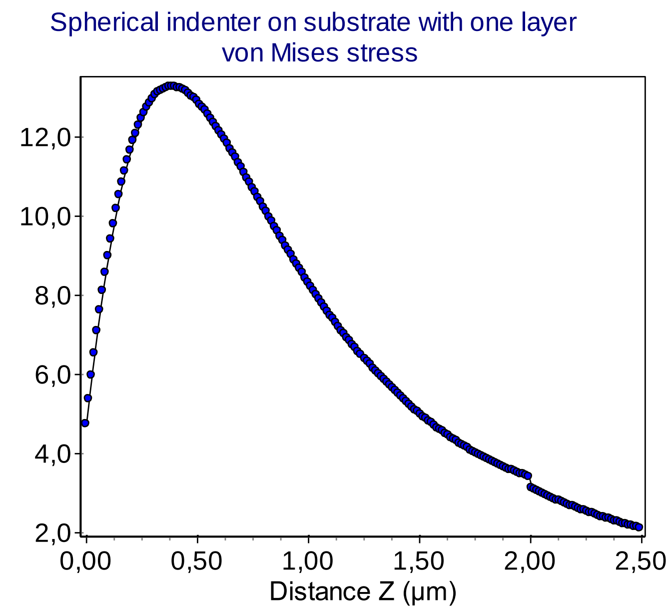


10µm radius

The first failure of a conventional scratch test occurs normally in the substrate.

Elastic-plastic transition gives yield strength





Scratch test with load ramp from 0 mN (left) to 35 mN (right).
The high displacement resolution in both directions allows to detect the point of first failure.

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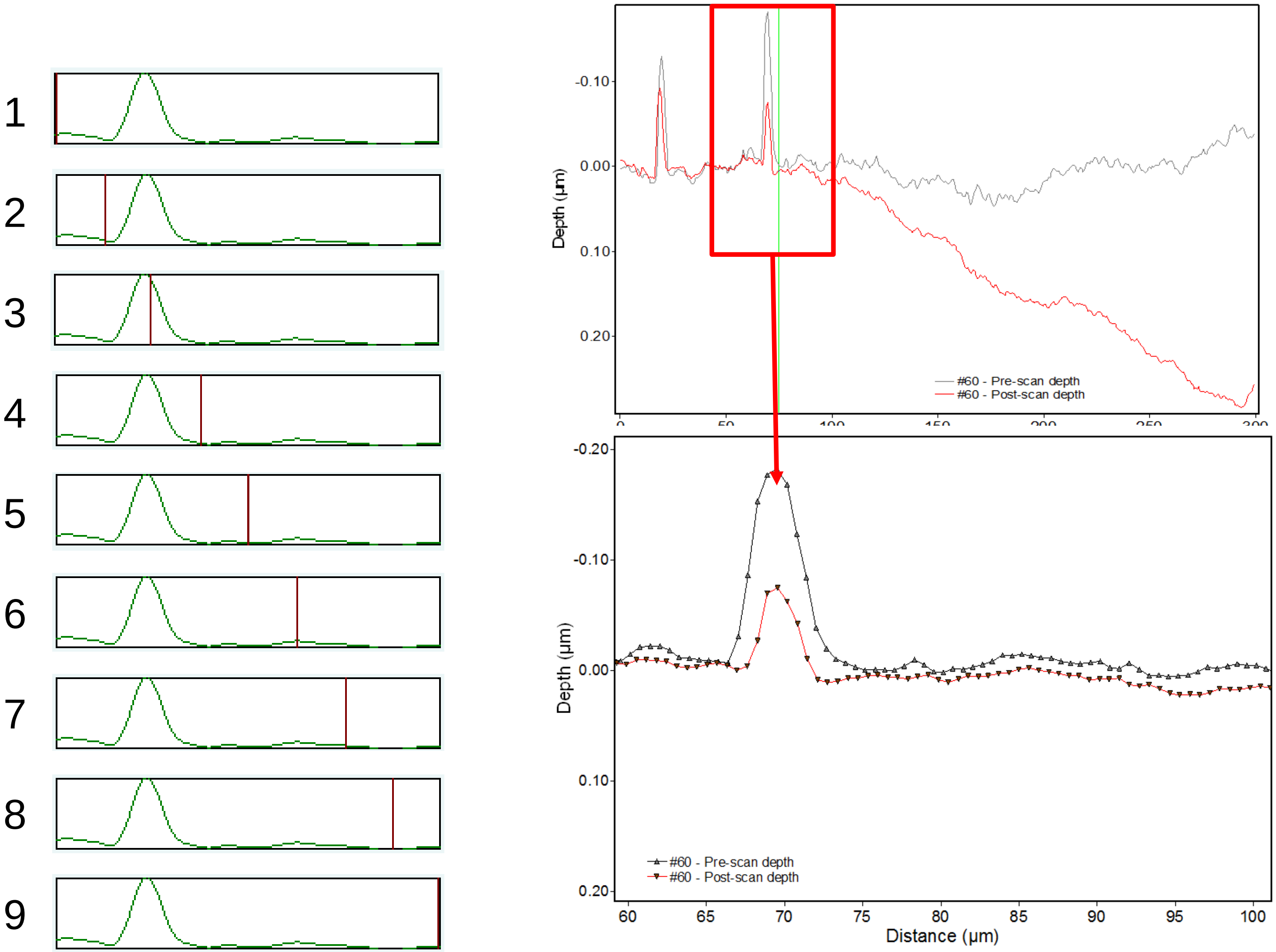
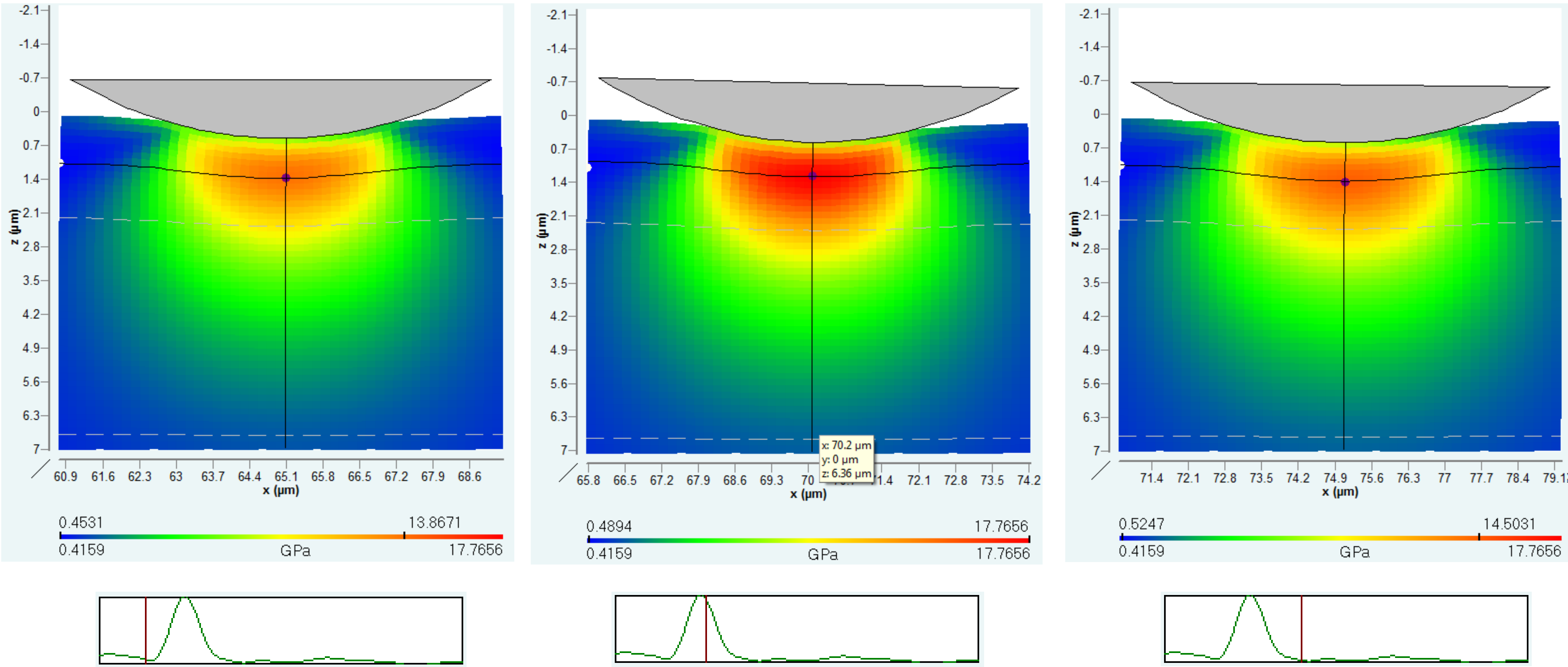
Scratch tests on a:C:H:W coatings (DLC) #60 and #62



Peak height: 180nm

Peak width: 5µm

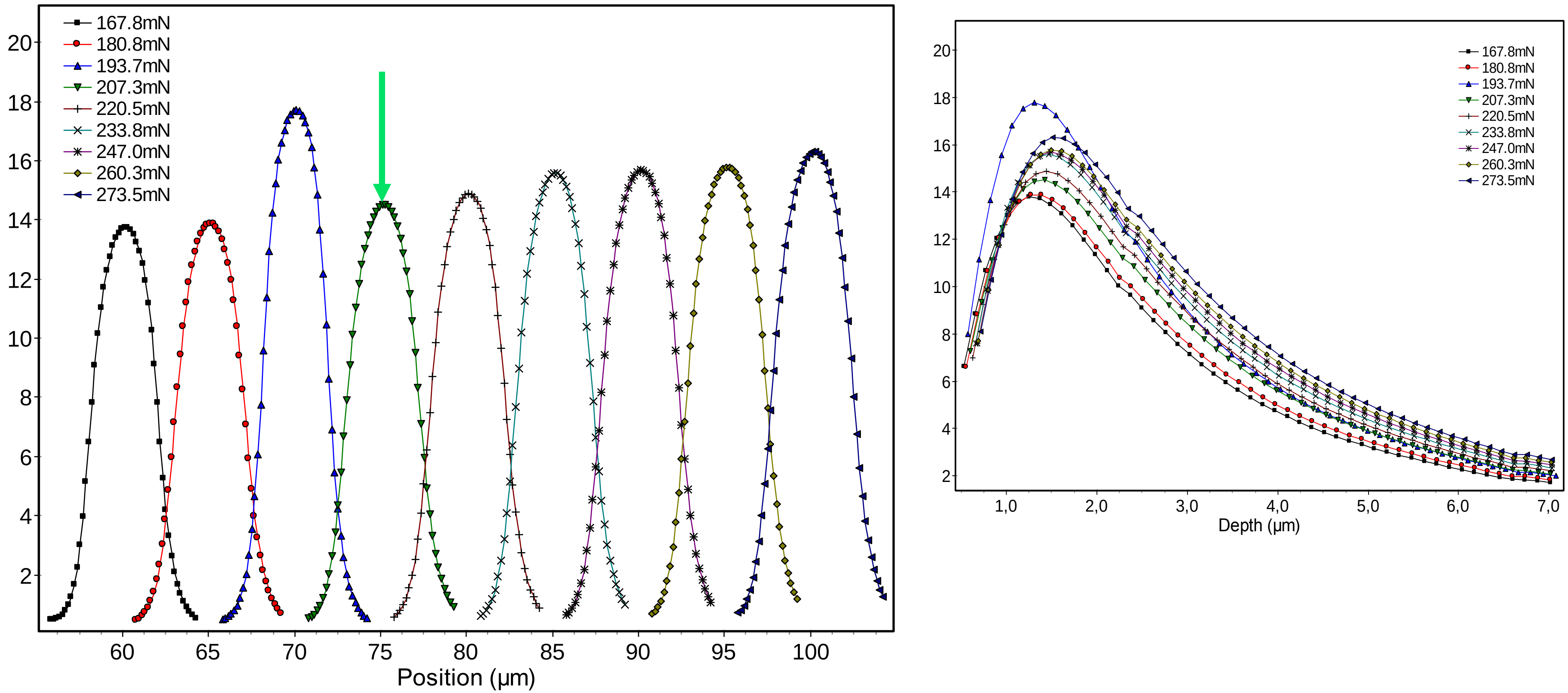
Von Mises stress profile, *FilmDoctor* calculation



180.8mN   193.7mN   207.3mN

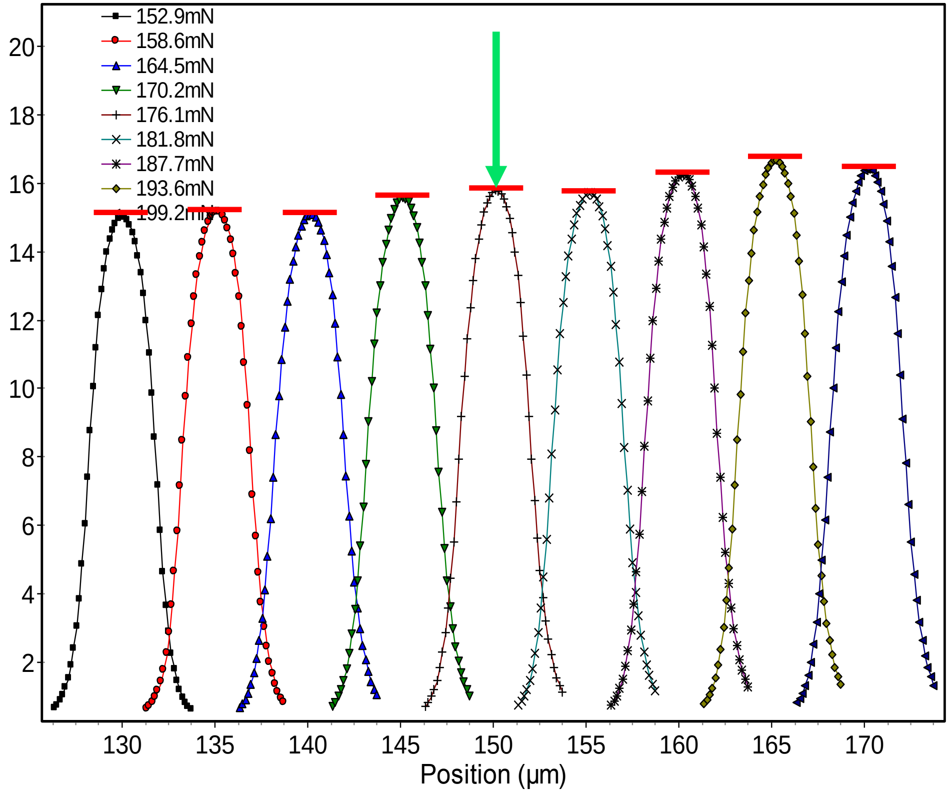
The von Mises stress is considerably higher on top of the peak

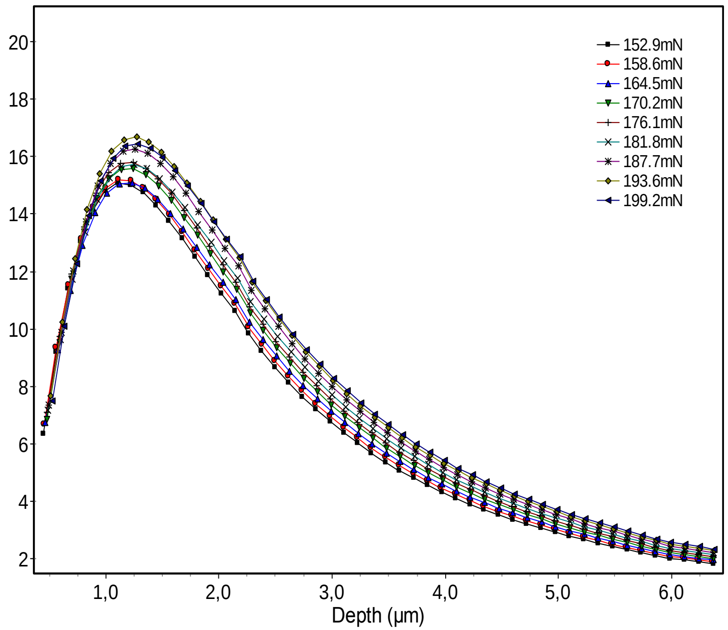
168mN →→→→→→→→→→→→→→→→→→→ → 274mN



Comparison of stress profiles from different positions

153mN →→→→→→→→→→→→→→→→ 199mN



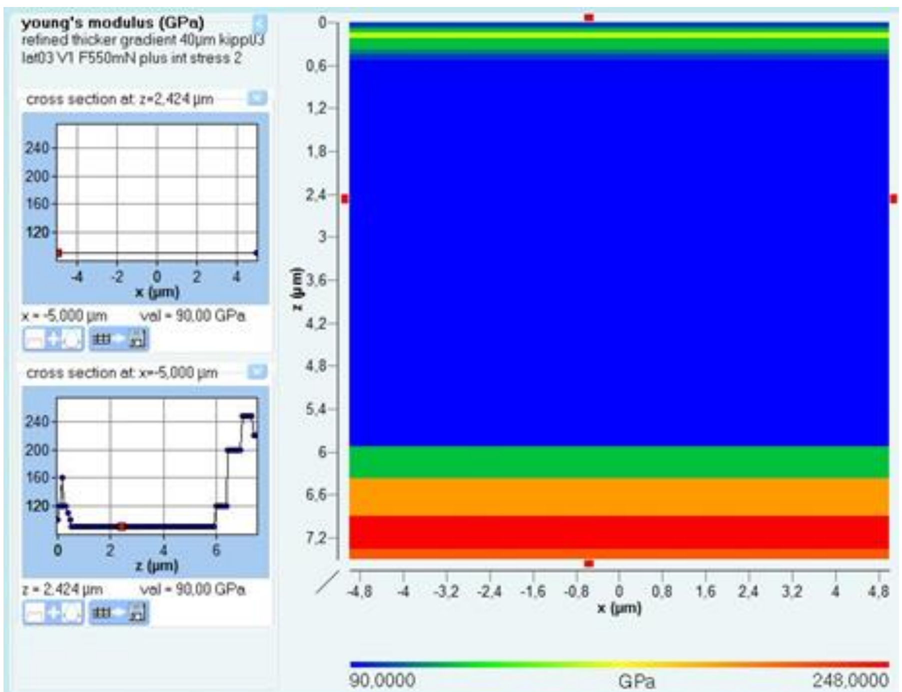


Comparison of stress profiles from different positions

The stress is not steadily increasing with force

Sample	#60	#62
Hardness H	11.3 GPa	14.8 GPa
Critical force	207 mN	176 mN
Yield strength Y	14.5 GPa	15.8 GPa

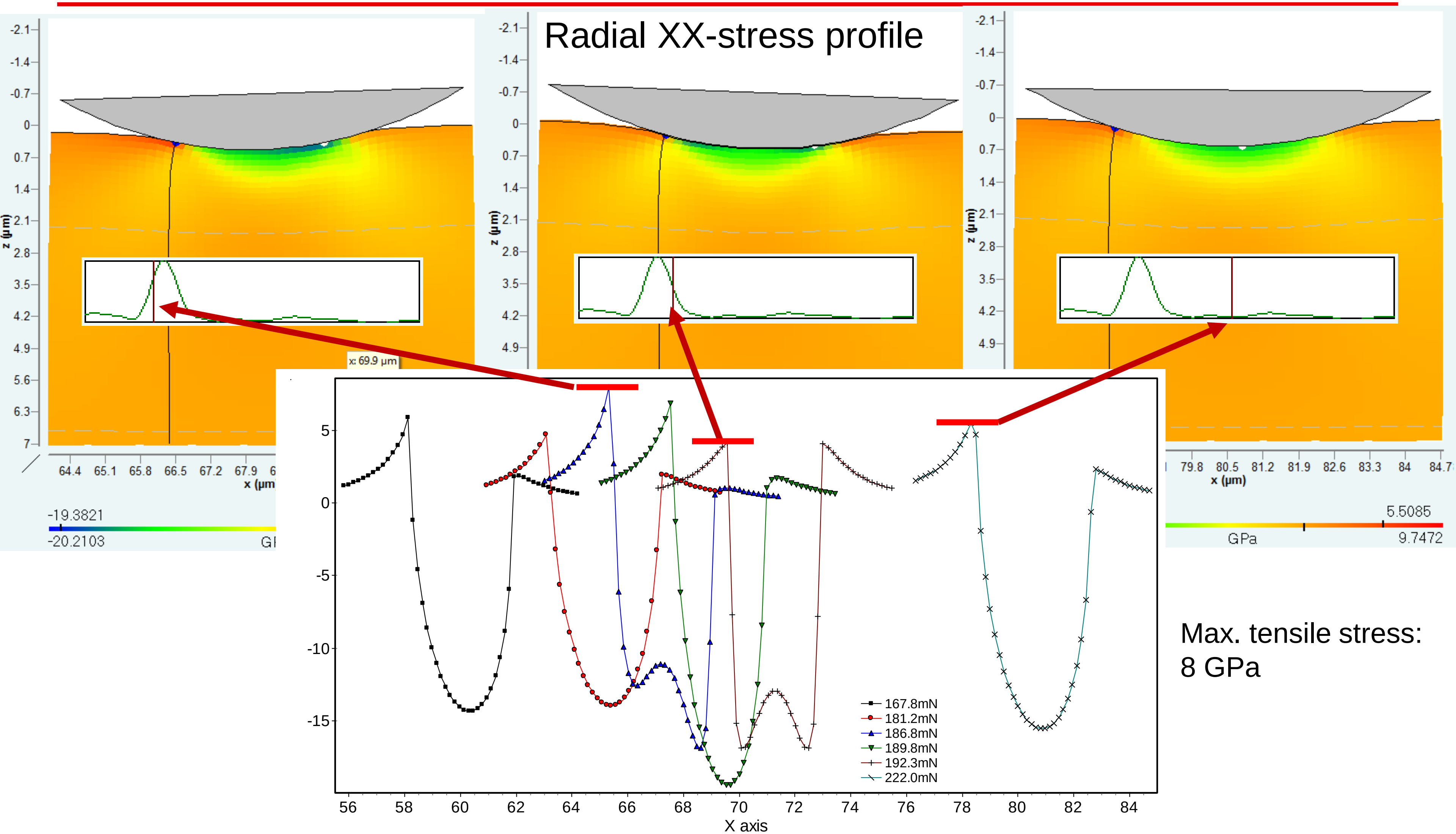
Sample #60 = gradient coating thickness 6.5µm
Sample #62 = homogeneous coating thickness 7.8µm



Example for a gradient coating

Sample #60

Radial XX-stress profile

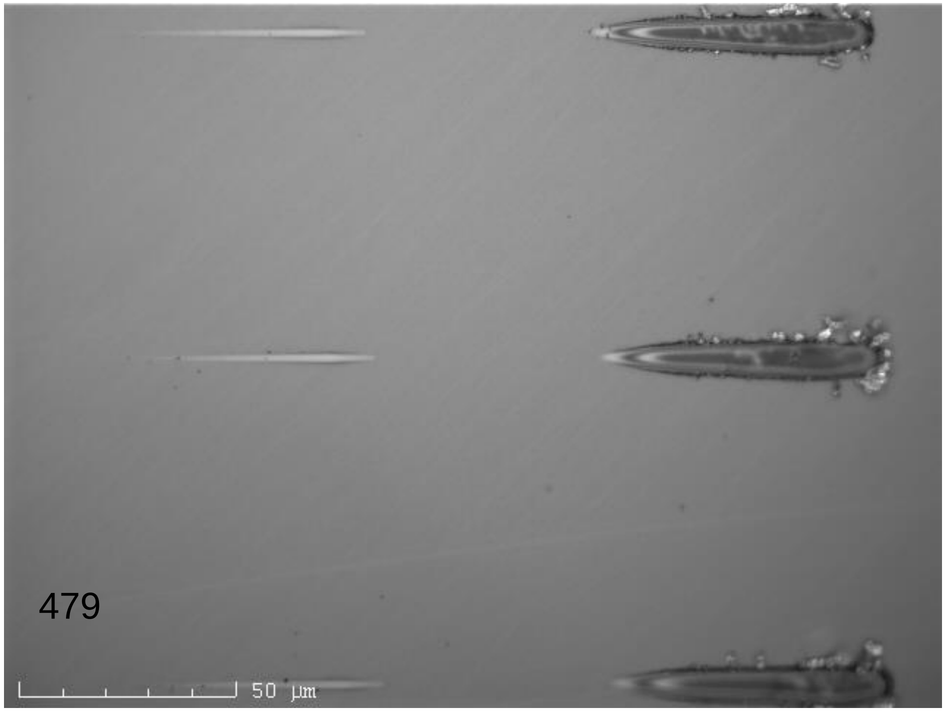


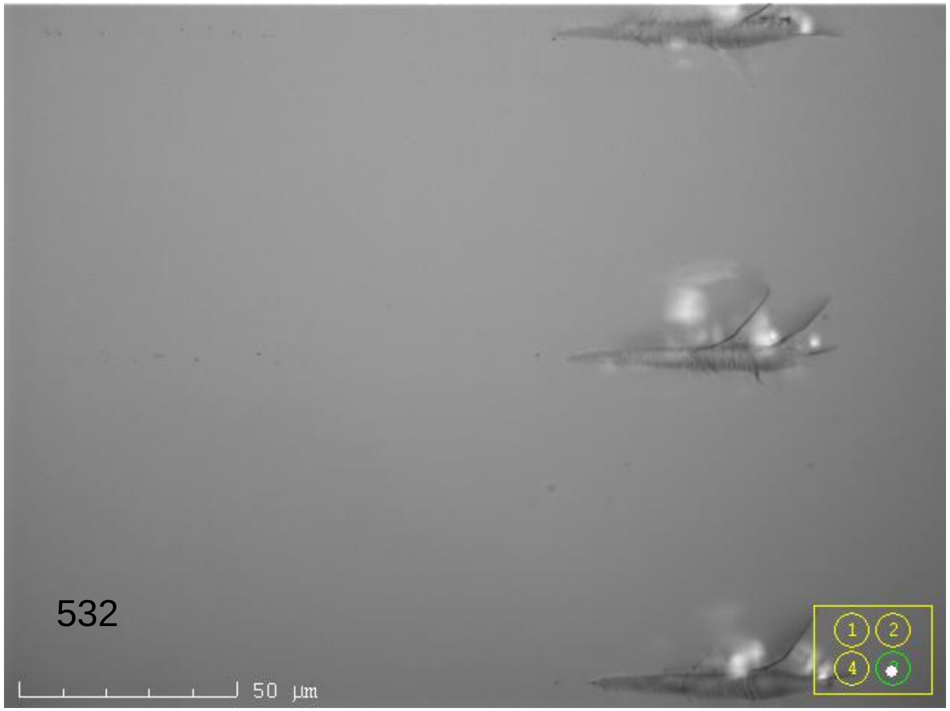
Max. tensile stress: 8 GPa

The tensile stress is considerably higher in regions with increasing surface profile

240 nm thick optical coatings on sapphire

Three 50mN und 700mN micro scratch tests over each other



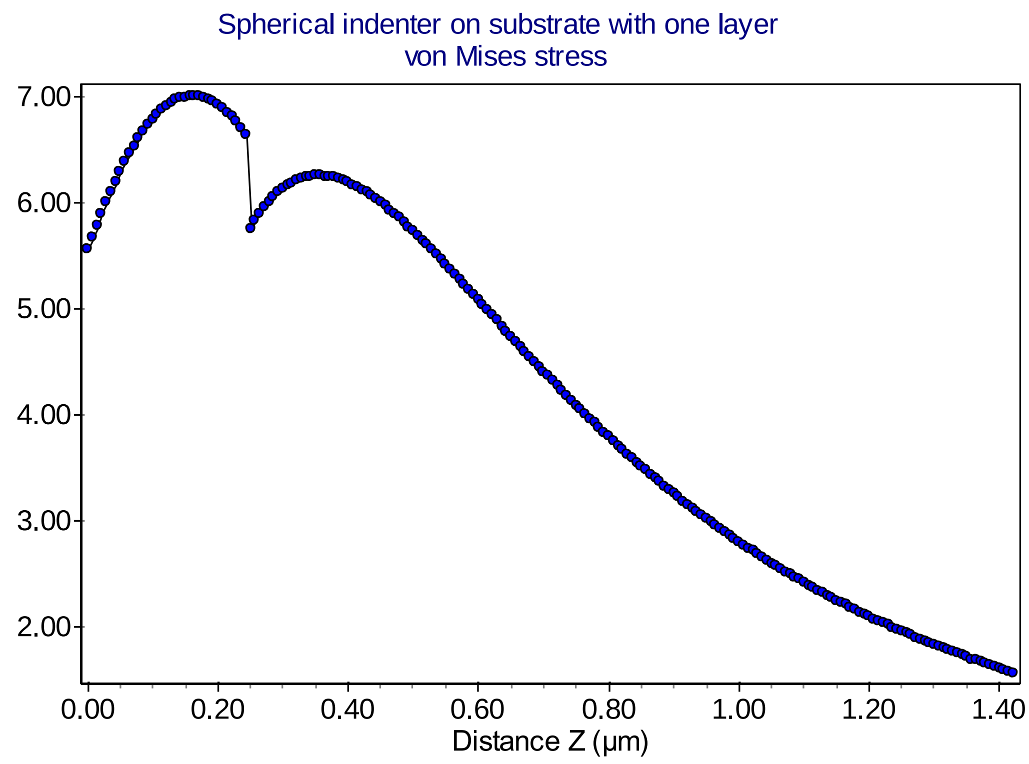


The two coatings show different failure modes

Yielding starts in the coating since the substrate was hard enough for these samples

Yield strength results

Sample number	Fcrit mN	µ	Yield strength GPa
479	**6.89**	**0.061**	**6.97**
486	6.60	0.067	6.5
488	8.30	0.078	7.4
489	8.49	0.088	7.64
531	12.75	0.110	8.79
532	**131.79**	**0.069**	**20.8**
485/sapphire	8.93	0.065	6.31
485 /glass	31.92	0.057	6.25
Sapphire	171.500	0.084	**27.7**



Von Mises stress profile for sample 479

Frictional and wear behavior

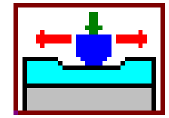
No sample but combinatorial properties

Friction coefficient

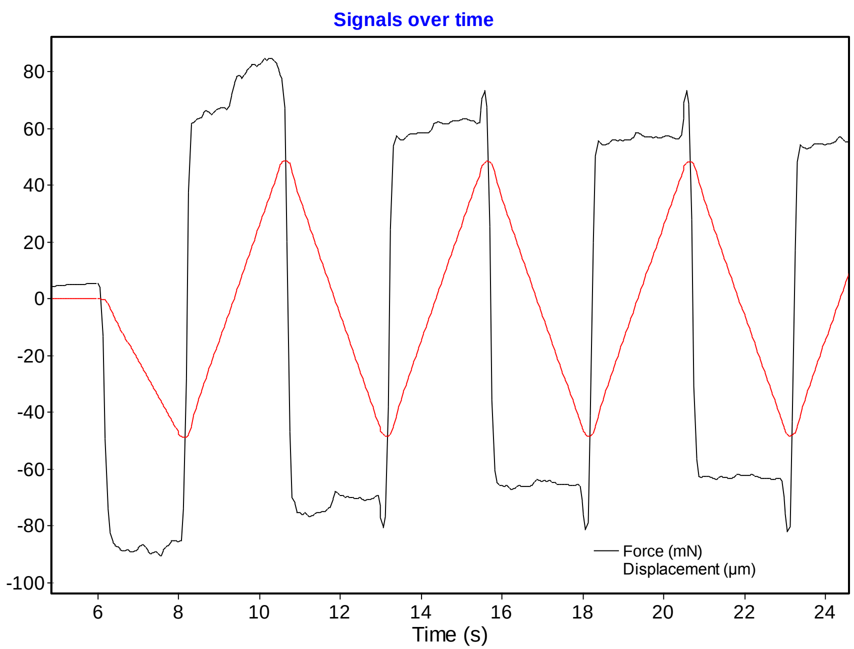
Wear coefficient

Stribeck curve

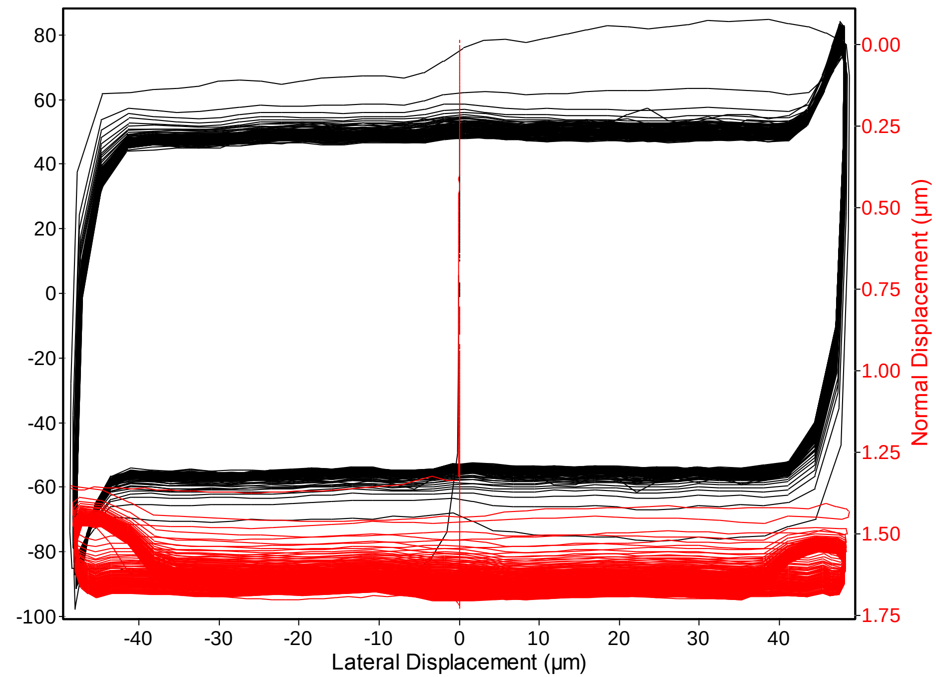
Micro wear test with LFU



Example for DLC on steel, normal force 500mN
Diamond tip with 10µm radius



Force and displacement signal of first 3 cycles over time

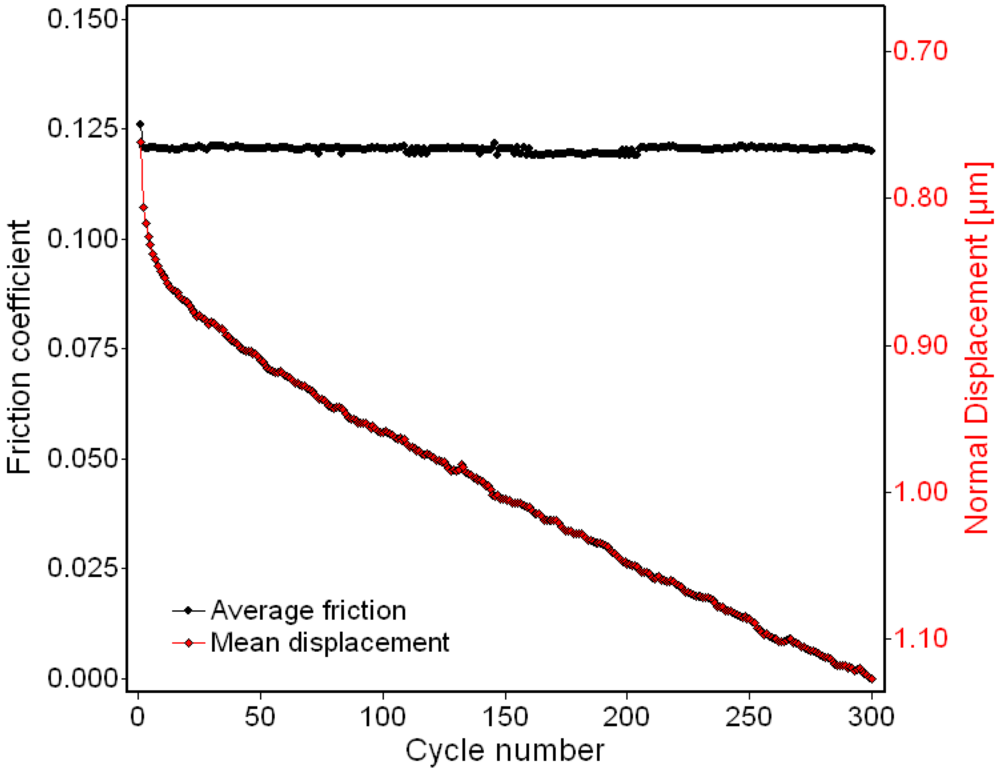


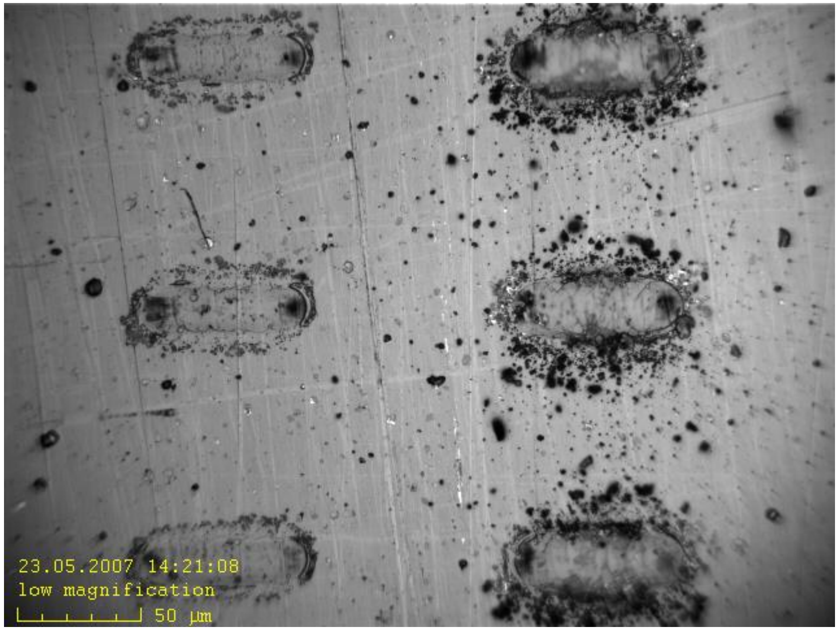
Data from 100cycles in one graph

Micro wear test

No intrinsic property test

Quantitative: No
Local





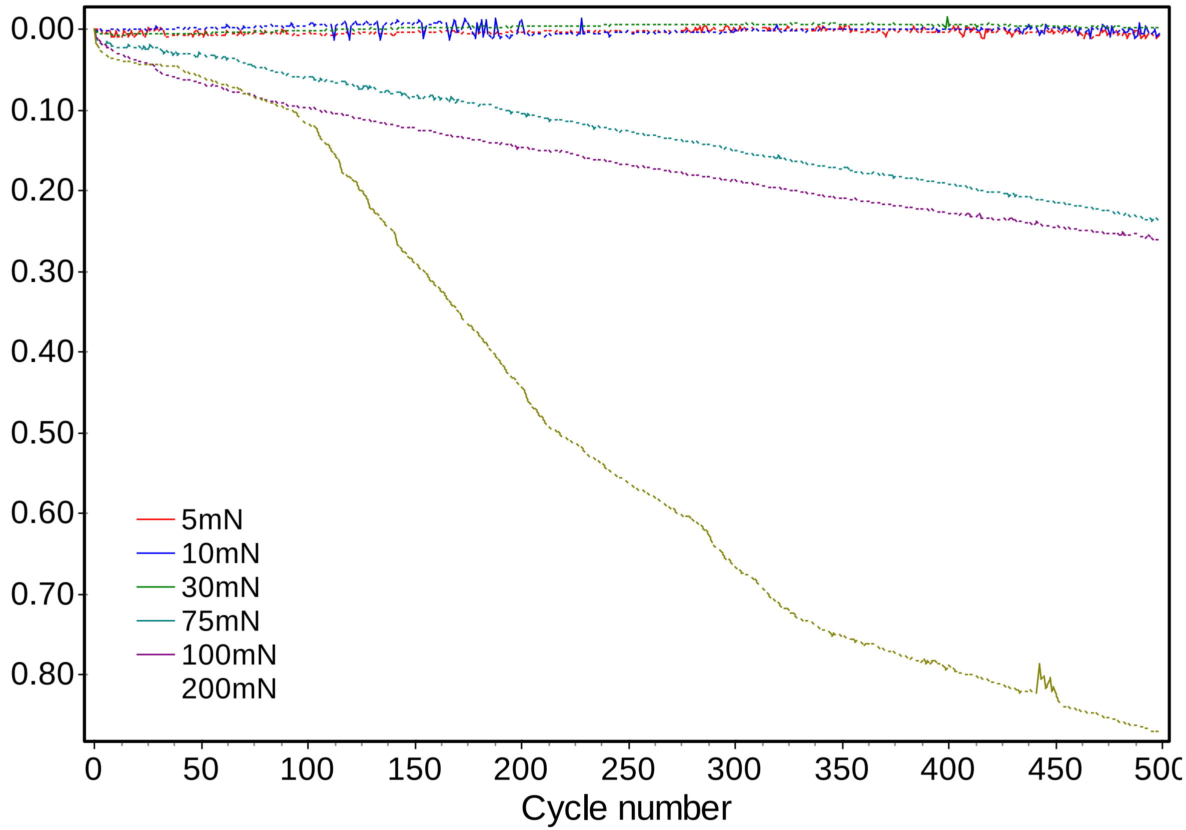
Wear rate: 1 nm / cycle

Force	1000mN	1500mN
Contact pressure	7.2 GPa	8.4 GPa

2.5µm DLC on steel, 55µm tip radius
Amplitude 50 µm, Measuring time 1800 s

CVD DLC on steel

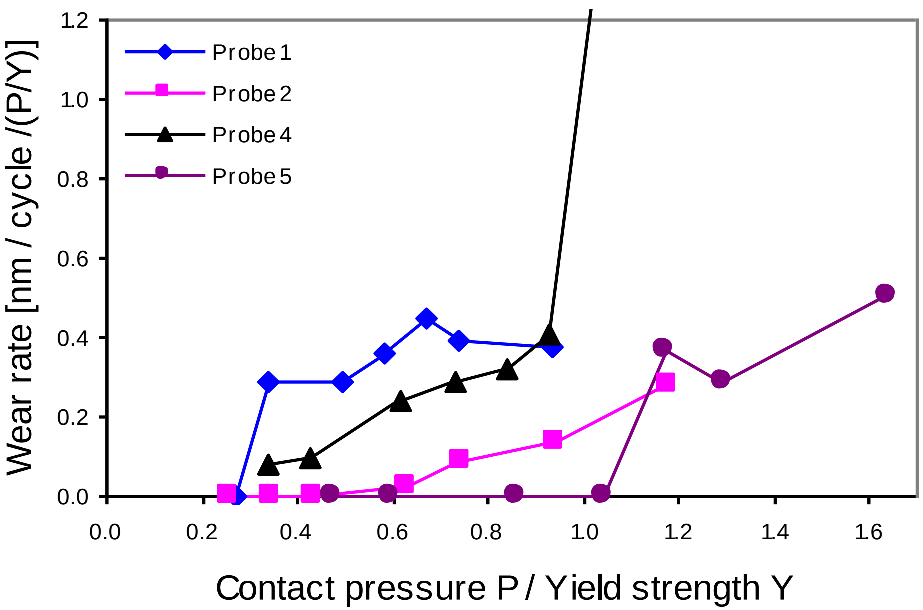
5,7µm film thickness, Film modulus: 100 GPa, Hardness: 12 GPa
Indenter: diamond sphere, 6 µm radius
Displacement amplitude 80µm measurement time 3144s



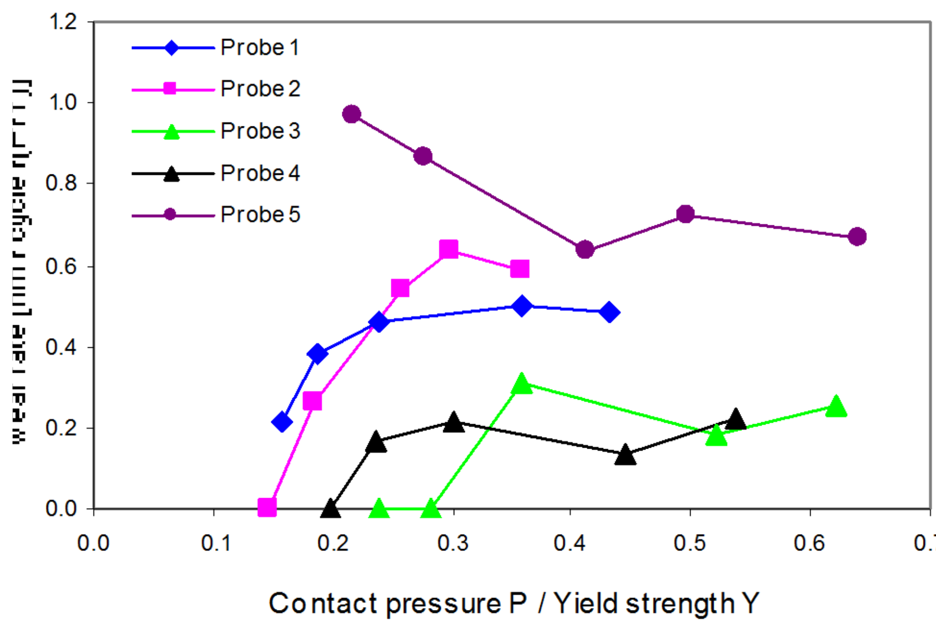
No wear until 50mN normal force
Wear rate at 75mN and 100mN: 0,4nm/cycle

Wear tests on different DLC coatings (a-C:H and t-aC)

Tests with diamond indenter of 6 µm radius

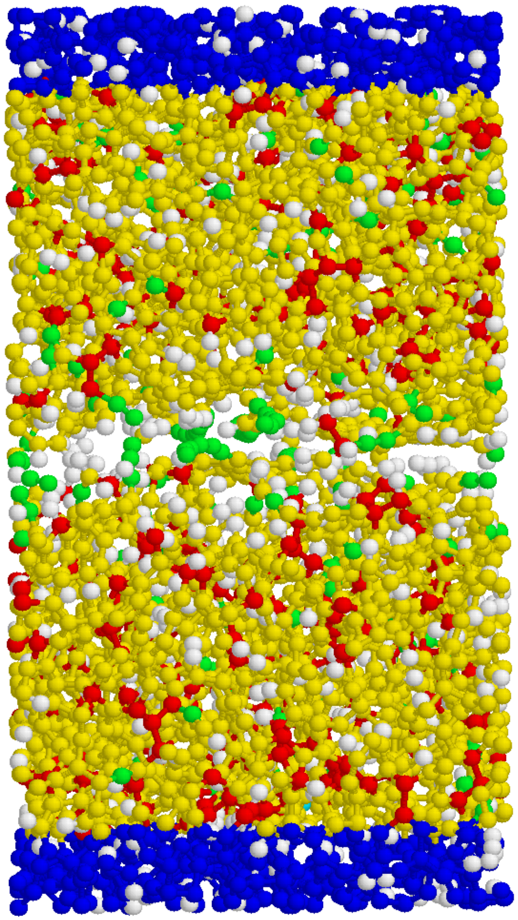


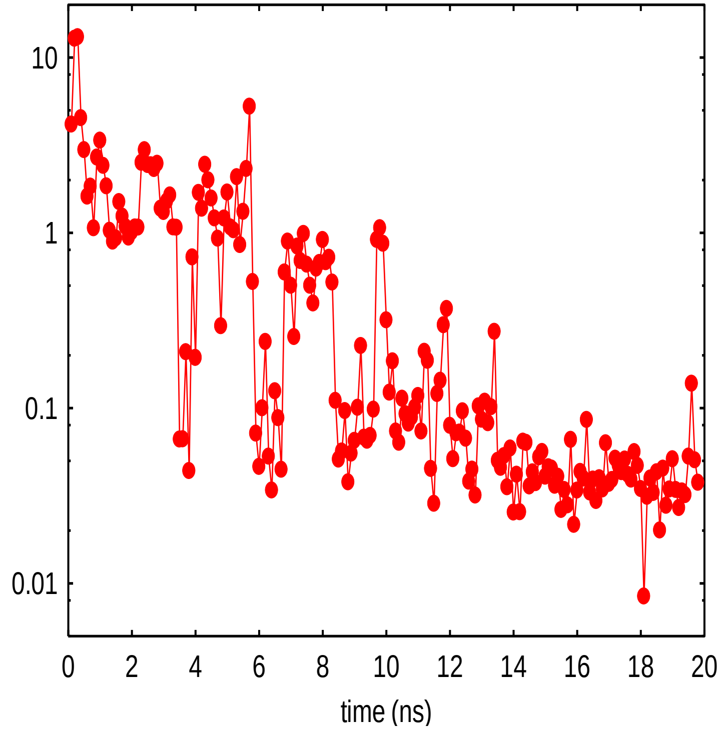
67 µm radius

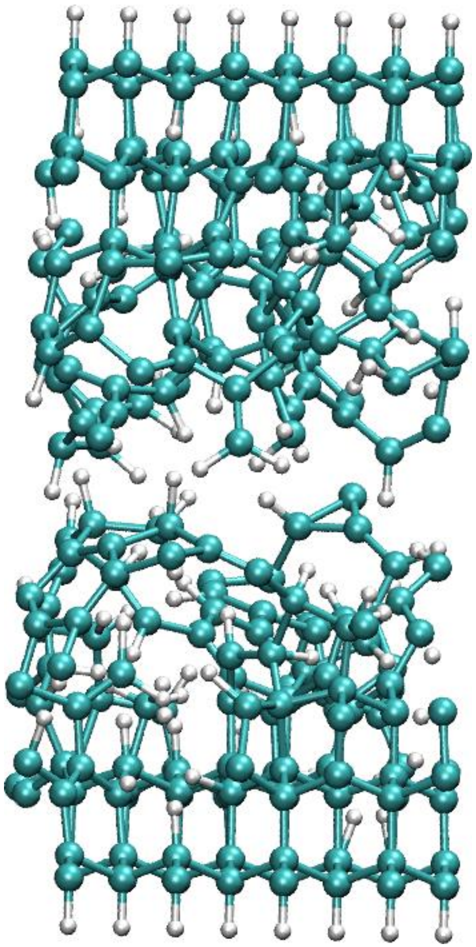


Normalization with yield strength Y (X-axis)
and P/Y- ratio (Y-axis)

Moleculardynamic simulation of running in behavior of DLC → graphitization observed

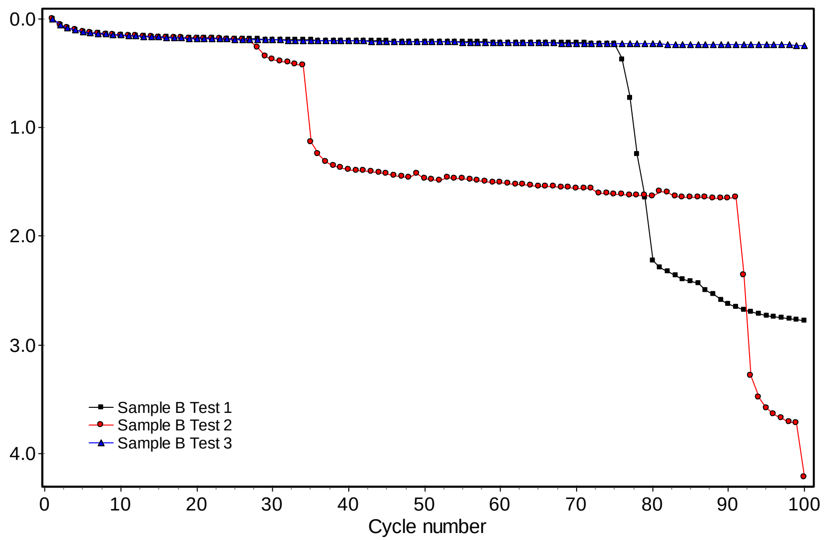


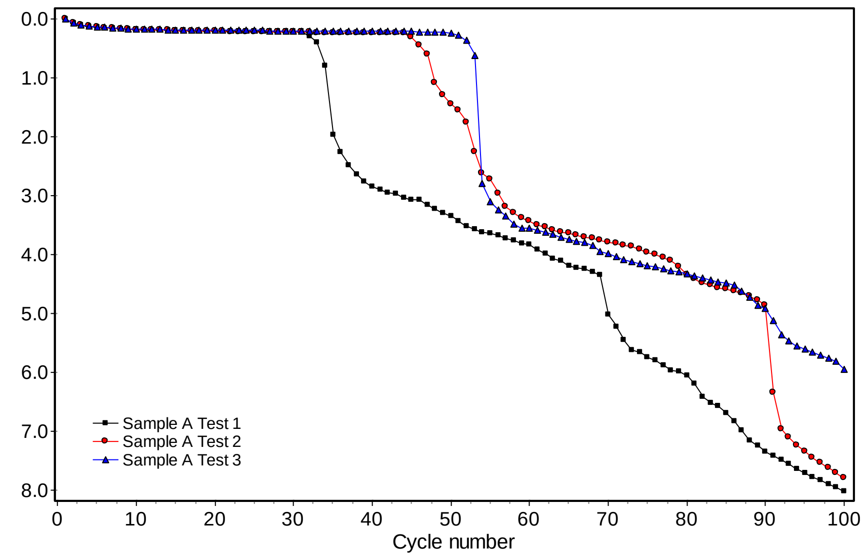


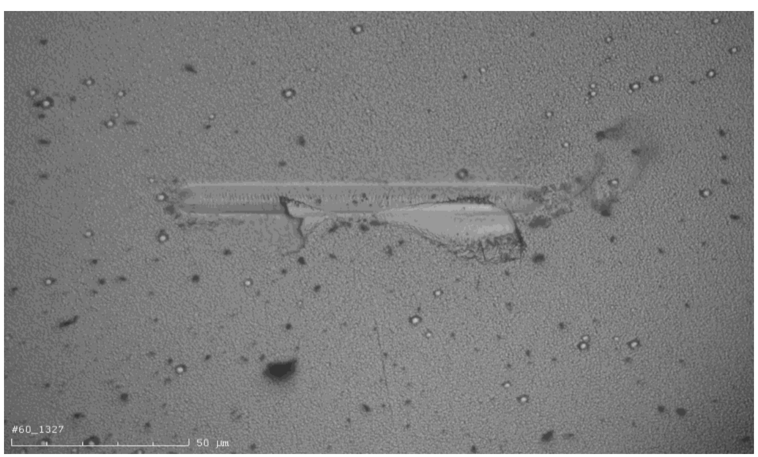


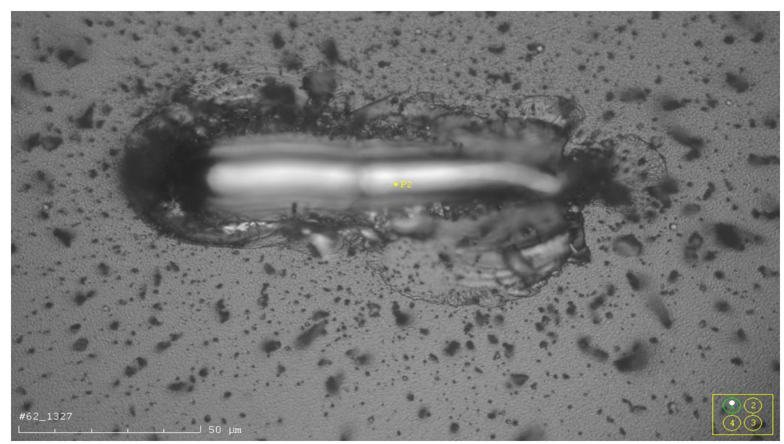
Source: Moseler, Fh IWM, Freiburg, Germany

Wear behavior of sample #60 is better than for sample #62 although the hardness is lower
Test conditions: 500mN, 9.3µm radius indenter

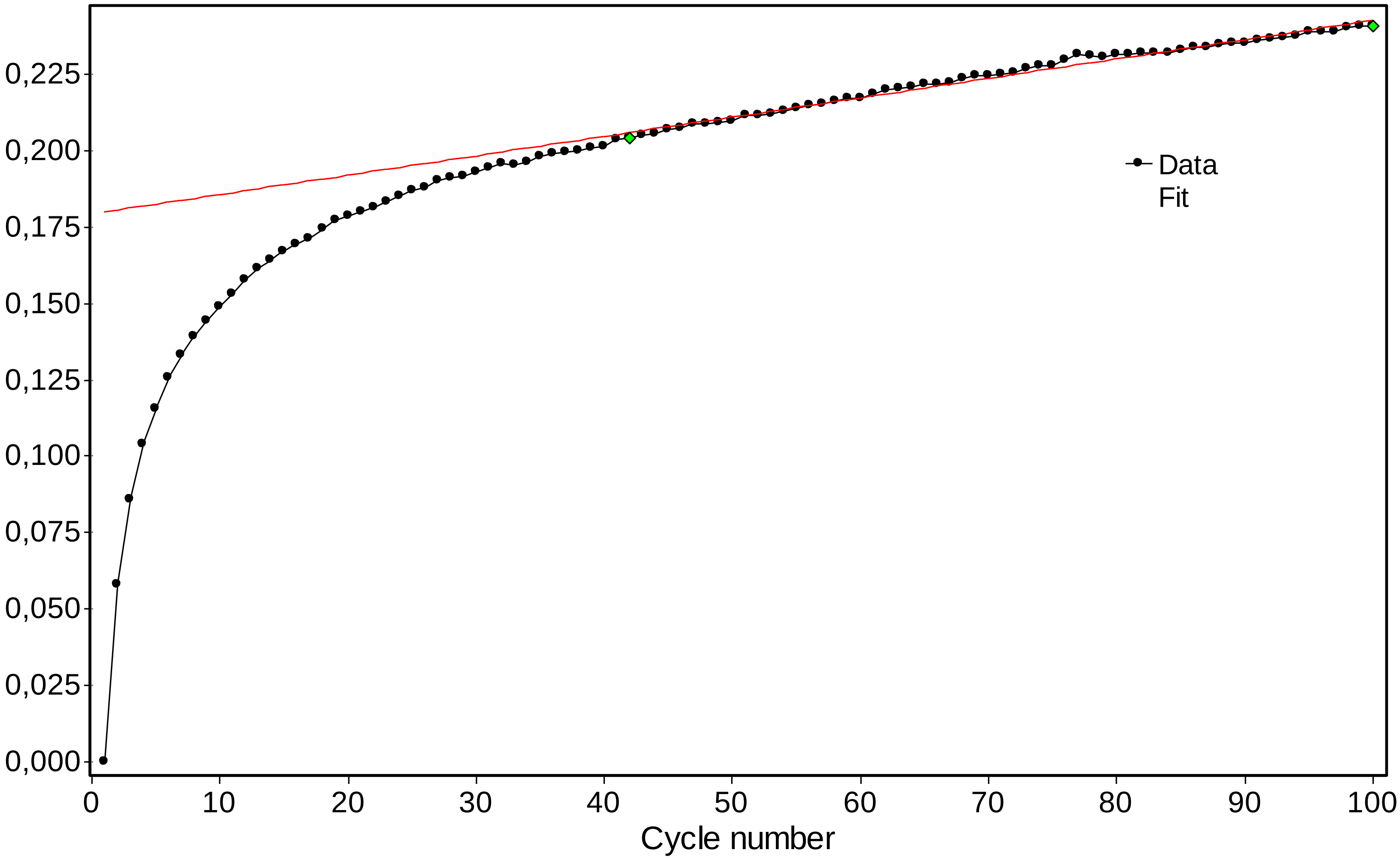








#60: wear rate = 0.63 nm/cycle



Conclusions

- Finding the mechanically best behaving coating-substrate combination for a certain application is time consuming and expensive.
- The quantification of the mechanical behavior is still a challenge. Not all necessary mechanical parameters of coatings can be measured with standard test methods up to now.
- For the understanding of failure mechanisms it is necessary to measure with nanometer resolution.
- A larger inclusion of modelling tools (FE, analytical) can considerably shorten the development process. For the calculations accurate and relevant mechanical parameters are necessary.
- A better reproduction of the conditions in an application is necessary in laboratory tests.
- This requires the inclusion of lateral force-displacement measurements with high precision
- In the future the significance of multi-axial testing in combination with stress calculation will increase.