Mechanical properties and Robustness evaluation of glass materials in building

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Why glass?

- Admit daylight
- Provide external views
- Achieve feeling of spaciousness
- Functionality: self-cleaning, solar-energy
  Photo-voltaic ，…..
- Create durable weatherproof building envelope
- New structural materials

Structural glass application

All-glass building

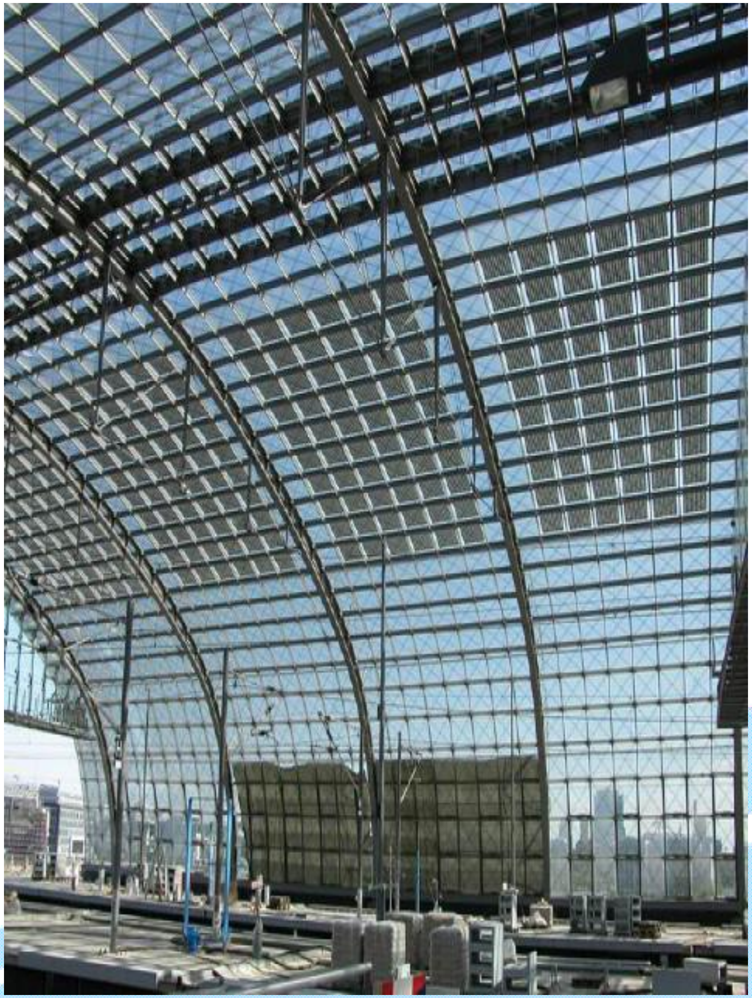
深圳三鑫公司所建的结构玻璃建筑

Structural/functional Combination

BIPV glass components

- applications

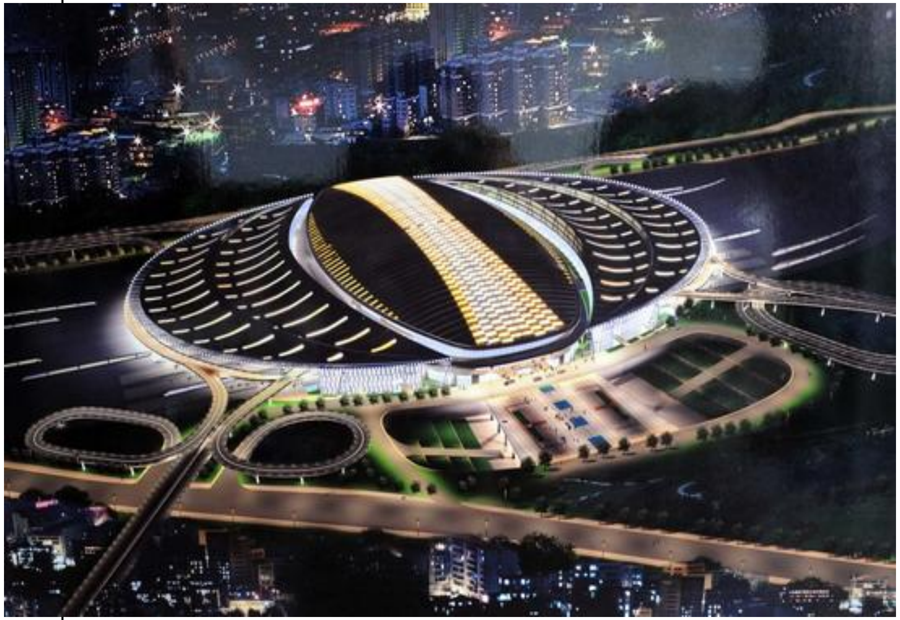
日本Sanyo太阳光电公司



德国柏林中央车站

BIPV glass components

- Applications



Beijing South station

Energy saving building in Qinghua Univ.

Dangerous glass from high building

Shanghai daily 2nd Aug. 2006：A glass curtain wall fall down from 36th floor of Shanghai Jingjiang shopping center. Debris and splinters covers 40 square meter. No body injured

Spontaneous breakage of glass curtain wall

辽宁新闻 A10都市

新闻热线96006 2006.6.20 星期二

玻璃幕墙飞下20楼砸伤16人

物业公司称，幕墙脱落是由于钢化玻璃被日照高温烘烤所致

玻璃从天降 砸伤一片人

情侣逛街被砸倒

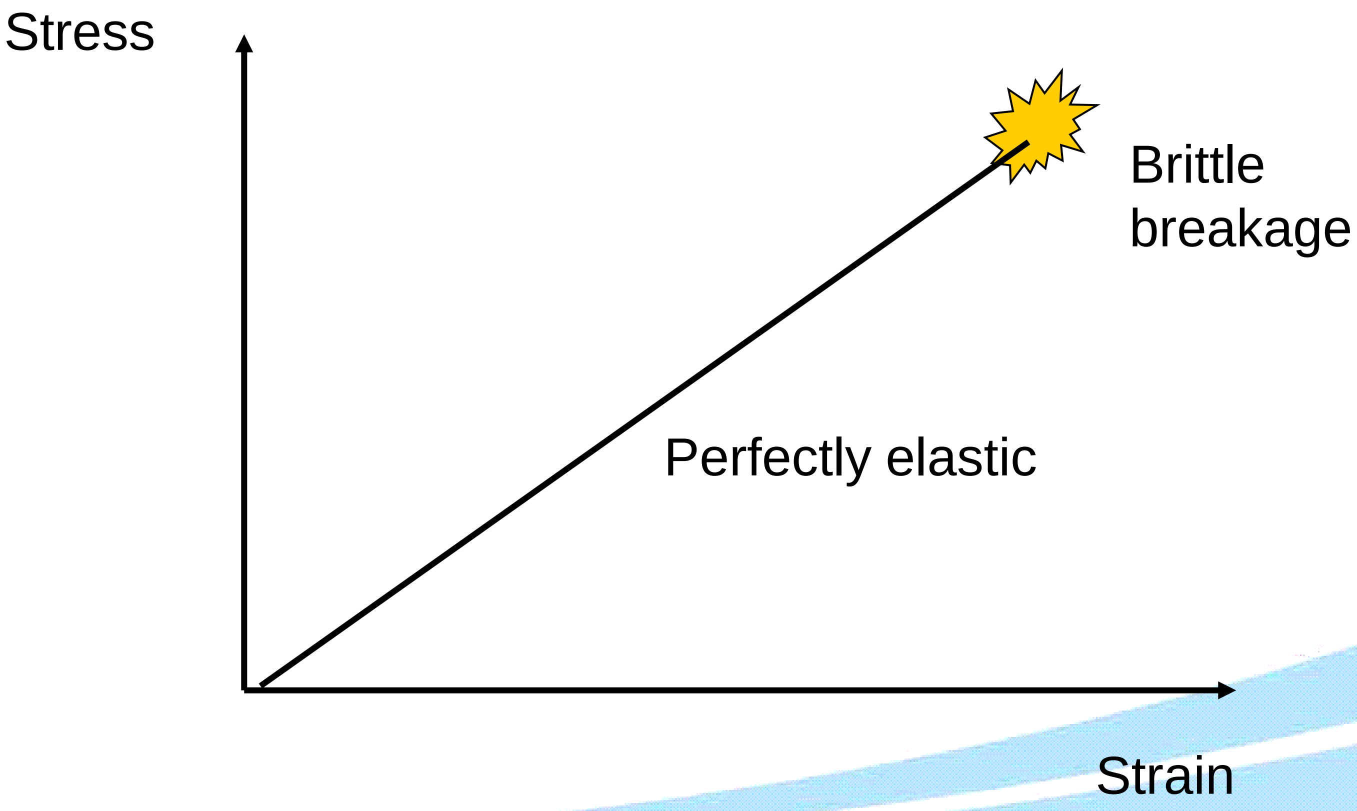
钢化玻璃被晒爆属正常?

玻璃被太阳晒爆几乎不可能

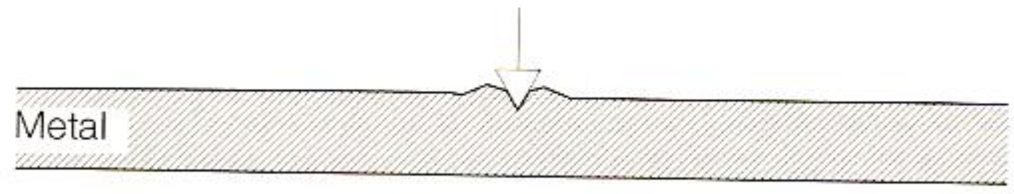
Glass rain

glass: typical brittle material

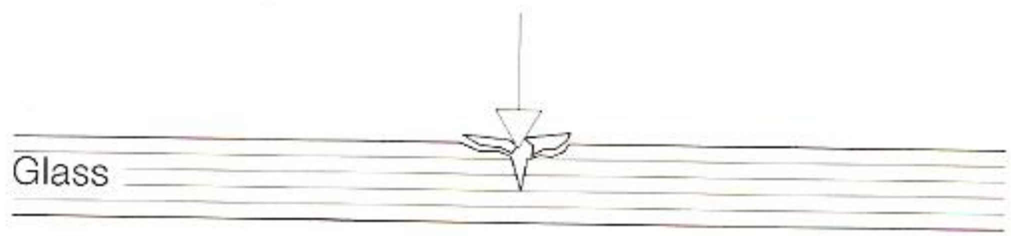
Brittle feature: no plastic deformation, low critical strain, high crack growth speed, stress concentration strong



Comparison of the deformation of metal and glass



Permanent deformation in metal following a point load.



Splinters are ejected from the glass – a sign of its brittleness.

Three modes of failure of building glass

1. Spontaneous breakage (tempered glass)
2. Fracture due to strength degradation
3. Fall dawn of whole glass due to loosed support or sealant.

Annealed glass

- Breaks in to large dagger like shards
- Sharp edges
- Dangerous to fall through
- Danger if falls

This kind of glass is not safe building material

Safety glass: laminated glass; tempered glass

Toughened glass

- Thermally toughened glass
  - Automotive glass
  - Glass for construction
  - Some domestic glass, e.g Pyrex dishes
- Chemically strengthened glass
  - Chemical modification of the surface
  - Used for laboratory glass, aeronautical glass, etc

Load bearing glass elements

weak tensile resistance but strong compressive

- Shells
  - Curvature provided by bent glass or by assembling the flat glass facets
  - Use laminated annealed glass may provide high residual strength for glass shells
  - Double curved glass is feasible only for large bending radii
- Walls
  - Stability

Try to form compressive stress, rather than tensile stress in the glass element for the sake of safety

Glass beams/fins

Important requirement for building glass ---Robustness（鲁棒性）

Strength ：the maximum tensile stress at fracture

Damage tolerance : capacity of bearing damage, or energy dissipation ability

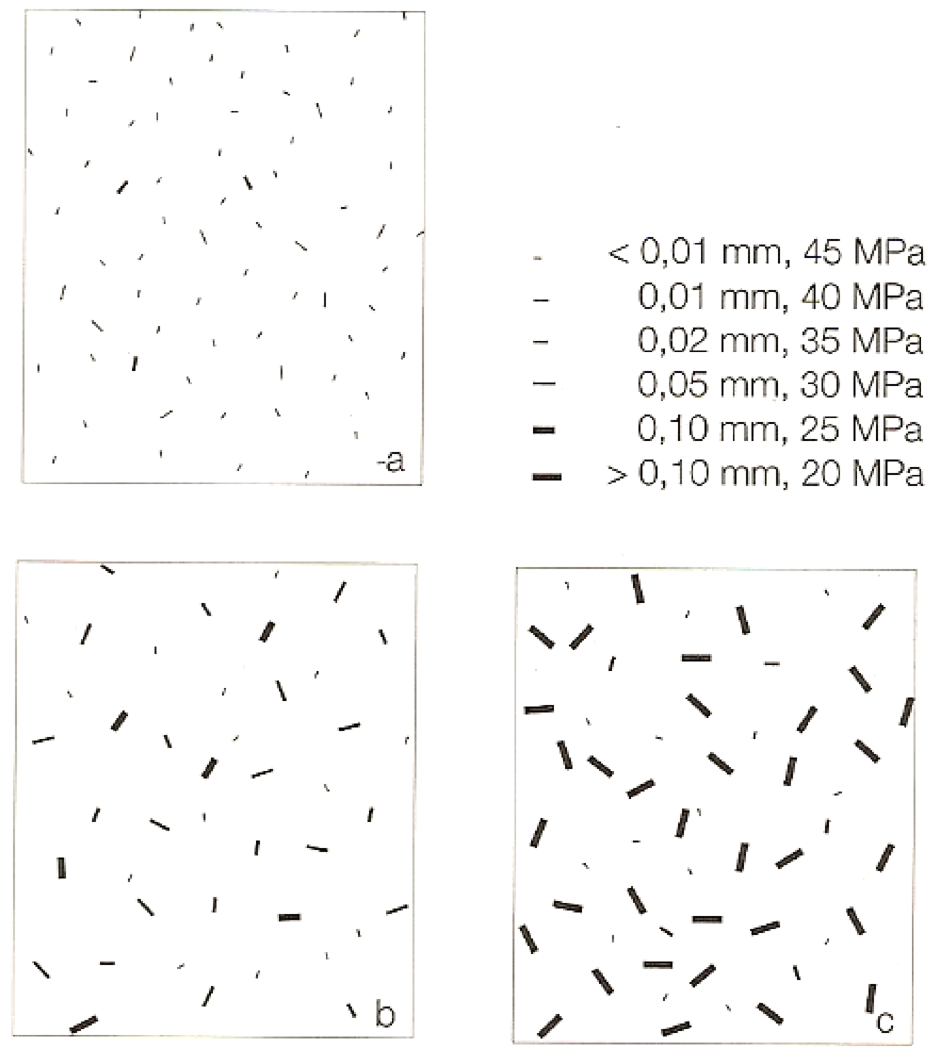
Post-breakage strength: residual strength after breakage

Durability: no degradation of strength with time

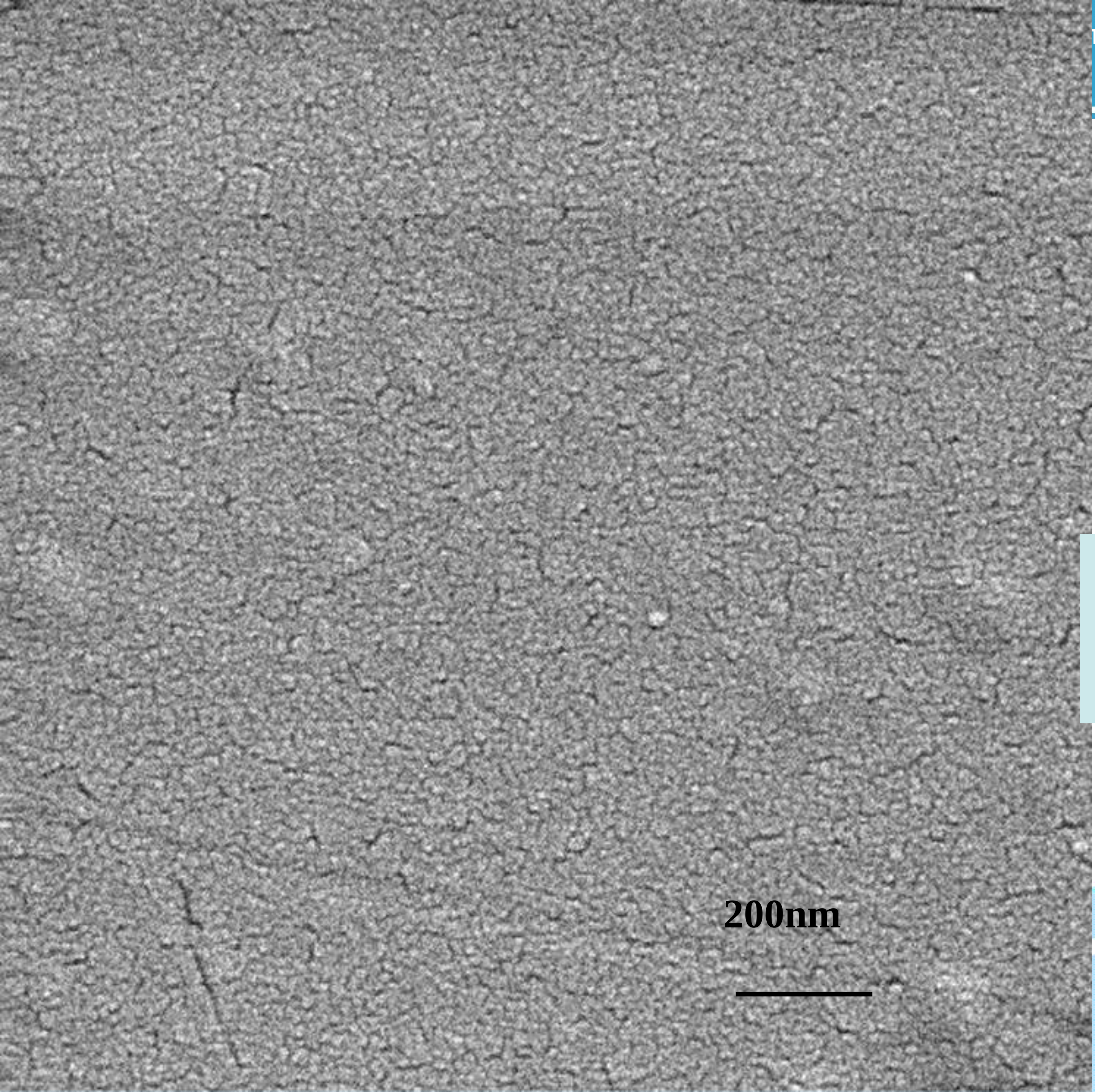
Weathering resistance: property variation with weather

Strength depending on surface crack sizes

表面缺陷影响强度



Distribution of surface damage for a) new glass, b) weathered glass, c) glass with inherent damage.



SEM photo of glass surface 2007.10

玻璃表面微裂纹的显微照片，2007.10

Size effect of strength

Short wire, high fracture strength

Long wire, lower strength

Over 500 year ago,（达芬奇）DaVinci found: strength decreases with increasing length of the steel wire.

contradiction to Galilei's (伽利略） theory

Traditional Material mechanics : strength is the force in unit area at fracture. It is related to only the section area, regardless of the length.

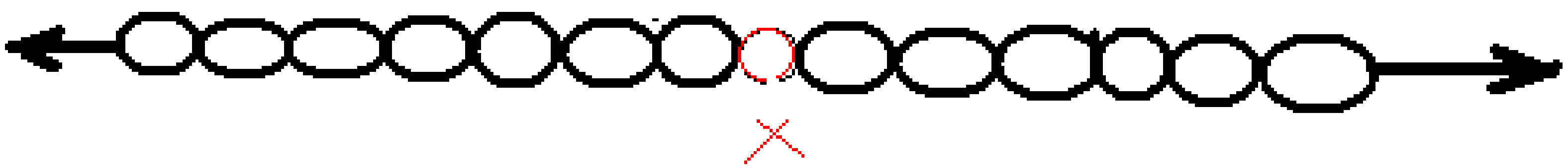
Griffith's experiment results: the larger the glass thickness, the lower the strength will be.

Explanation : large specimen contains more defects

Weibull: **probability of the defect (causing-failure crack) depends on the sample size.**

suppose Material is consisted by many units, and the strength depends on the weakest unit (maximum crack), like a stressed chain.

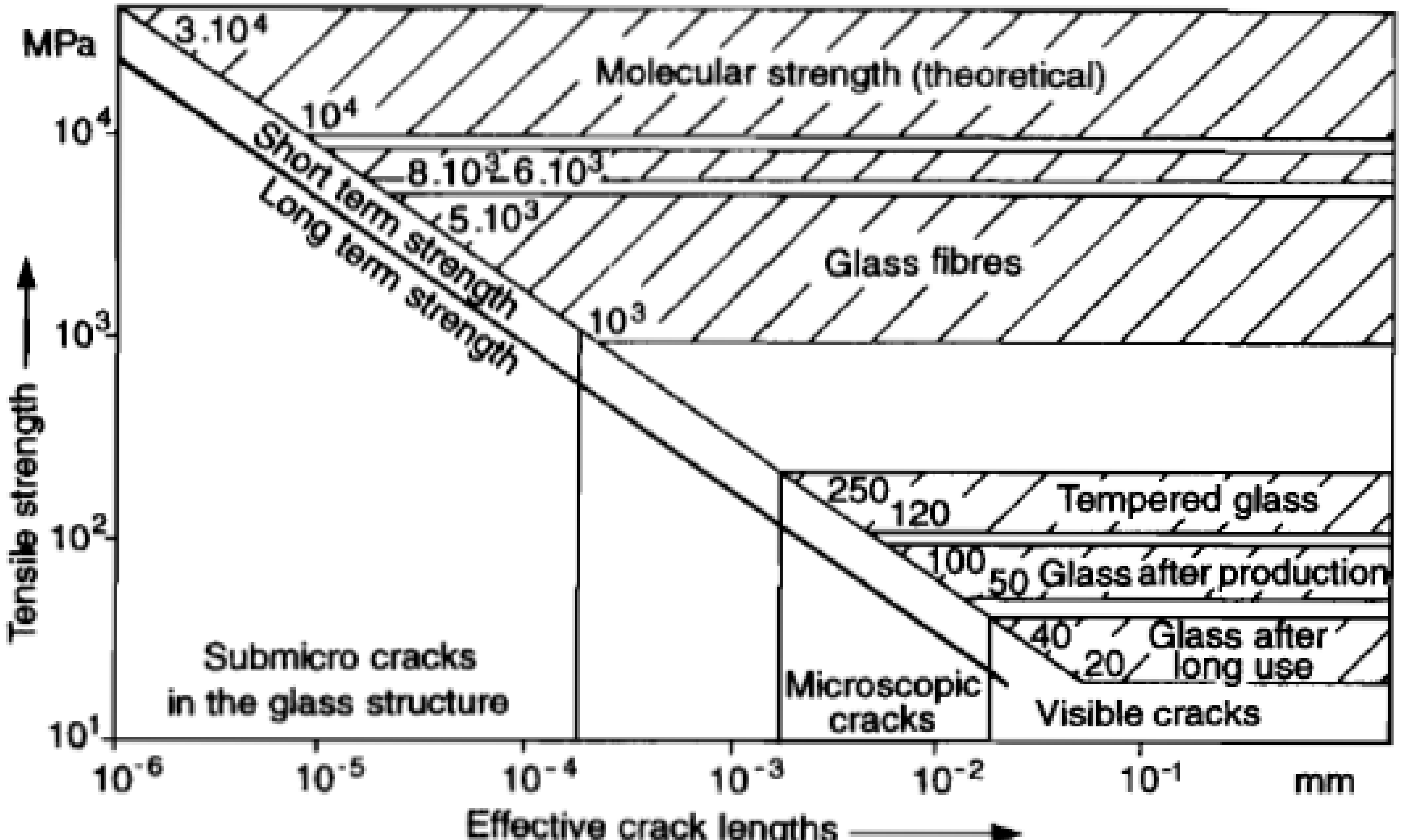
Fracture initiates form the crack -----the origin of the fracture mechanics



Weakest link theory

Statistic fracture mechanics

Glass strength depend on crack sizes



Strength data of glass

- Sensitive to surface crack size and impact load
- Great scatter (standard deviation: great)
- Low Weibull modulus

An approach to improve the deviation :

Two-step tempering (engineered stress glass)

1) Thermally tempered glass + 2) and then chemically (ion exchange) tempered

or

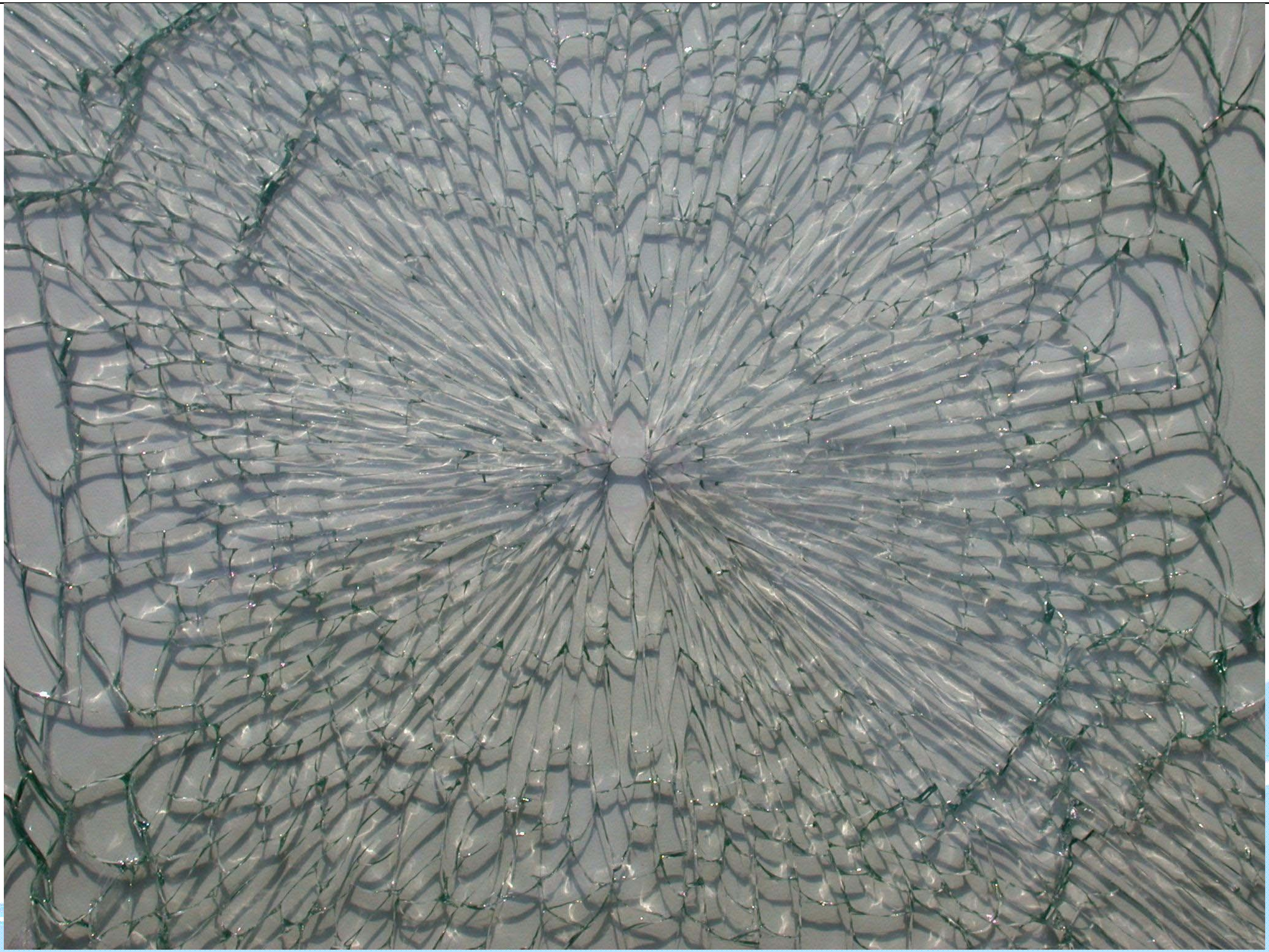
1) Chemically tempered + 2) chemically tempering

Results of the two-step method

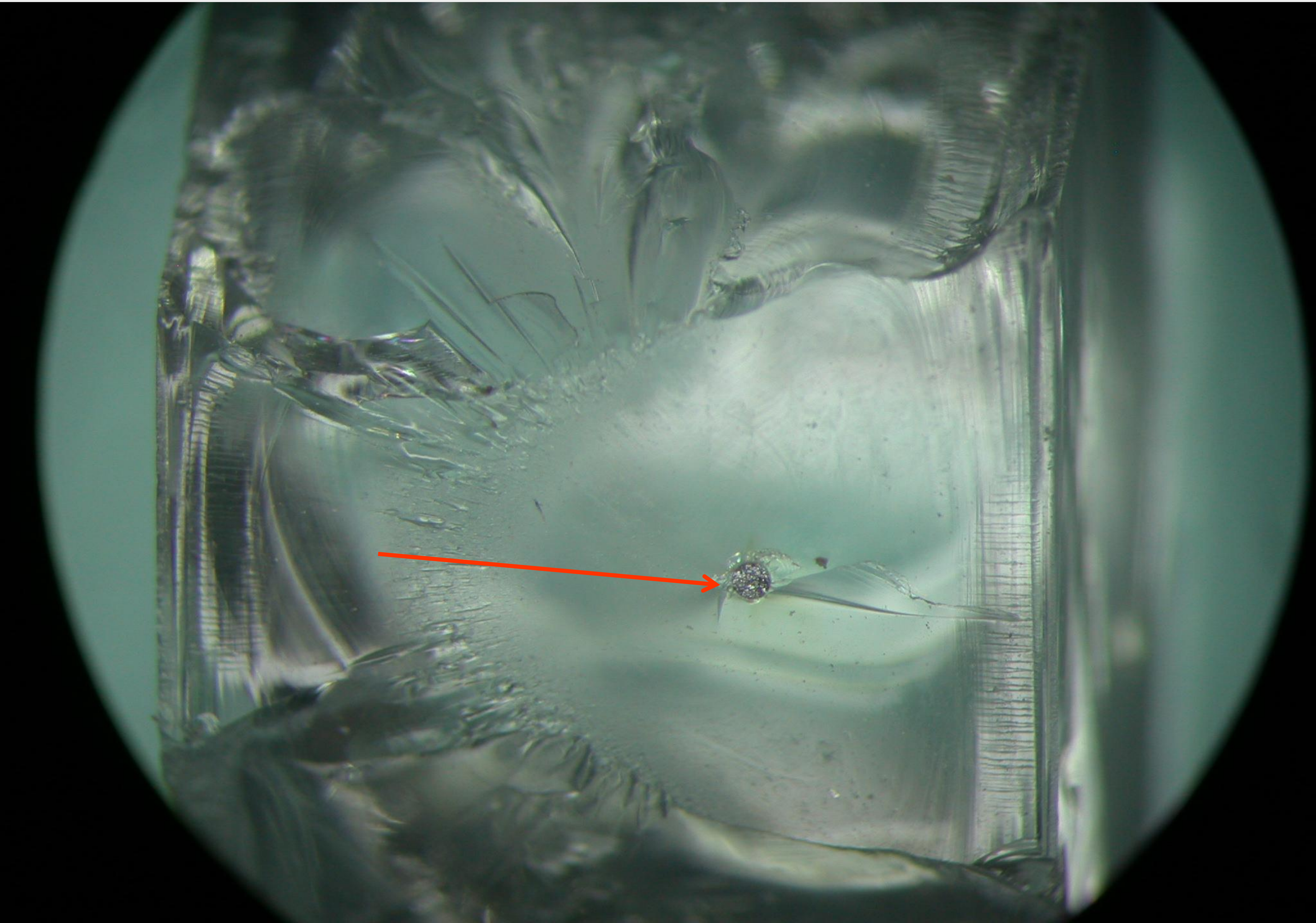
---- Low deviation , high Weibull modulus, but higher cost,

Spontaneous breakage of tempered glass due to silicon particle in the tensile zone

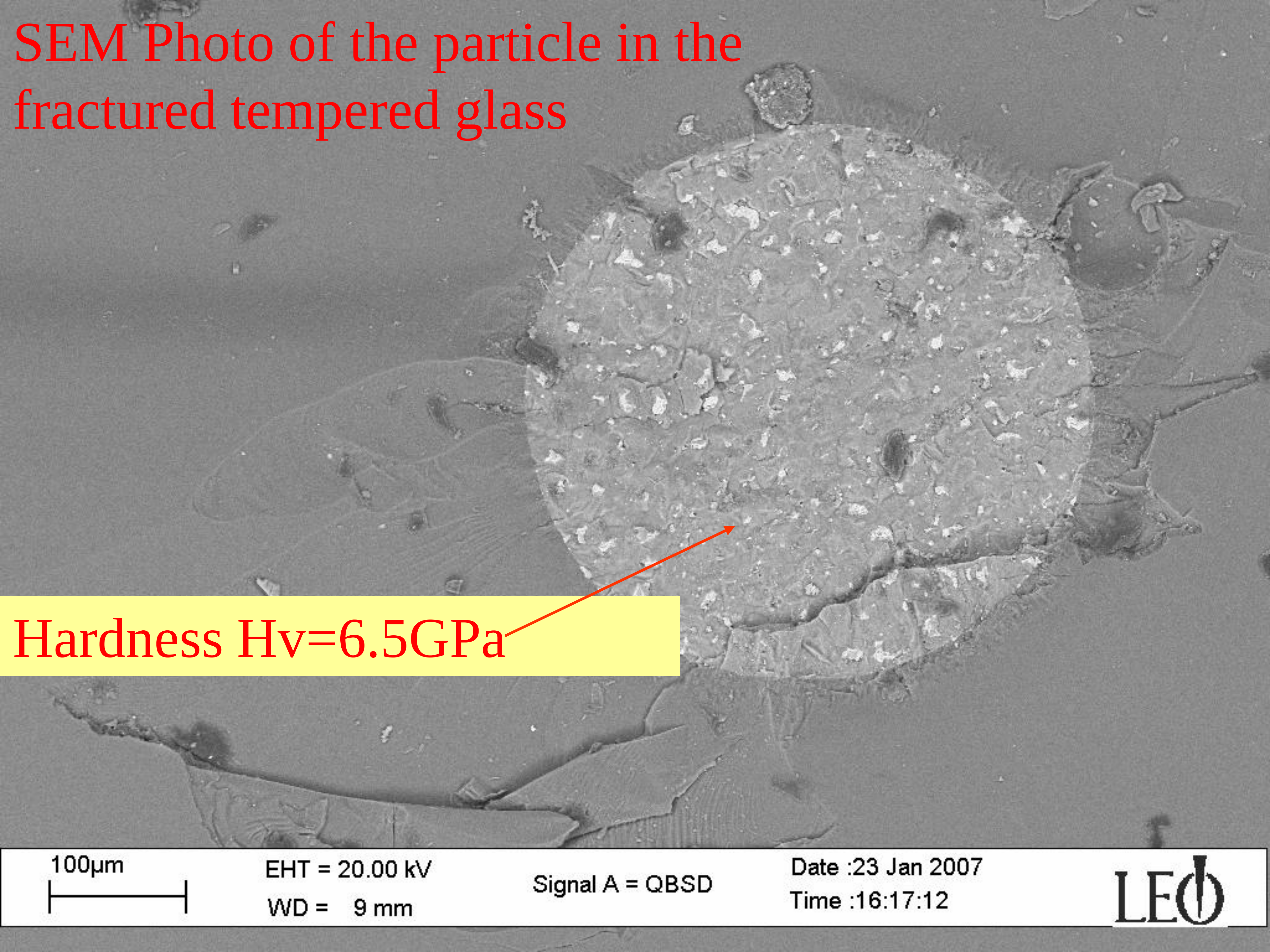
The breakage from a indent, under uniform load.

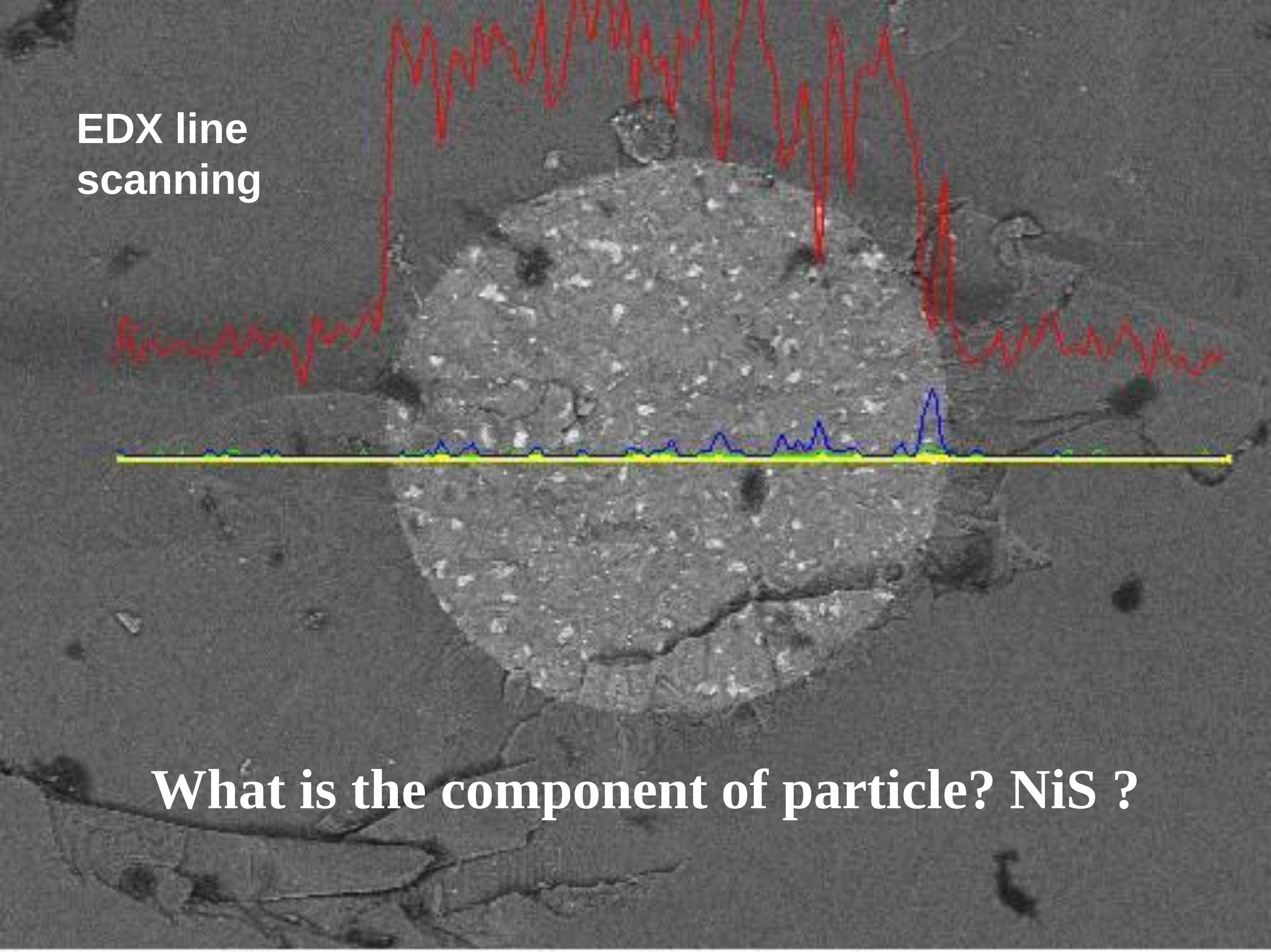


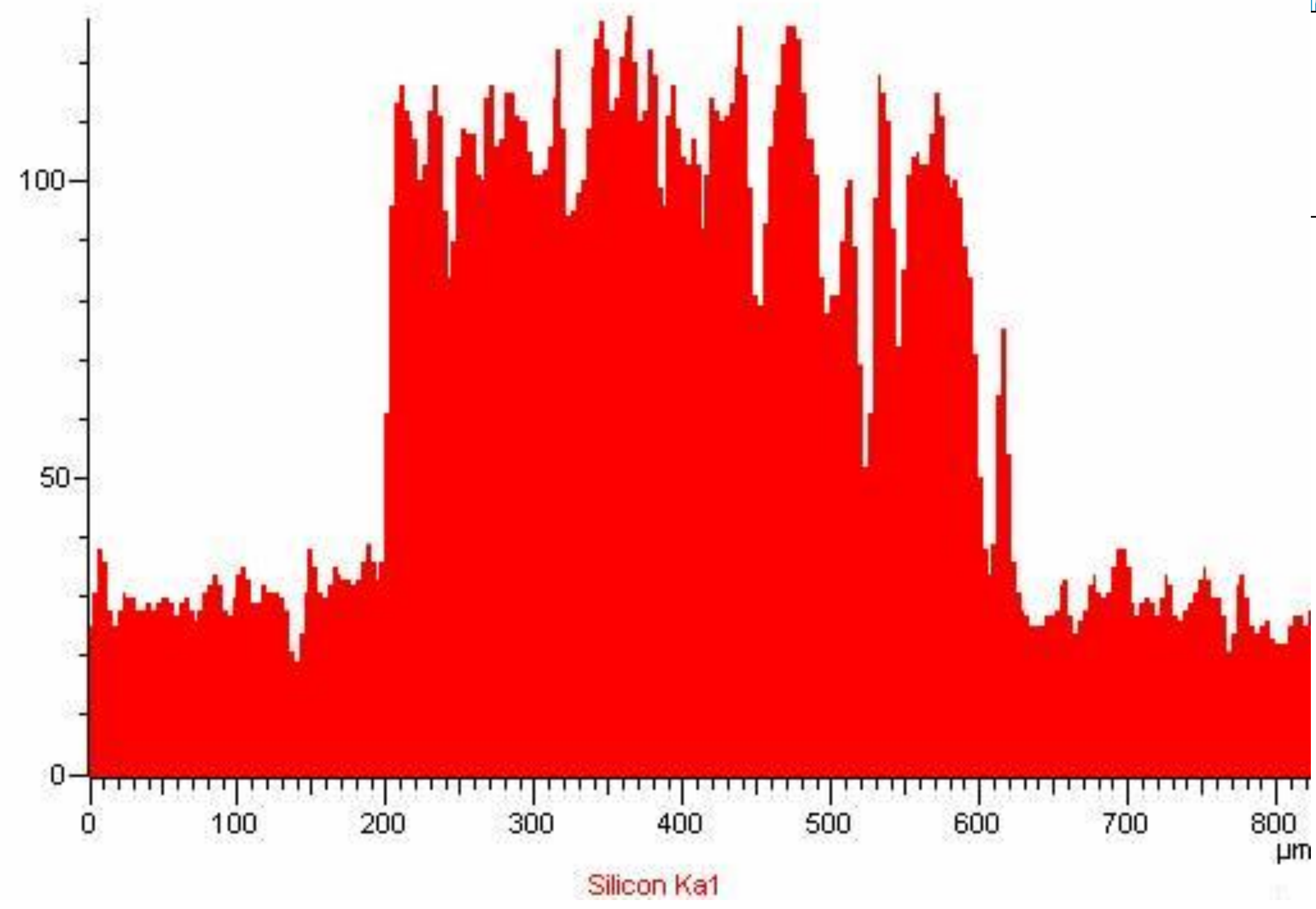
Impurity in the fracture section of the glass



SEM Photo of the particle in the fractured tempered glass

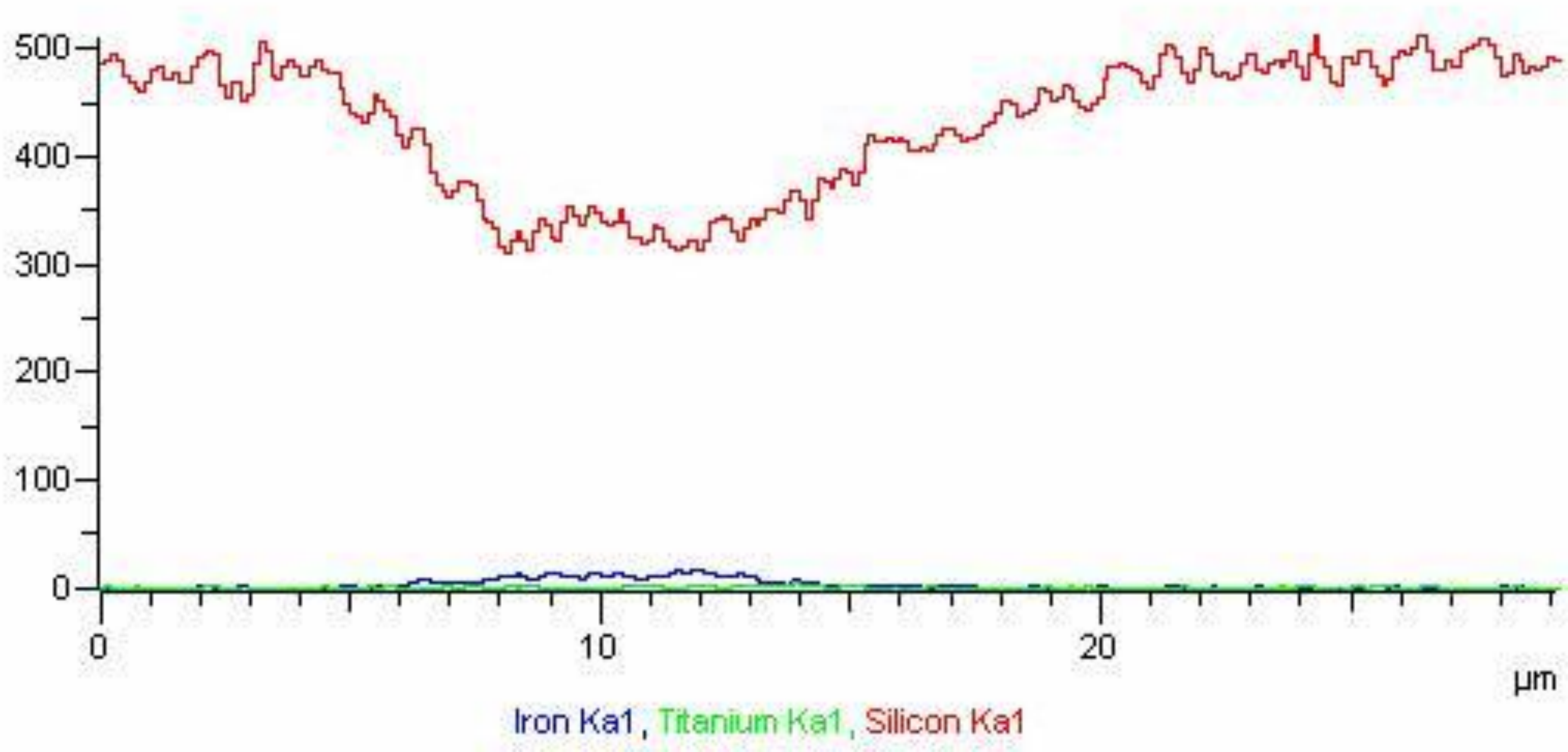



EDX line scanning
What is the component of particle? NiS ?

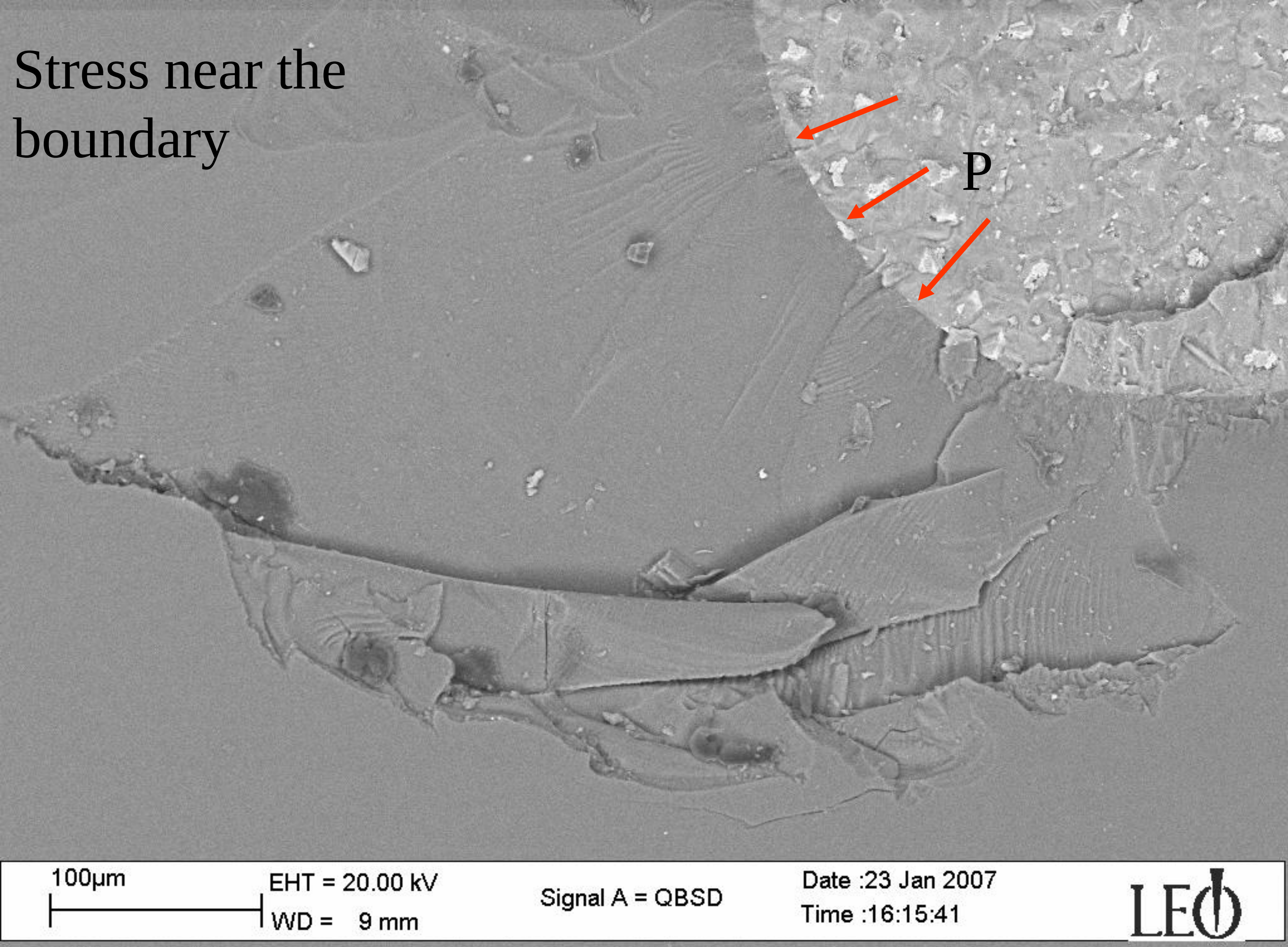


Silicon fraction along the line. No Ni and S was found, the particle is monolithic silicon

Component analysis in the particle



Stress near the boundary



Stresses in and near the particle

$$P = \frac{(\alpha_m - \alpha_p) \cdot \Delta T \cdot E_m}{[(1+\nu_m)/2] + [(1-2\nu_p) \cdot E_m / E_p]}$$

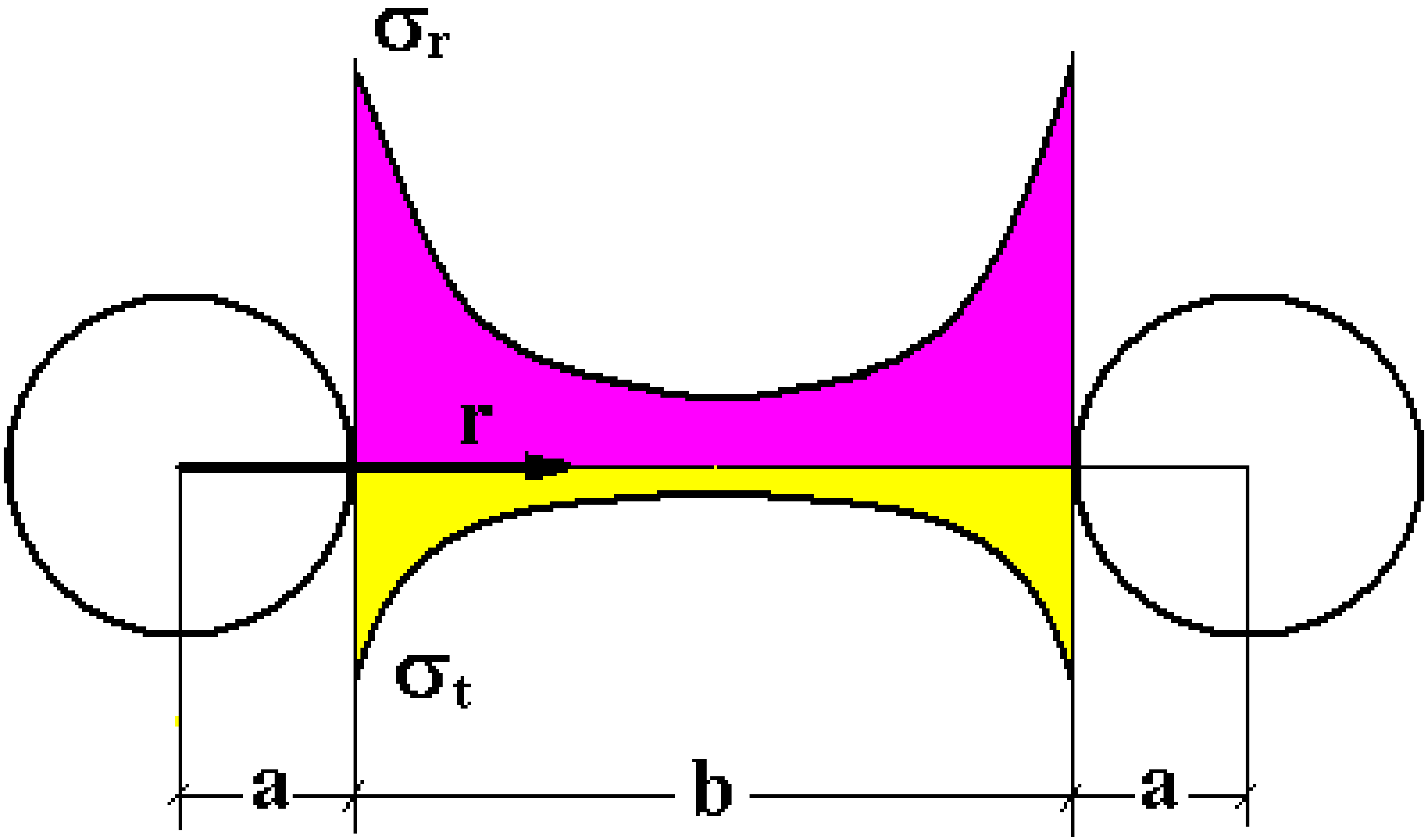
$$\sigma_{r1} = -P \cdot \left(\frac{a}{r}\right)^3$$

for r≥a (a)

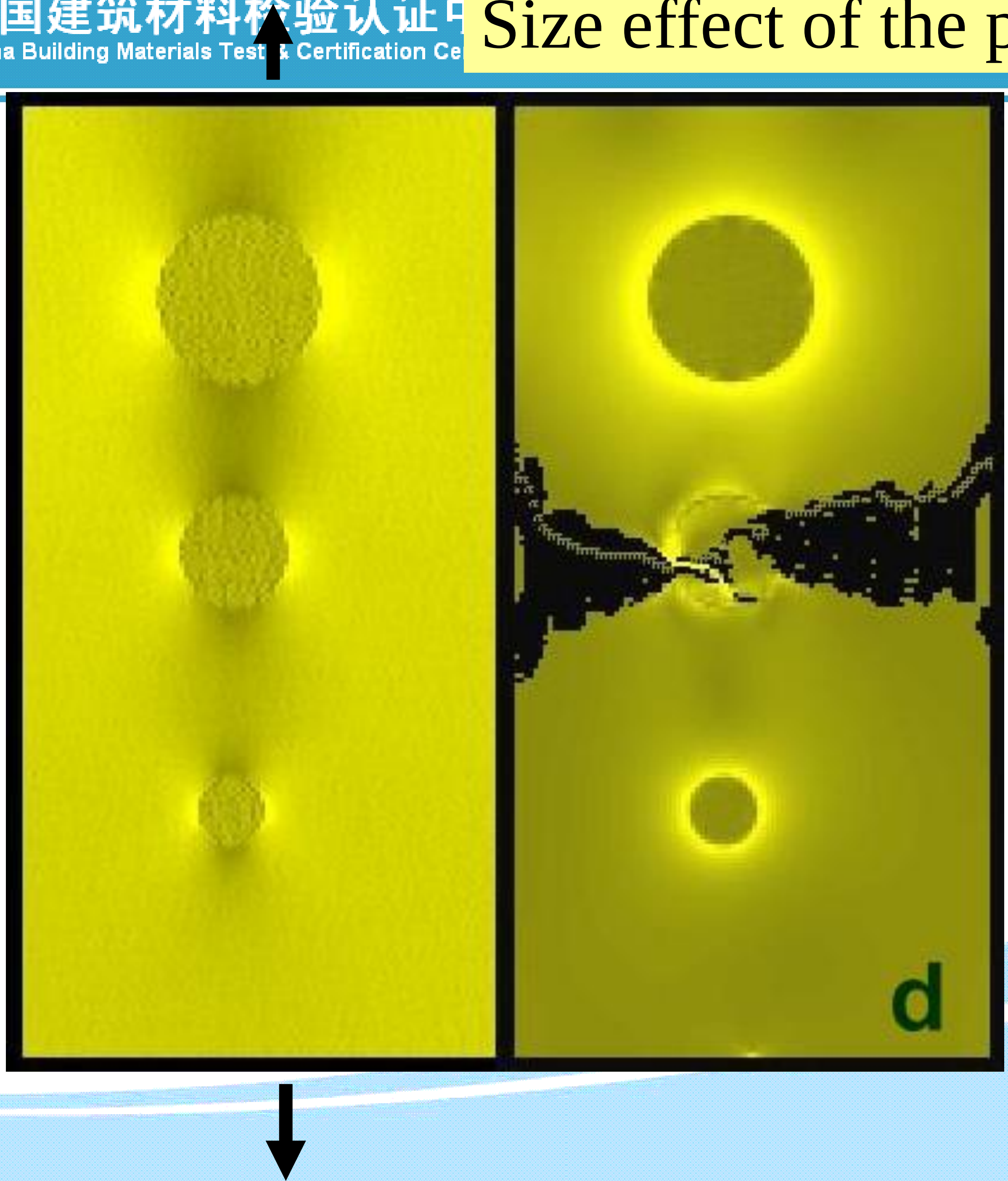
$$\sigma_{t1} = \frac{P}{2} \cdot \left(\frac{a}{r}\right)^3$$

for r≥a (b)

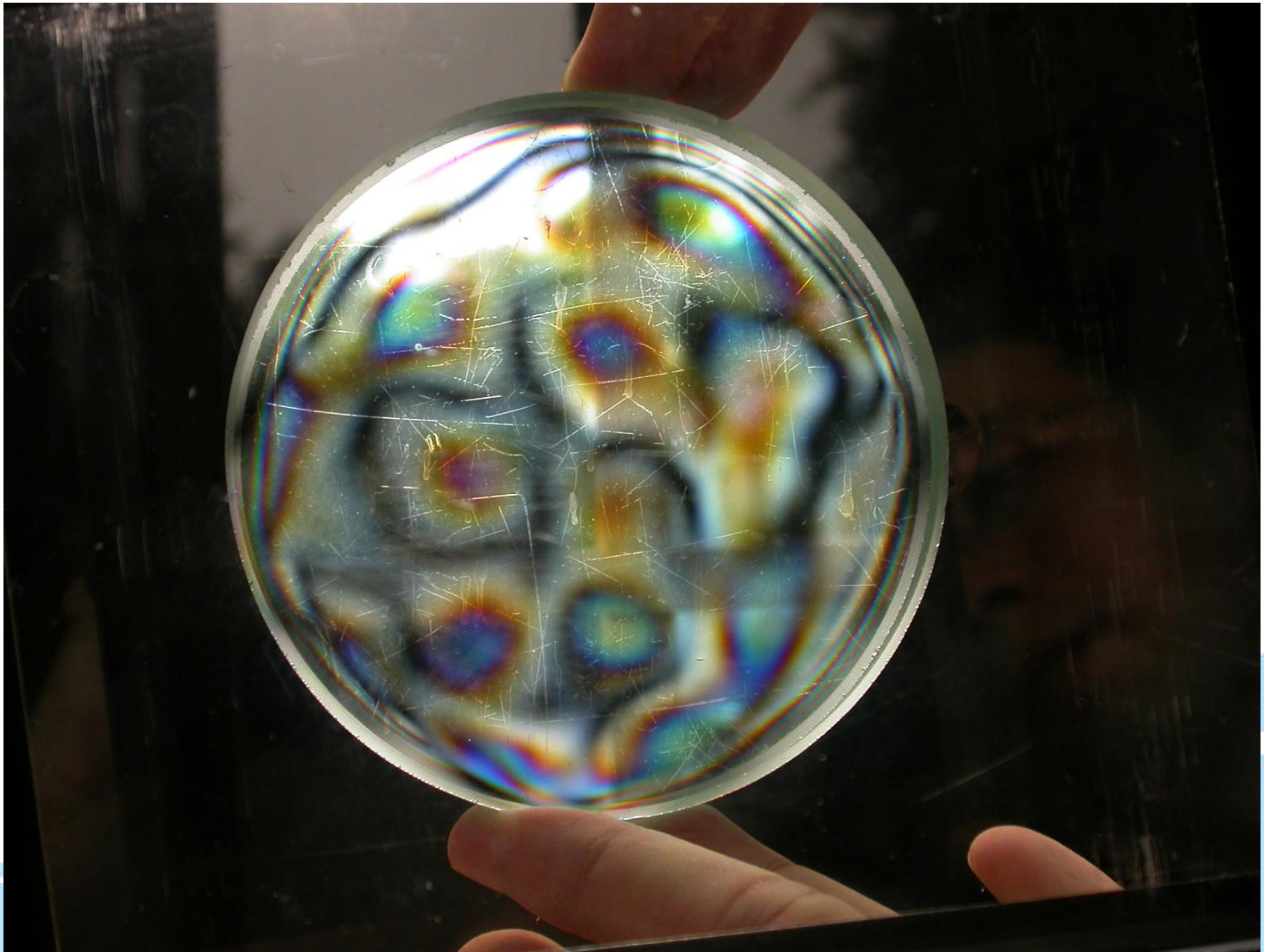
Stress distribution around the particle and between two particles



Size effect of the particle



Identify tempered glass and defects in the glass by photo-elastic method



Inspecting defect by Photo-elastic method
----stress concentration point

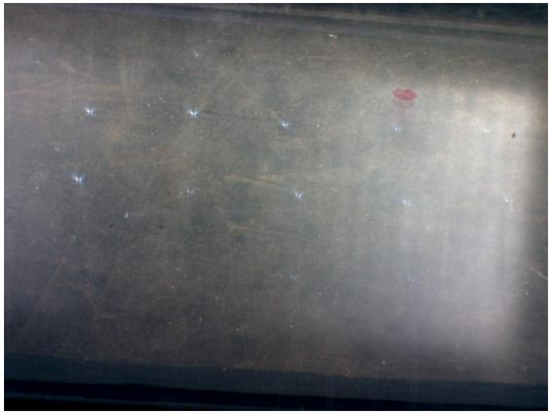
light spots in the vacuum glass under difference vacuum degree

0 MPa

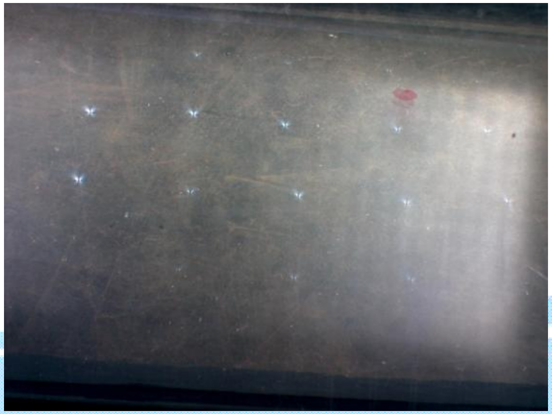
-0.02MPa

-0.04MPa

-0.06MPa

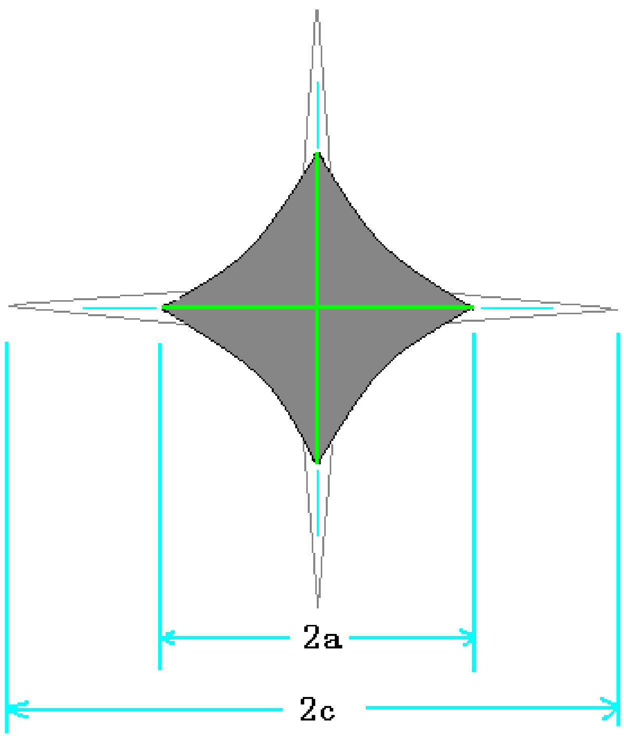


-0.08MPa

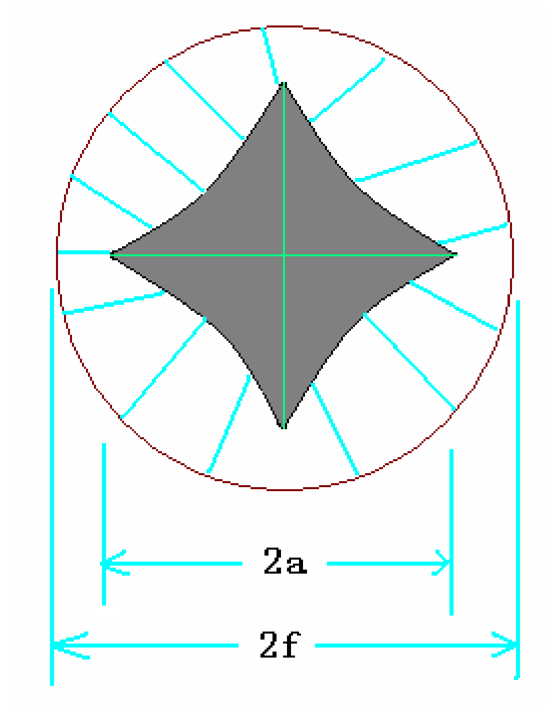


-0.1MPa

Indentation diagram of soda-lime glass before and after chemical strengthening

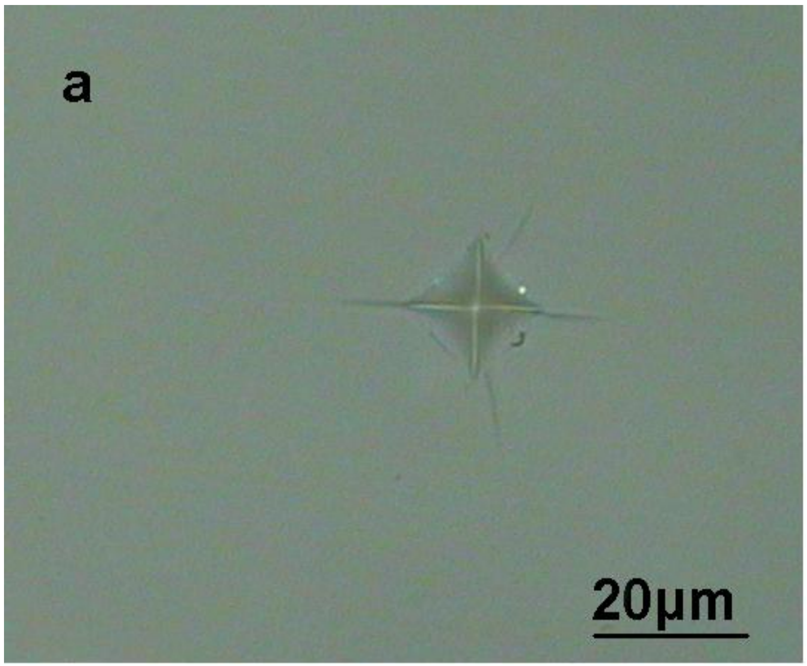


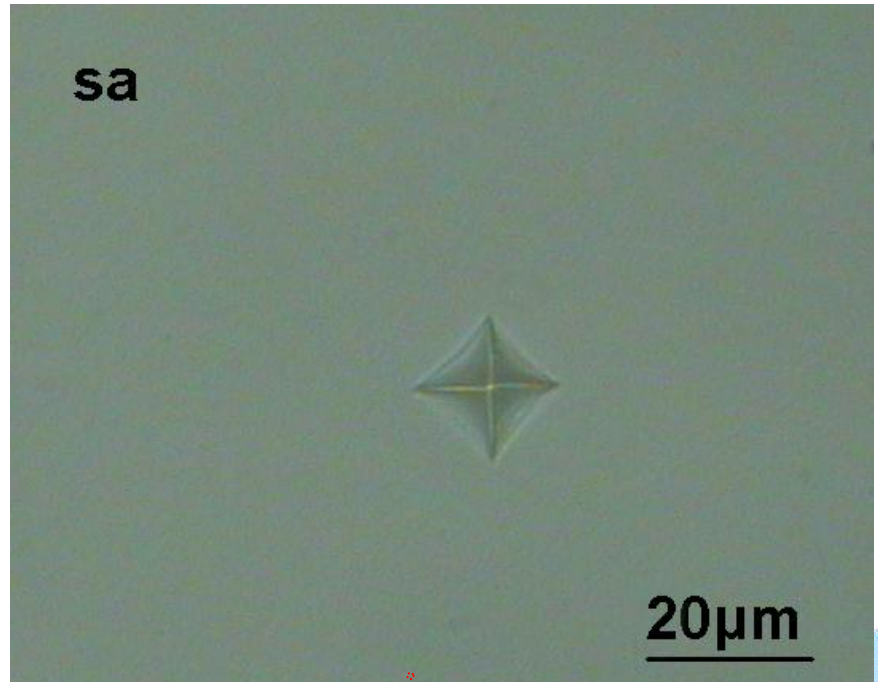
a）裂纹从压痕尖端扩展



b）压痕周围呈放射状光斑

Different indentations for soda-lime glass and strengthened glass



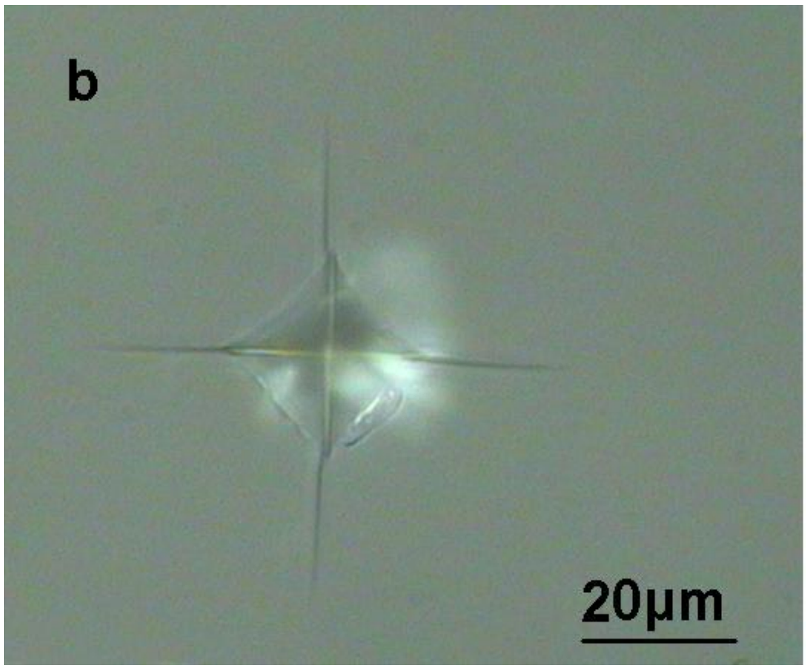


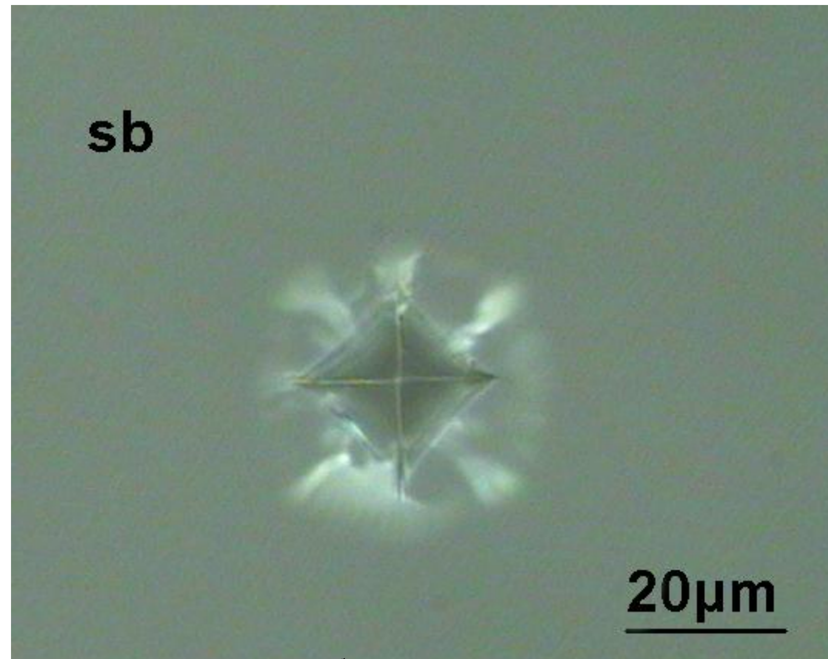
Common glass

Tempered glass

最大载荷为100g 的压痕形貌

after indentation load of 200g

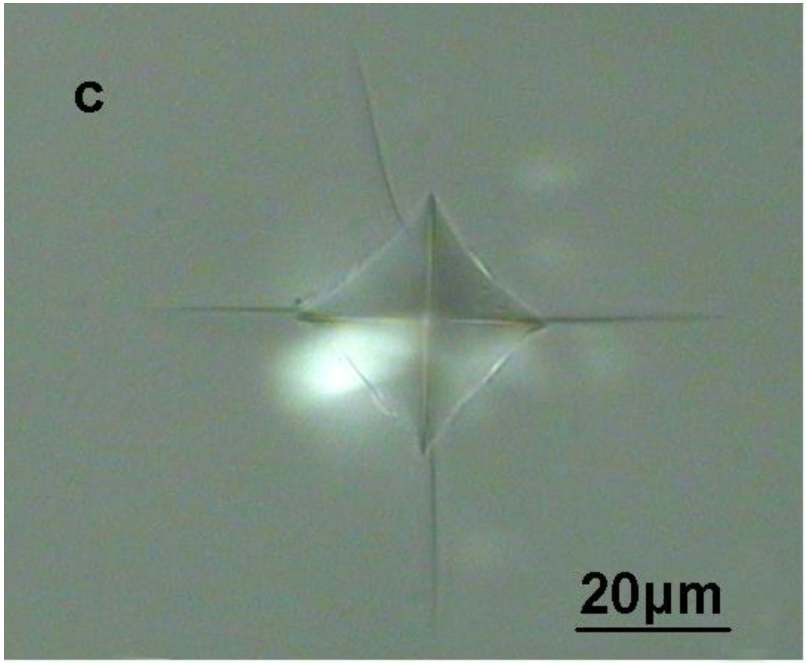


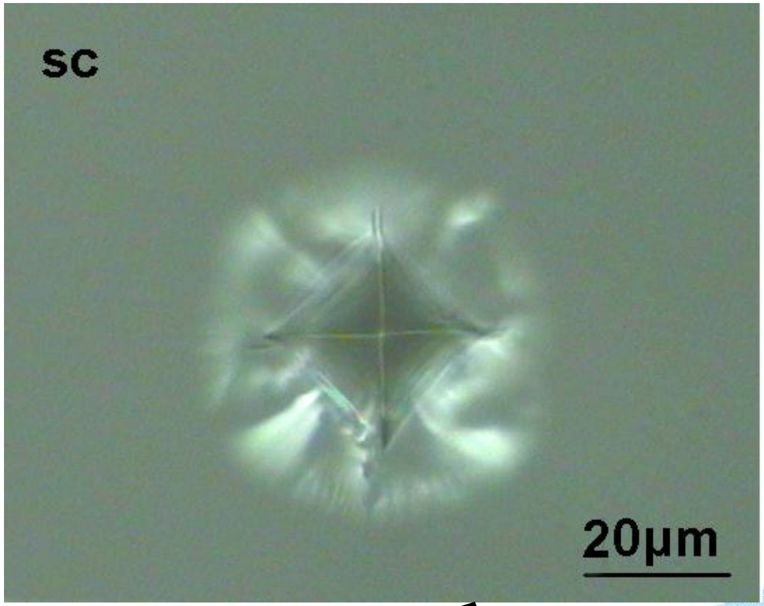


no strengthening

Strengthened glass

after indentation load of 300g





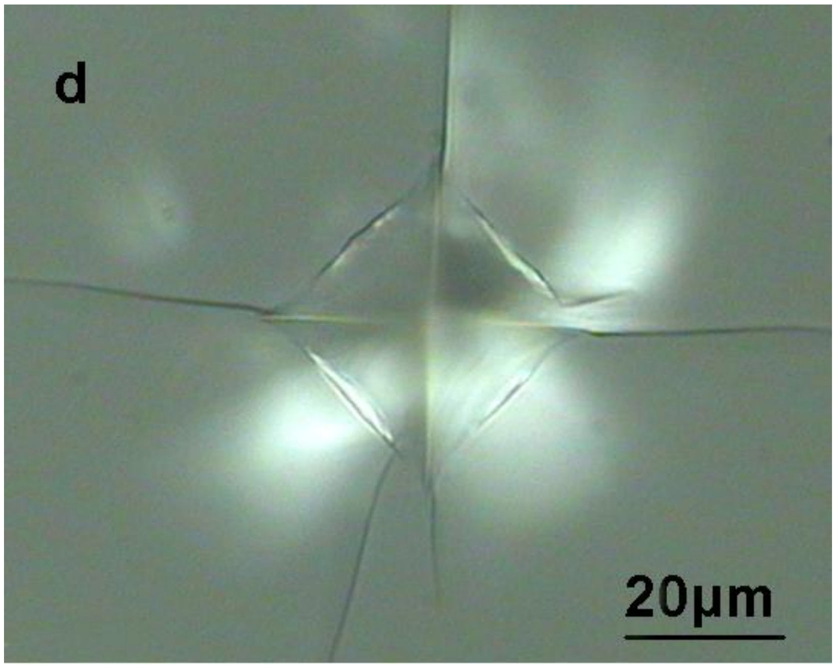
钢化前

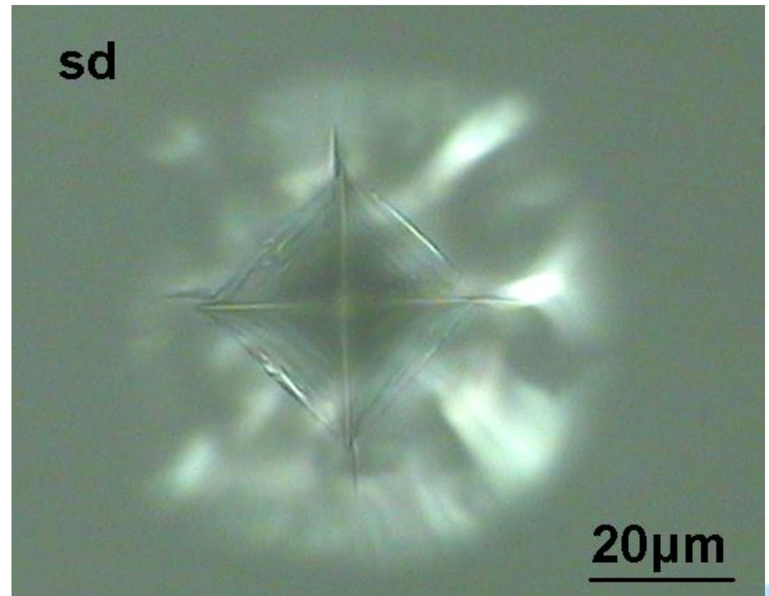
钢化后

Without tempered

tempered glass

after indentation load of 500g





2c≈101μm

钢化前

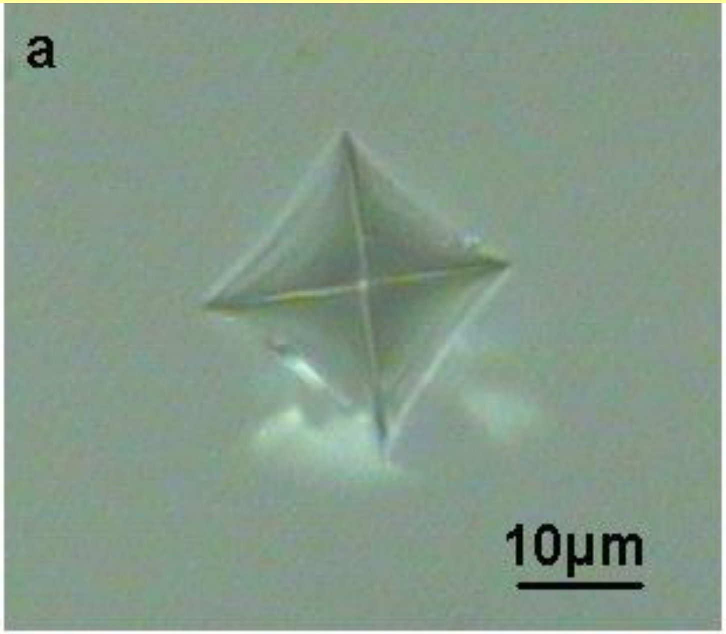
钢化后

2c≈48μm

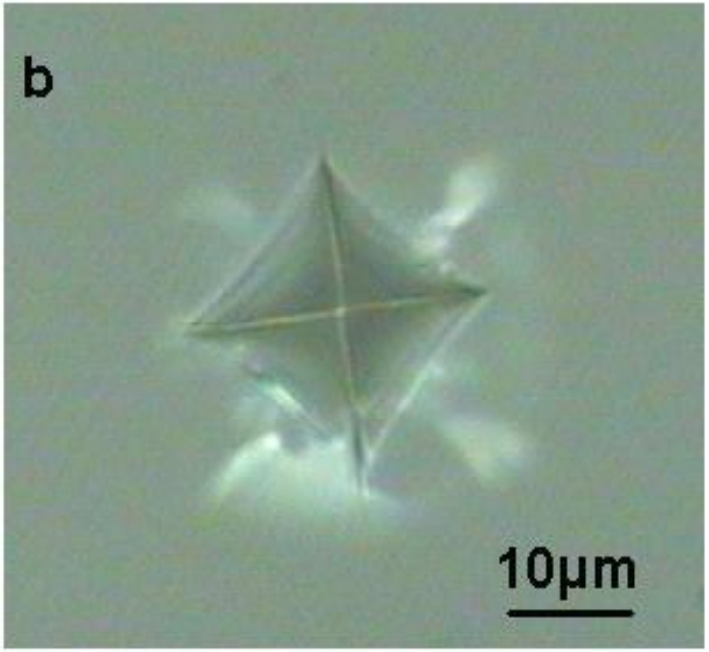
2f ≈64μm

卸载后钢化玻璃表面压痕参数随时间变化(最大载荷为200g)

Indentation evolution after unloading (200g)

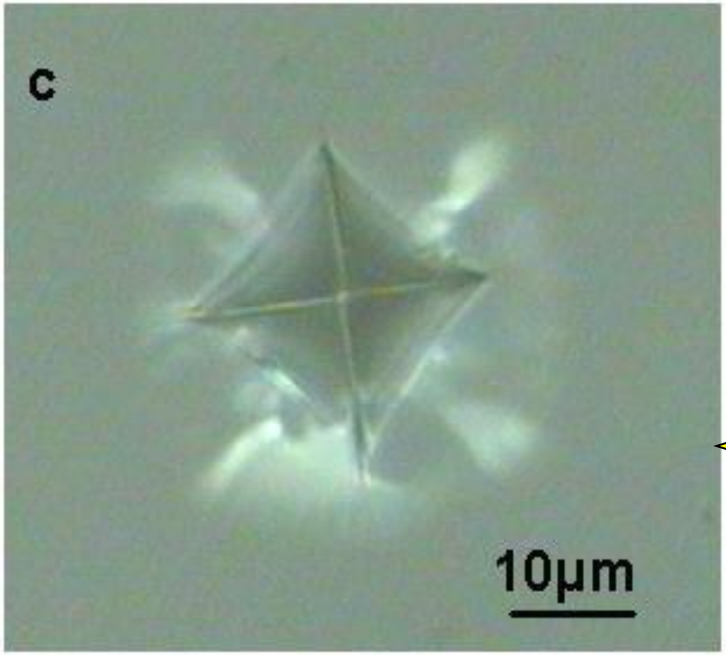


卸载后10s后情况



卸载1min后情况

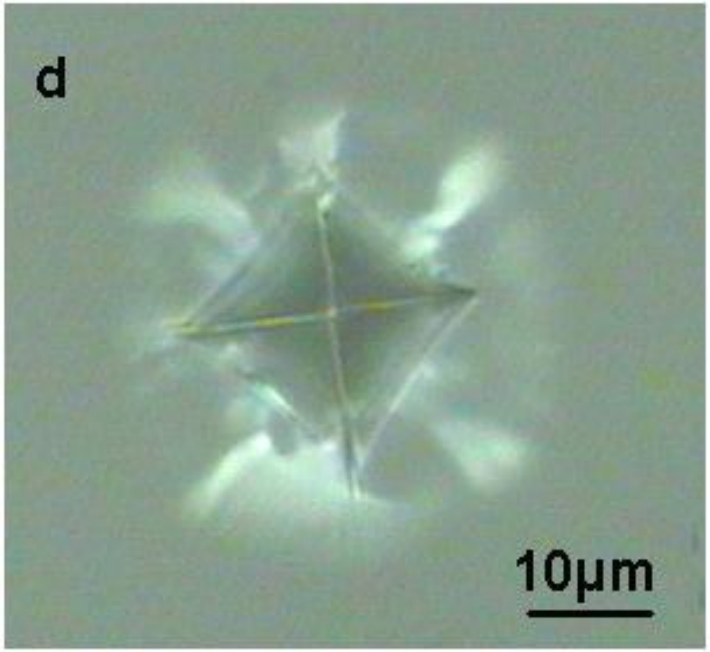
6min after unloading of 200g indentation load



卸载

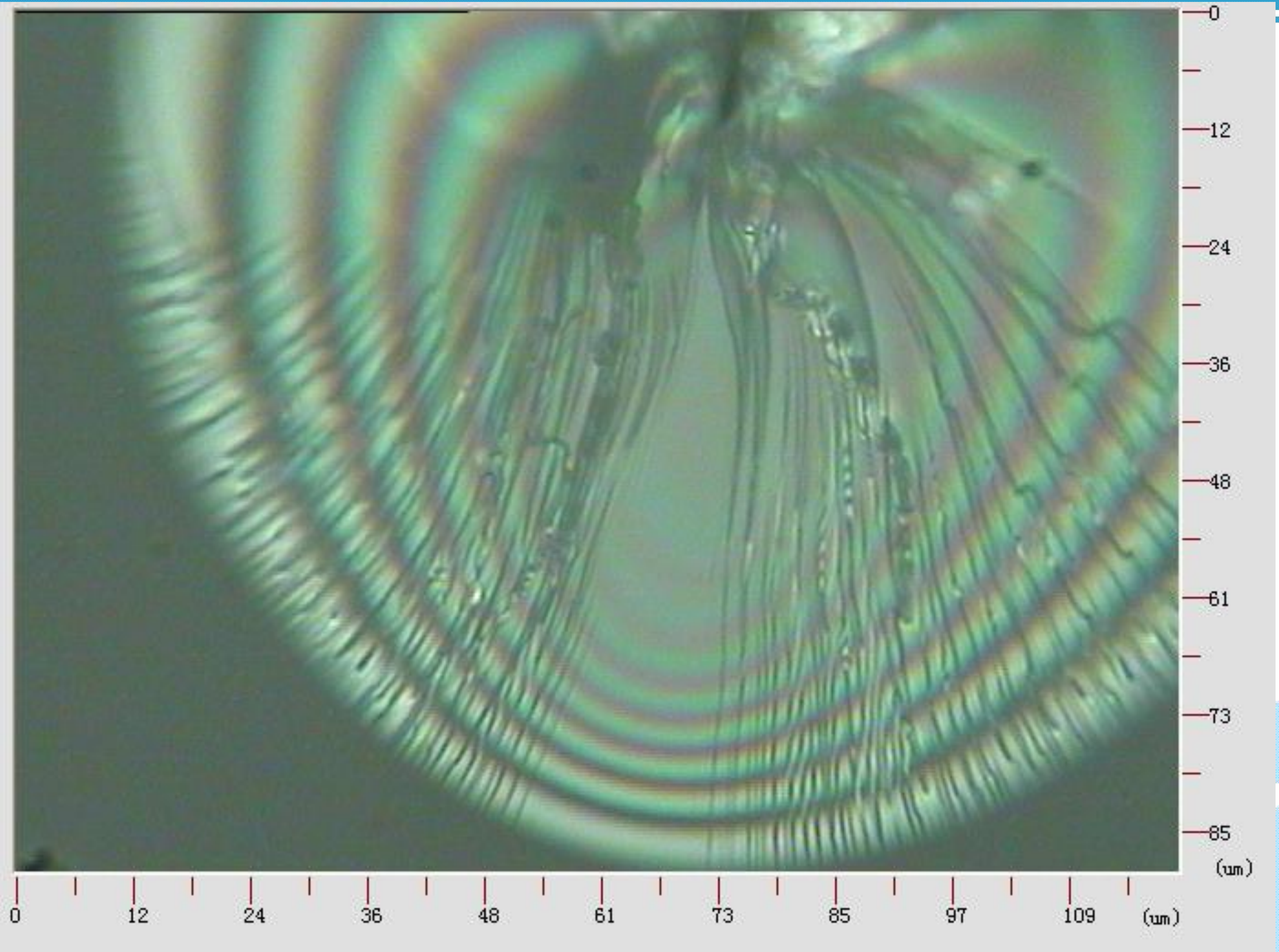
6min后

压痕情况

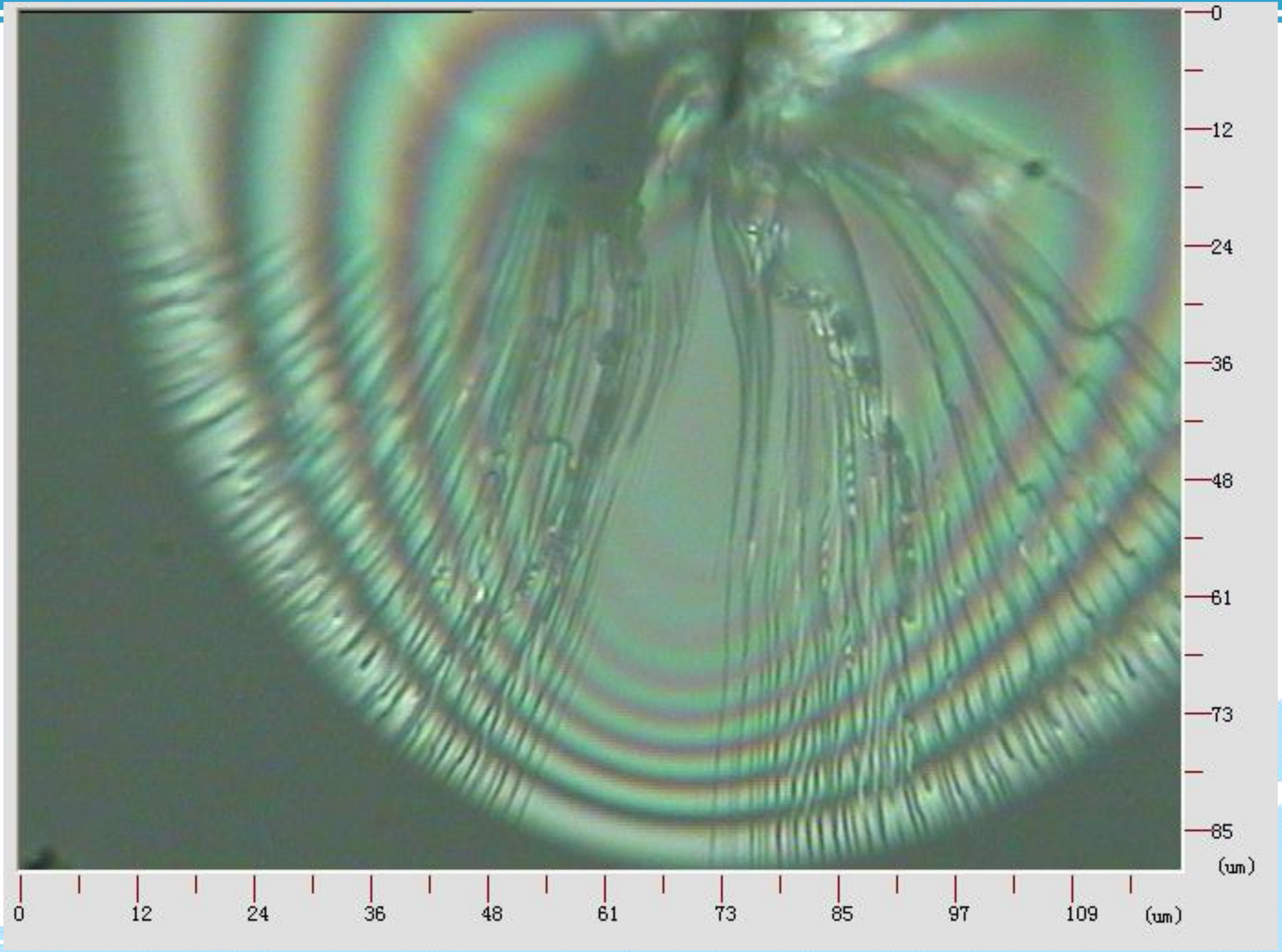


卸载13min后

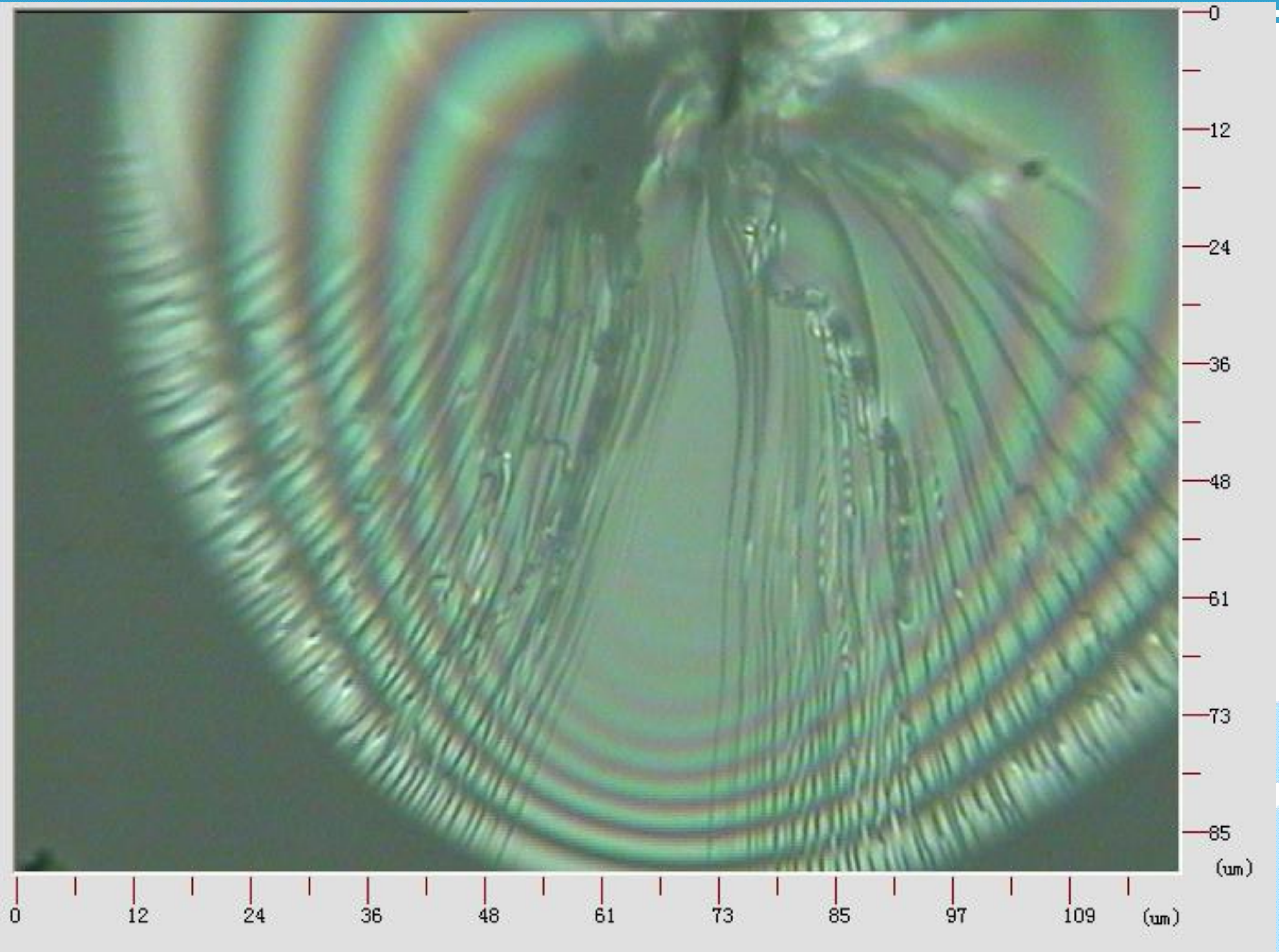
Indentation cracks in tempered glass under 1000g



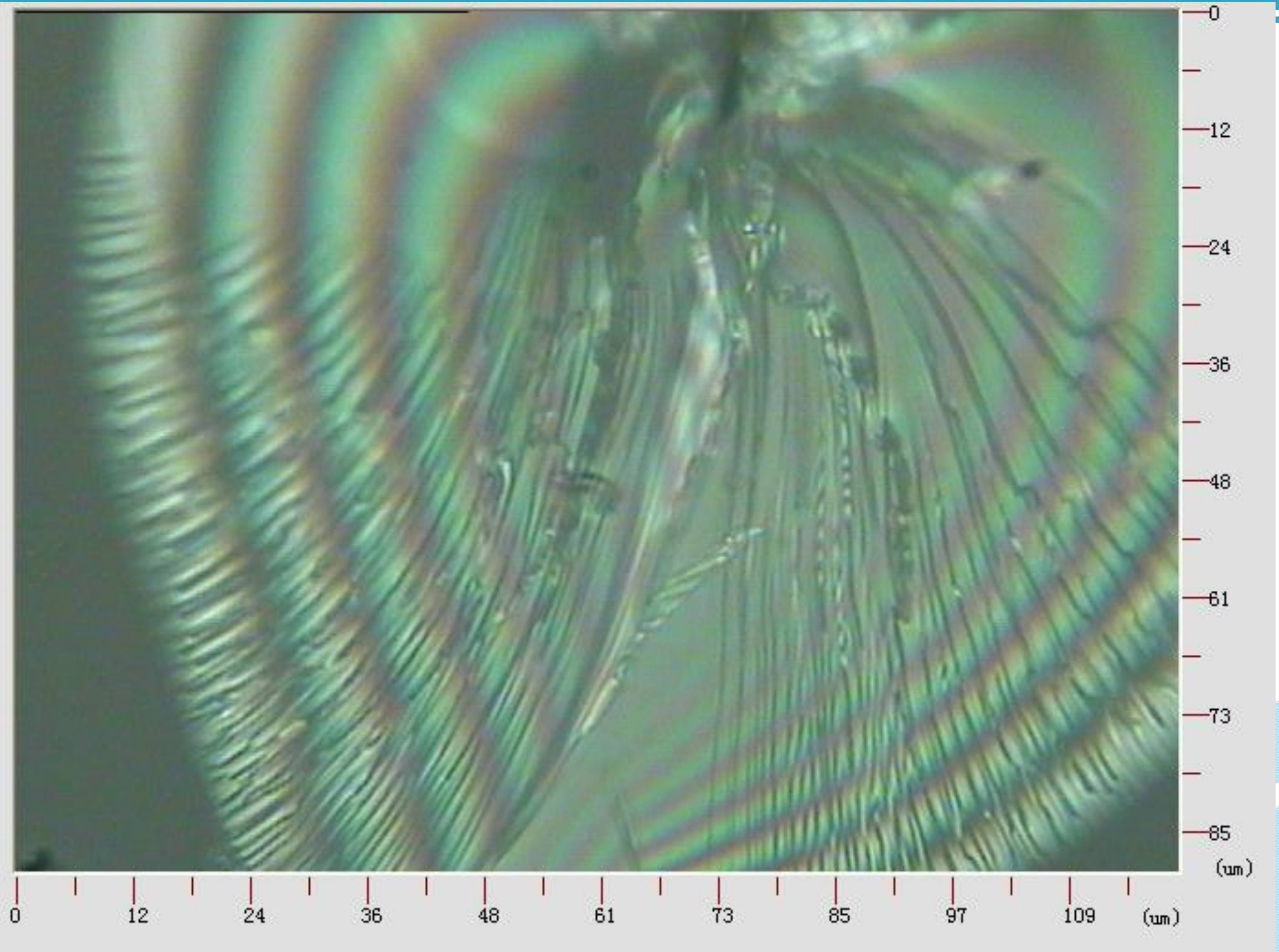
10 sec after unloading



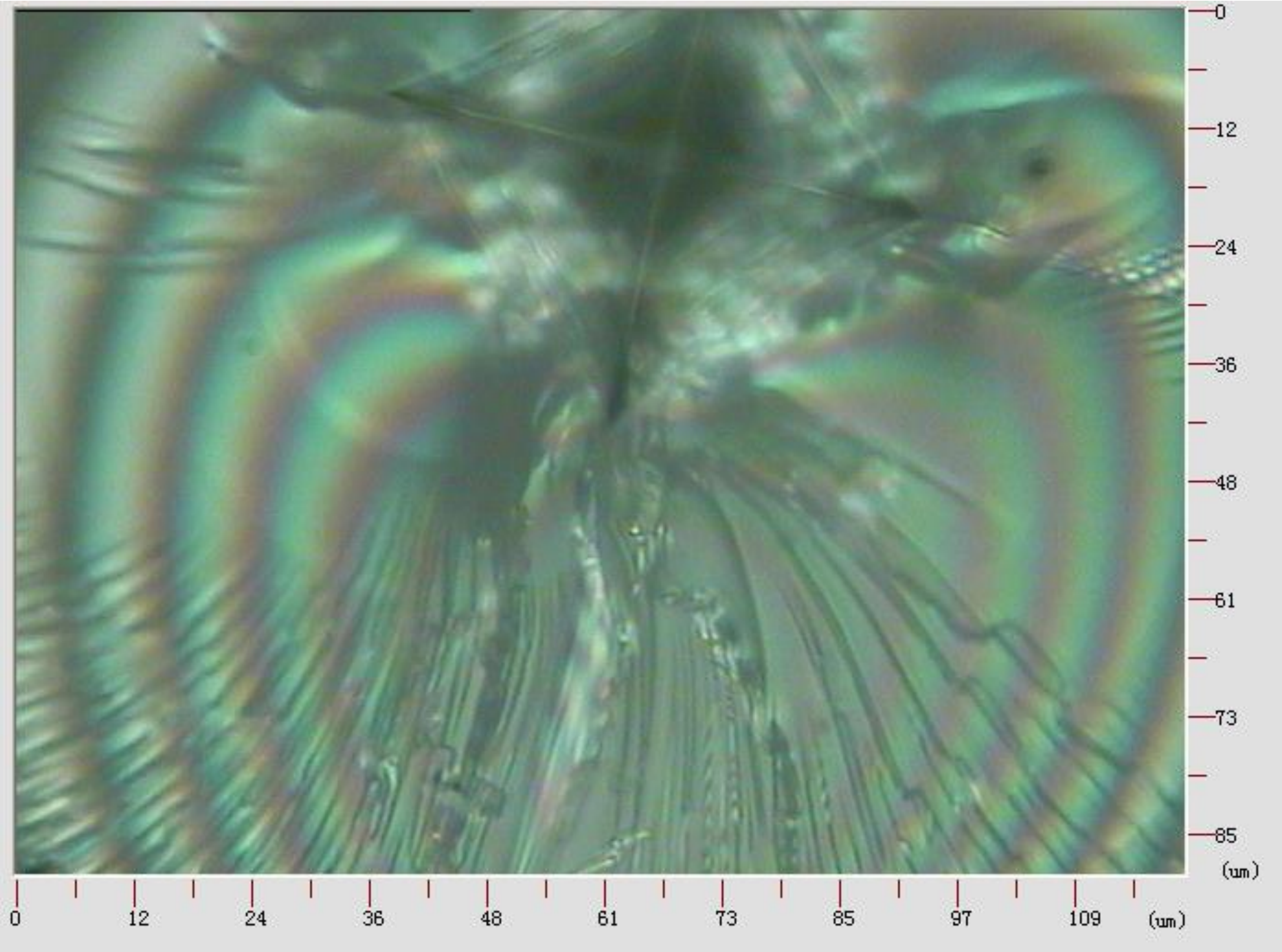
After 20 sec



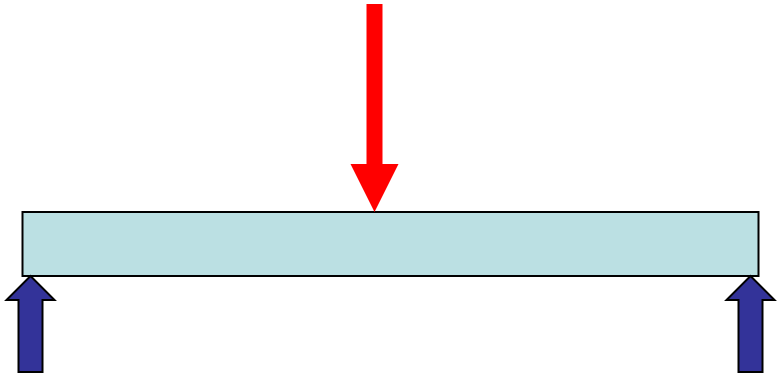
After 30 sec



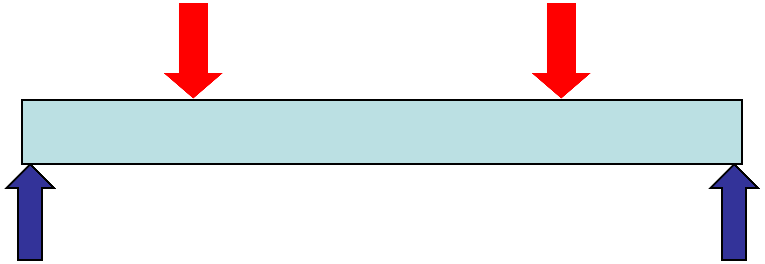
Micro-cracks near the indent due to residual stress



Conventional strength test for glass ---bending strength



Three-point bending test



Four-point bending test

The strength is calculated by the Critical load at fracture and the size of the sample and the span

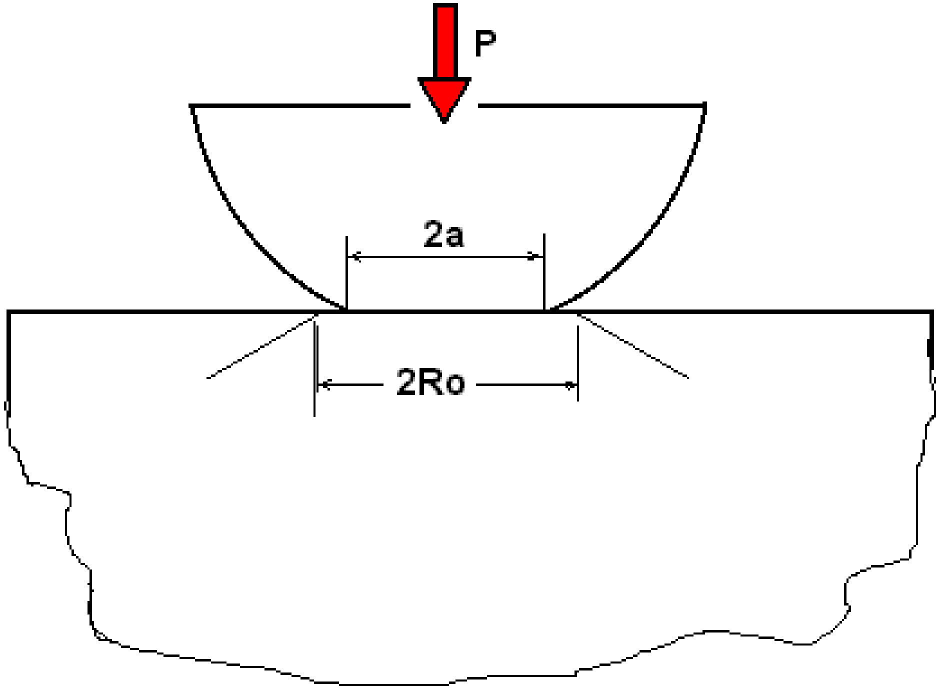
Questions

- Can we evaluate the strength of glass nondestructively?
- How to know if the strength of a glass element meet the need of expected value?
- How to measure the local strength in situ ?

Evaluating the properties by using nondestructive test
—— diagnosing like traditional Chinese medicine

象中医号脉那样通过弹性接触无损测试材料的性能---- 一个探索性的思路

Spherical (Hertzian) indentation



Brittle Material

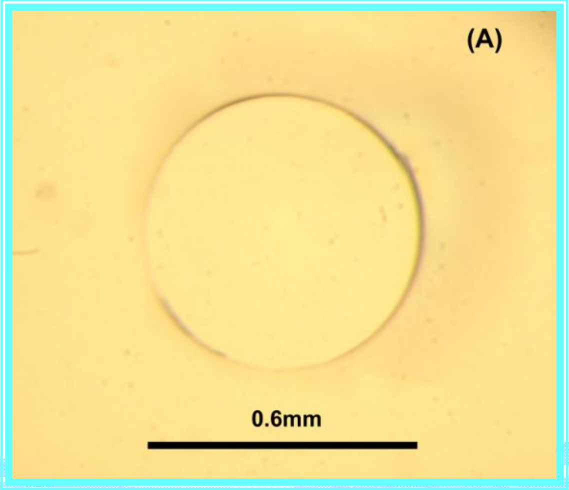
脆性材料

The properties of the ball is known. The critical load for cracking reflects the strength. So it is possible to evaluate the local strength by Hertzian indentation.

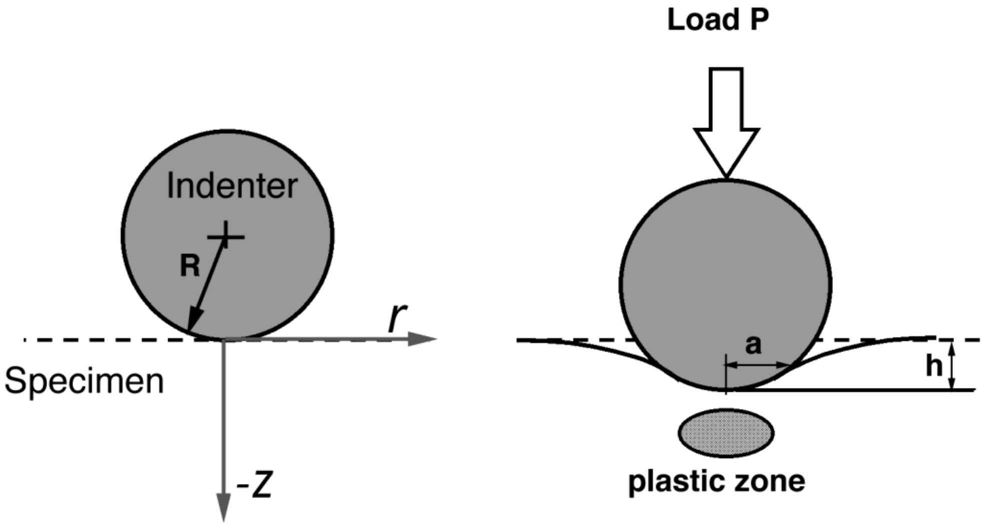
Local strength evaluation by spherical indention

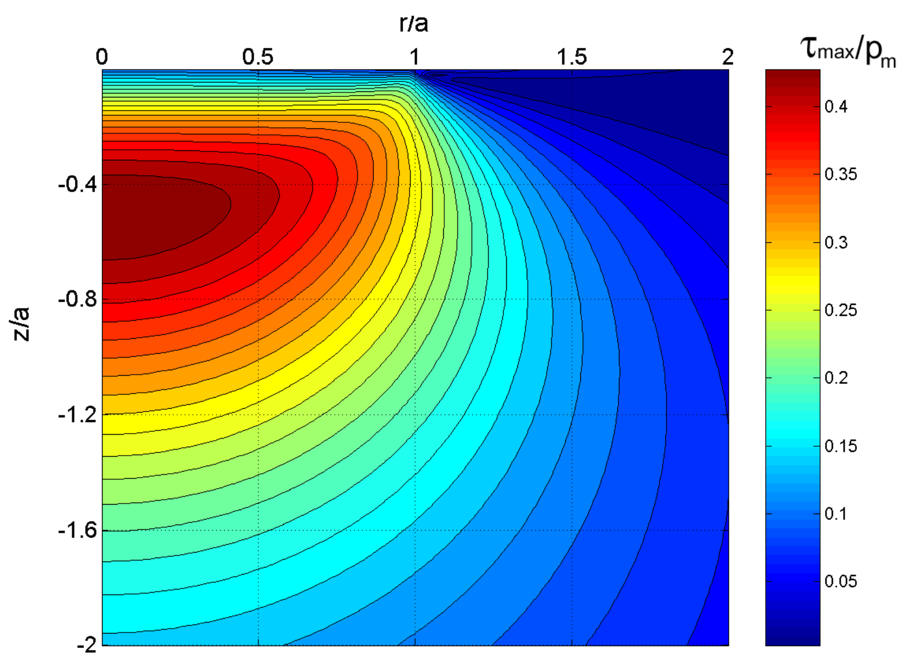
$$P = \frac{4 \cdot E_r a^3}{3R}$$

$$\tau_{max} = 0.31 \frac{2}{\pi} E_r \sqrt{\frac{h}{R}}$$



Hertz crack in glass



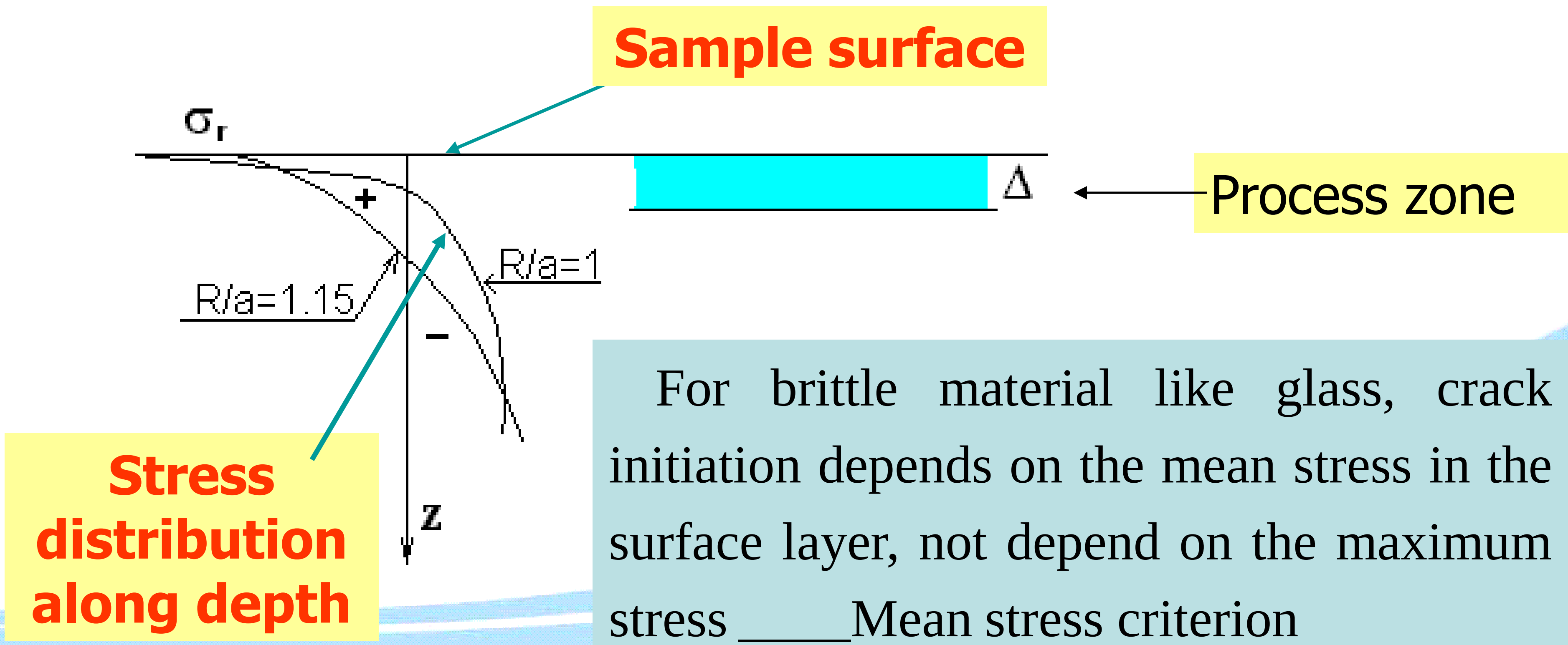


Hertzian indentation

The maximum stress: at R=a

The maximum mean stress: at R>a

对球压法：最大应力在接触区边缘，最大平均应力在接触区外面



For brittle material like glass, crack initiation depends on the mean stress in the surface layer, not depend on the maximum stress ____Mean stress criterion

Mean-stress criterion for contact stress to determine local strength

$$\frac{1}{\Delta}\int_0^{\Delta} \sigma_R \, dz = \sigma_i$$

通过均强度准则
计算局部强度

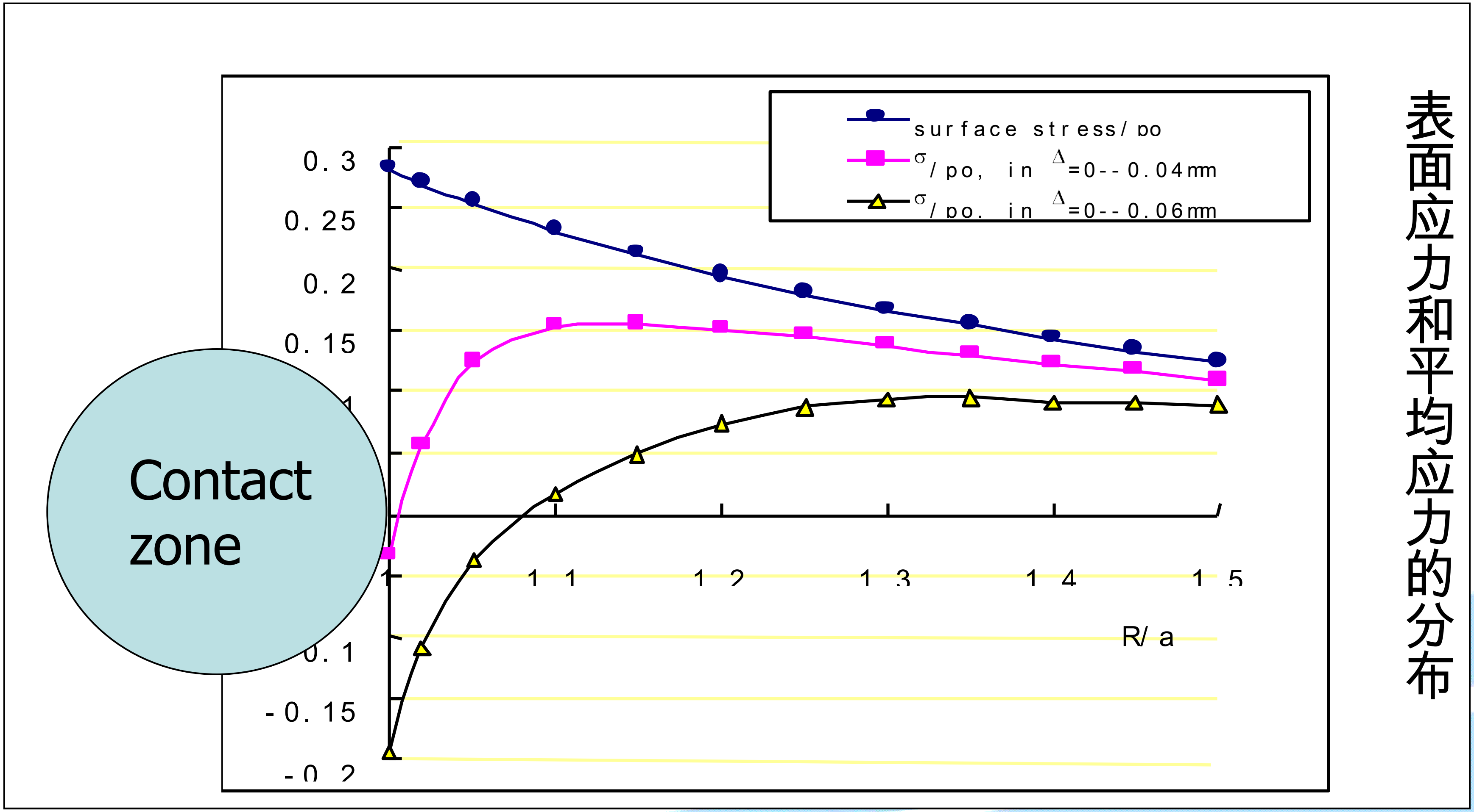
By Numerical integral

Not simply use the criterion $\sigma_R \geq \sigma_i$

$$\frac{\sigma_R}{p_o} = \frac{1}{2}(1-2\nu)\left(\frac{a}{R}\right)^2\left[1-\left(\frac{z}{\sqrt{u}}\right)^3\right] + \frac{3z}{2\sqrt{u}}\left[\frac{(1-\nu)u}{(a^2+u)} + (1+\nu)\frac{\sqrt{u}}{a}\arctan\left(\frac{a}{\sqrt{u}}\right) - 2\right]$$

$$u = \frac{1}{2}\left\{(R^2+z^2-a^2) + \left[(R^2+z^2-a^2)^2 + 4a^2z^2\right]^{1/2}\right\}$$

Distribution of surface stress and mean stress (R>=a)



表面应力和平均应力的分布

Local strength of glass

The process zone, ~0.03 mm

$$\sigma_{loc} = \left[0.1373\, a_c^2 + 0.2862\, a_c + 0.0236\right] \cdot \frac{P_c}{\pi a_c^2}$$

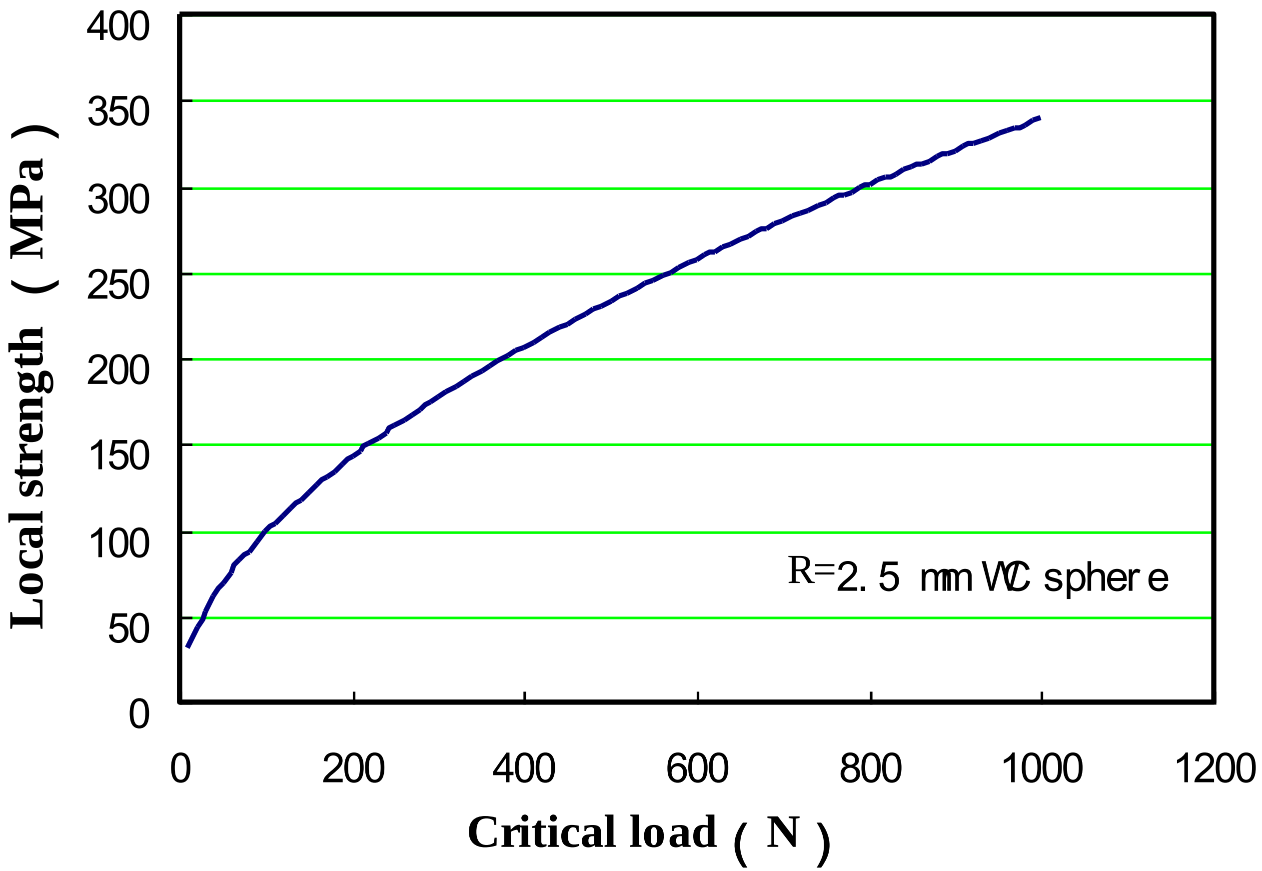
Where a_c can be expressed by P_c , we get

$$\sigma_{loc} = \left[0.1373\, a_c^2 + 0.2862\, a_c + 0.0236\right] \cdot \left(\frac{3E}{4k}\right)^{2/3} \cdot \frac{1}{\pi} \cdot \left(\frac{P_c}{r^2}\right)^{1/3}$$

The local strength can be evaluated using only P_c

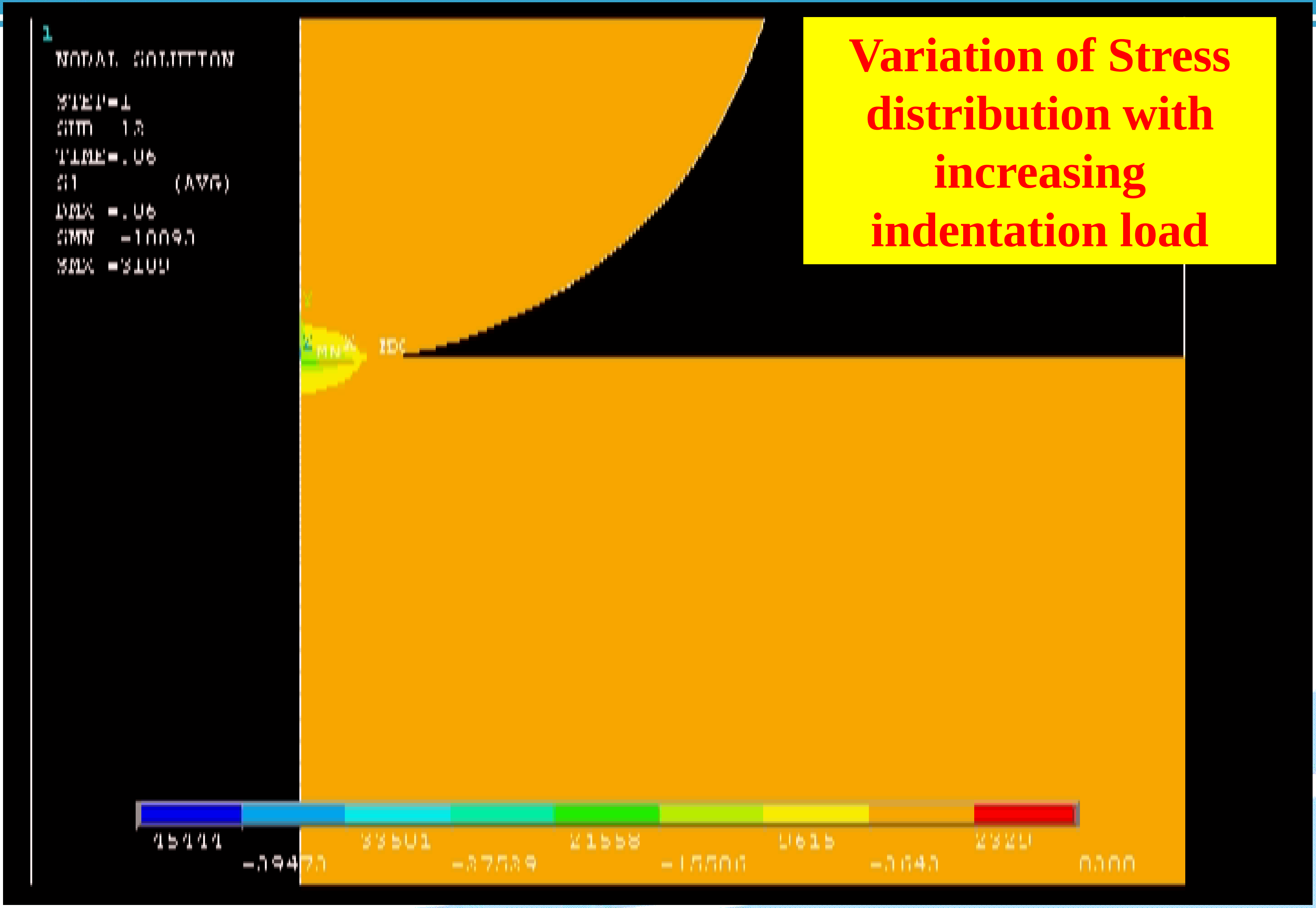
对给定的压球,局部强度可以由临界压力确定

Local strength as a function of the critical load for given ball and glass

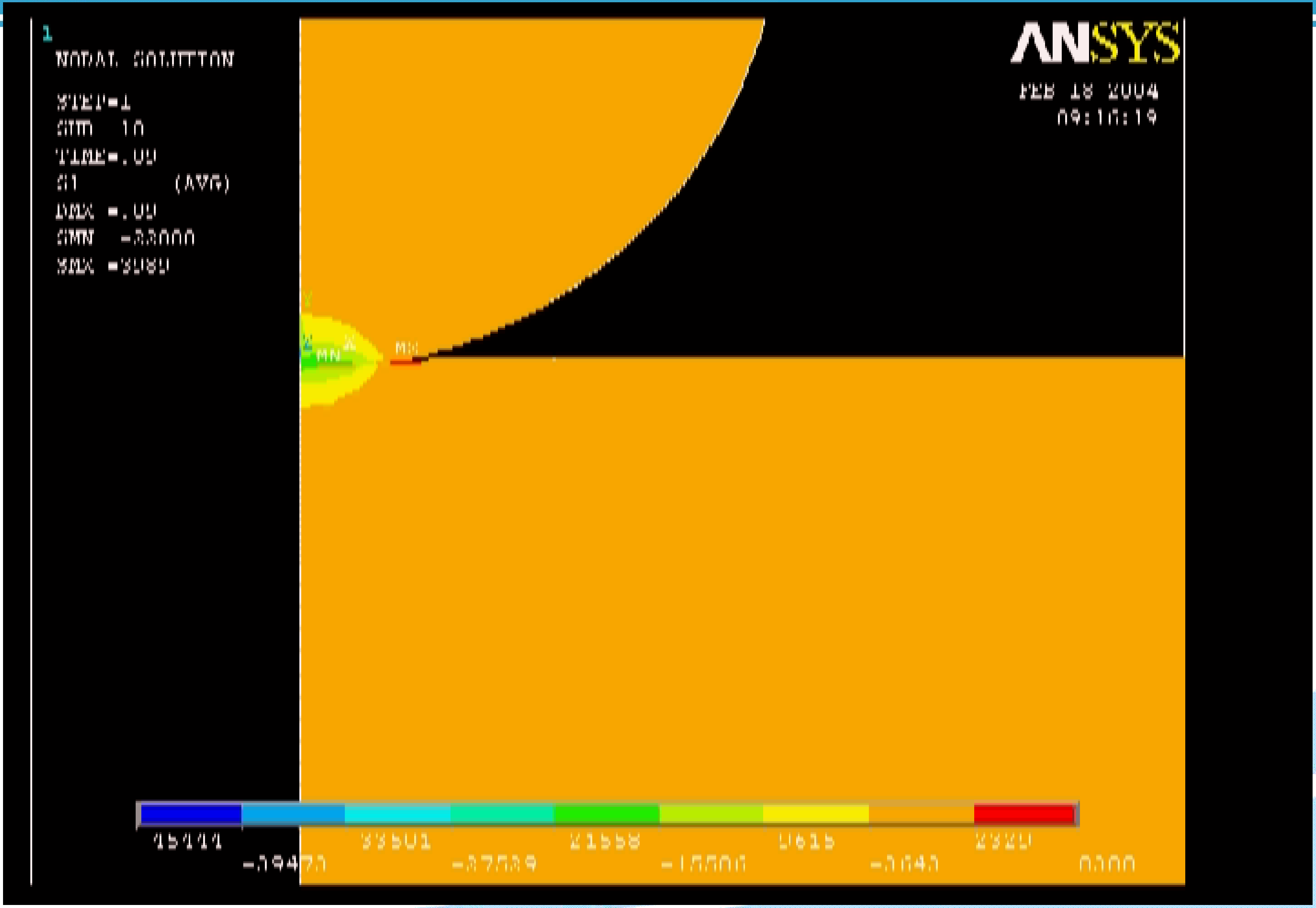


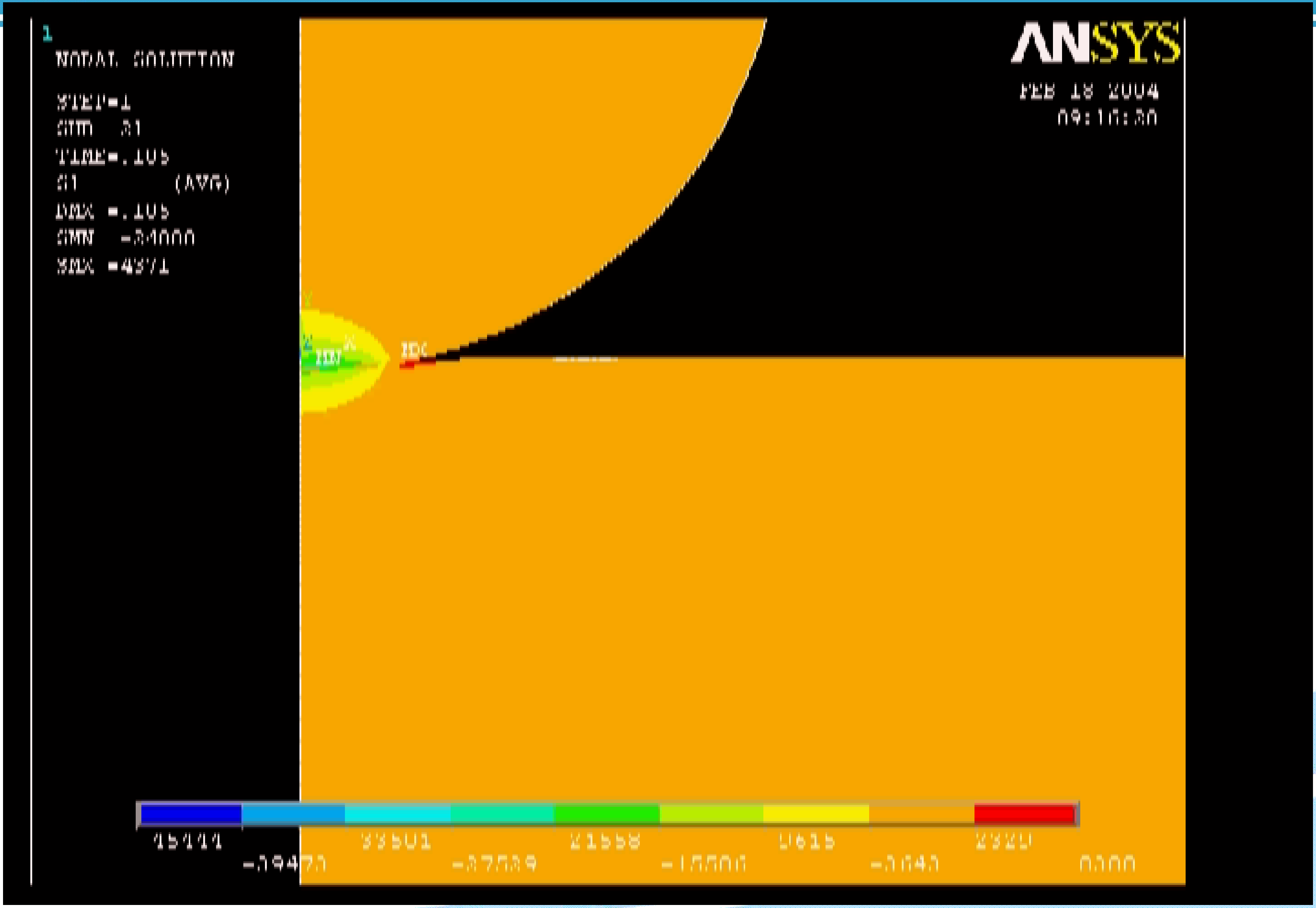
局部强度随临界载荷的变化

Stress analysis by Finite element method



Variation of Stress distribution with increasing indentation load


ANSYS
FEB 18 2004
NODAL SOLUTION
STEP=1
(AVG)
MN
MX


NODAL SOLUTION
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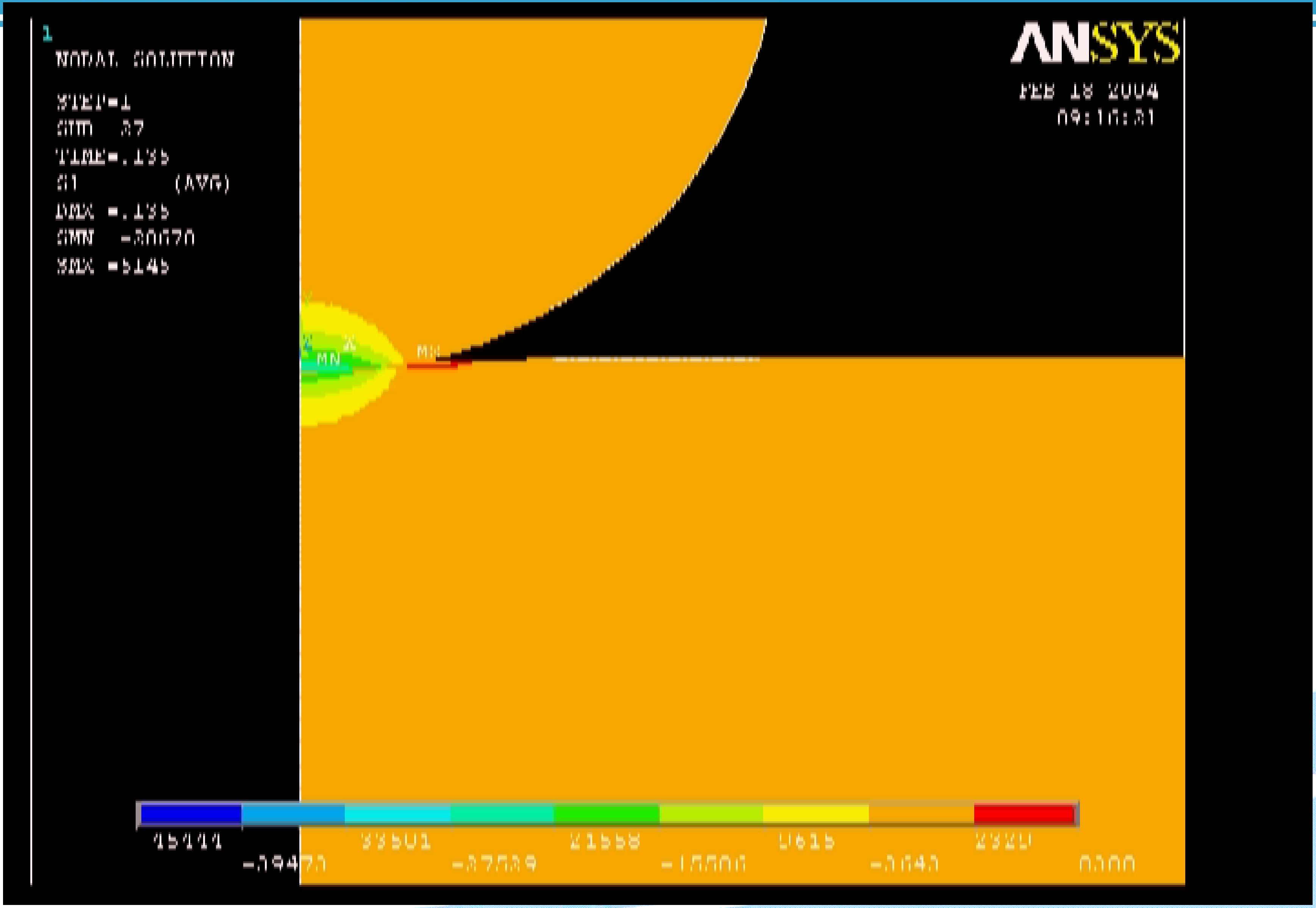
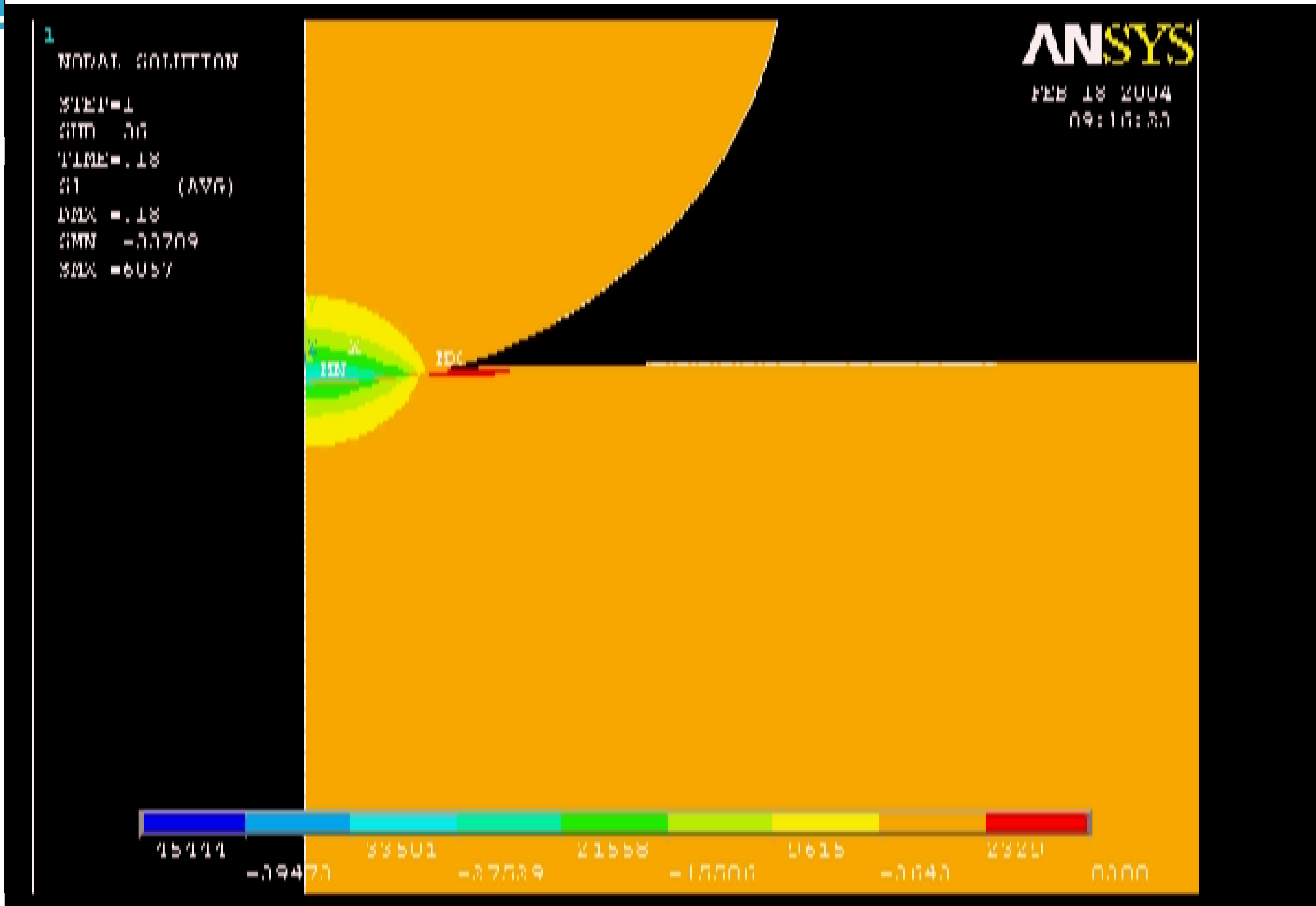
TIME=.105
(AVG)
ANSYS
FEB 18 2004


ANSYS
NODAL SOLUTION
STEP=1
FEB 18 2004
MN
MX


NODAL SOLUTION
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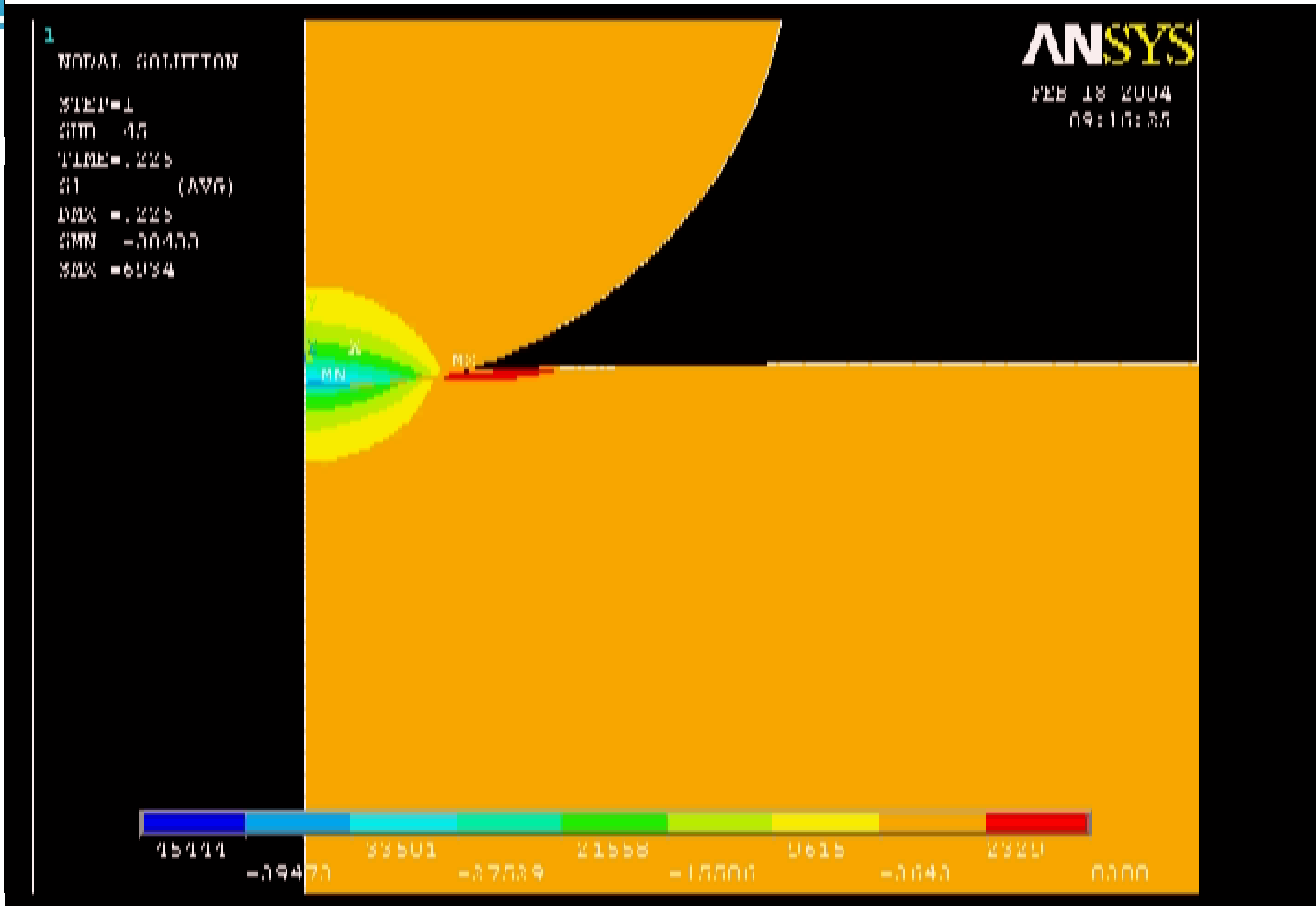
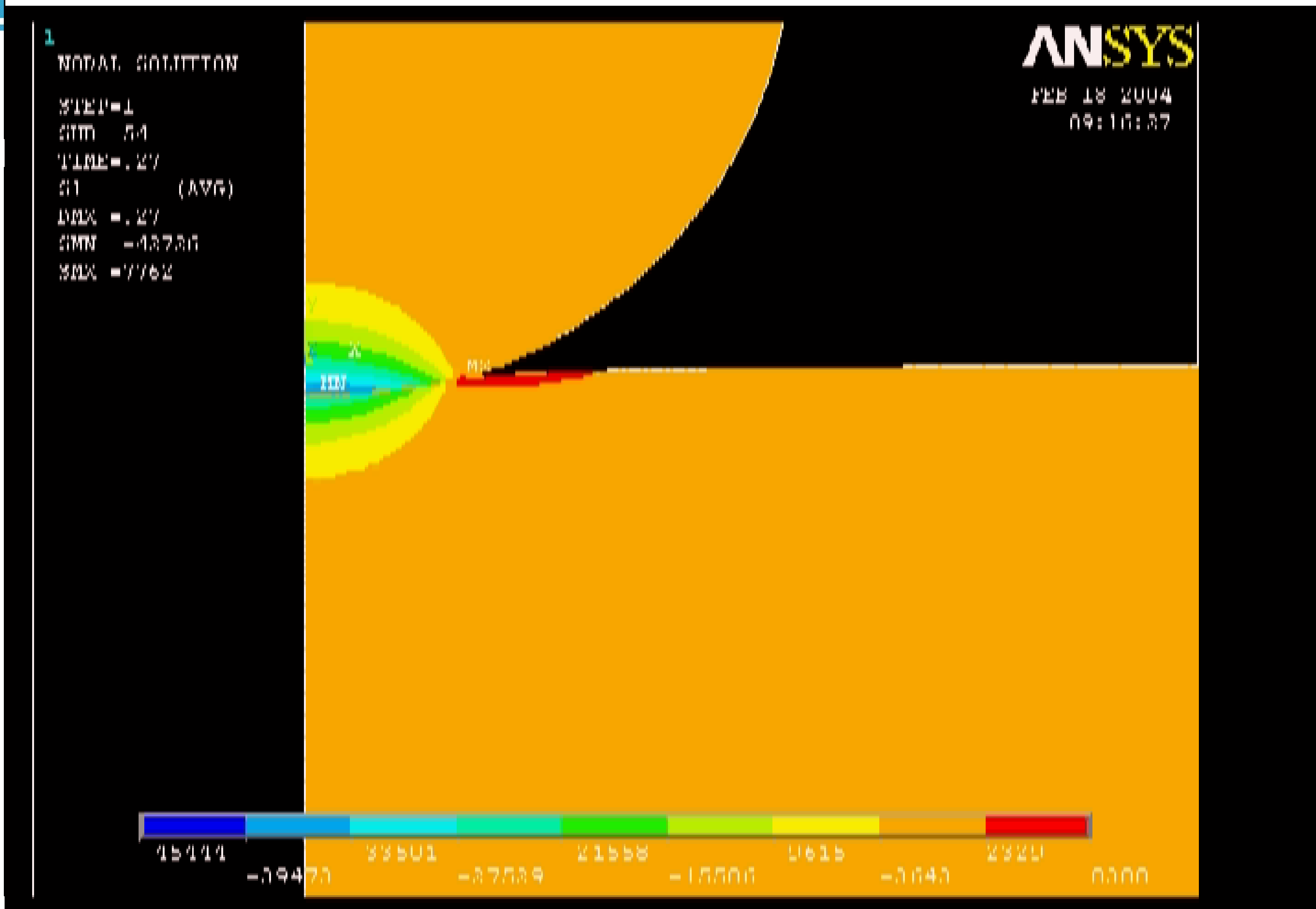
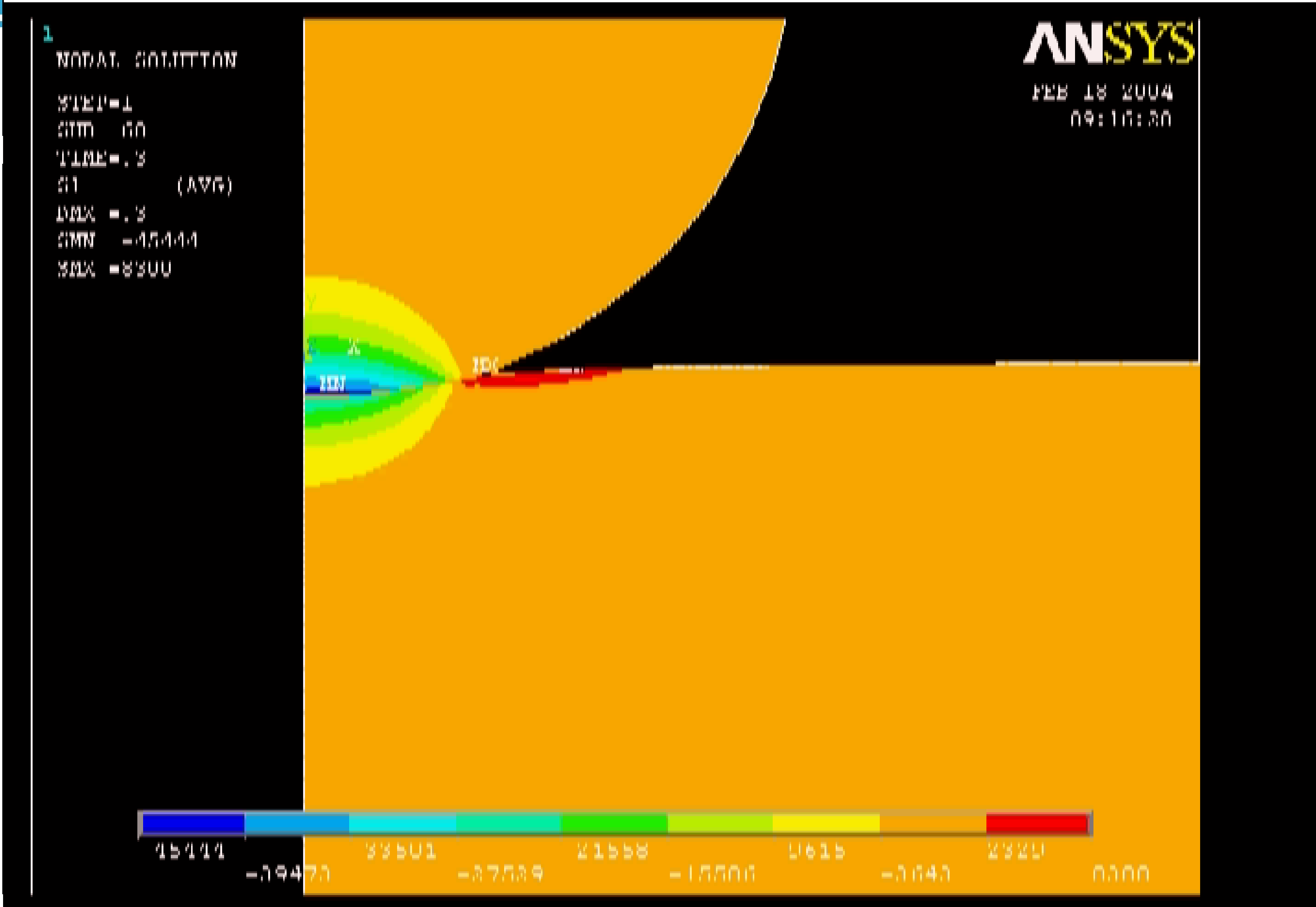
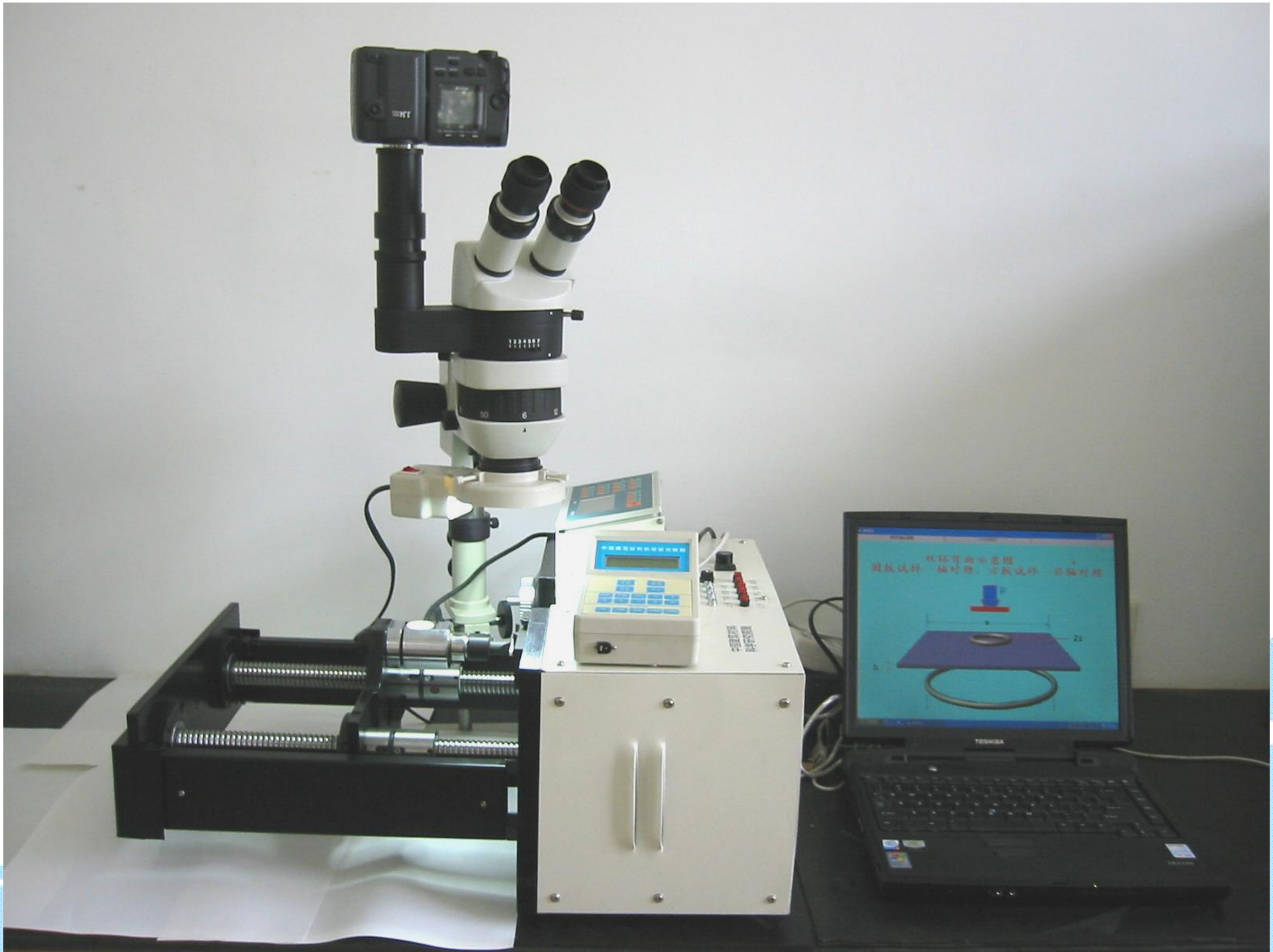
TIME=.18
(AVG)
DMX =.18
ANSYS
FEB 18 2004


ANSYS
NODAL SOLUTION
STEP=1
TIME=.225
(AVG)
DMX =.225
SMX =6934
FEB 18 2004


NODAL SOLUTION
STEP=1
(AVG)
ANSYS
FEB 18 2004

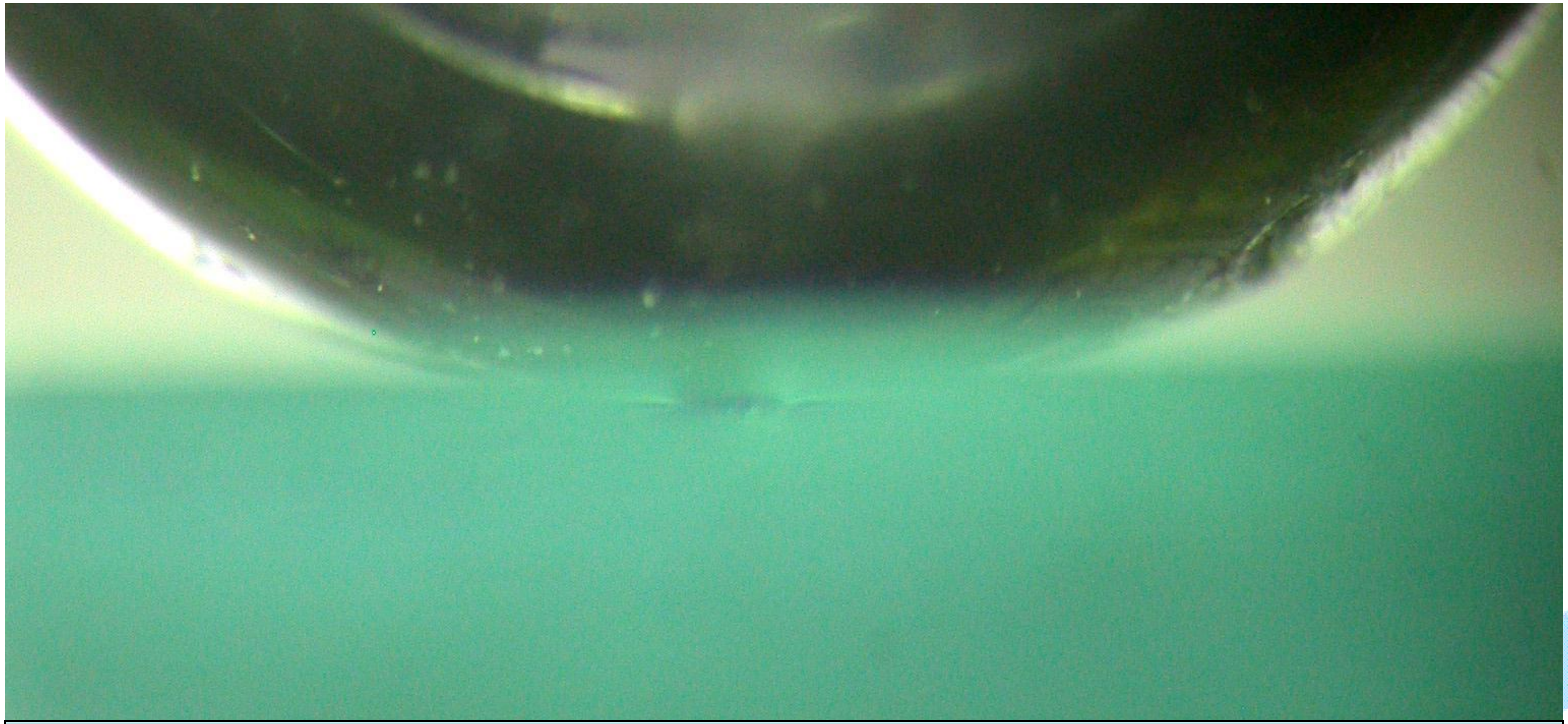

NODAL SOLUTION
STEP=1
TIME=.3
S1 (AVG)
DMX =.3
SMX =8300
ANSYS
FEB 18 2004

In situ measurement and observation



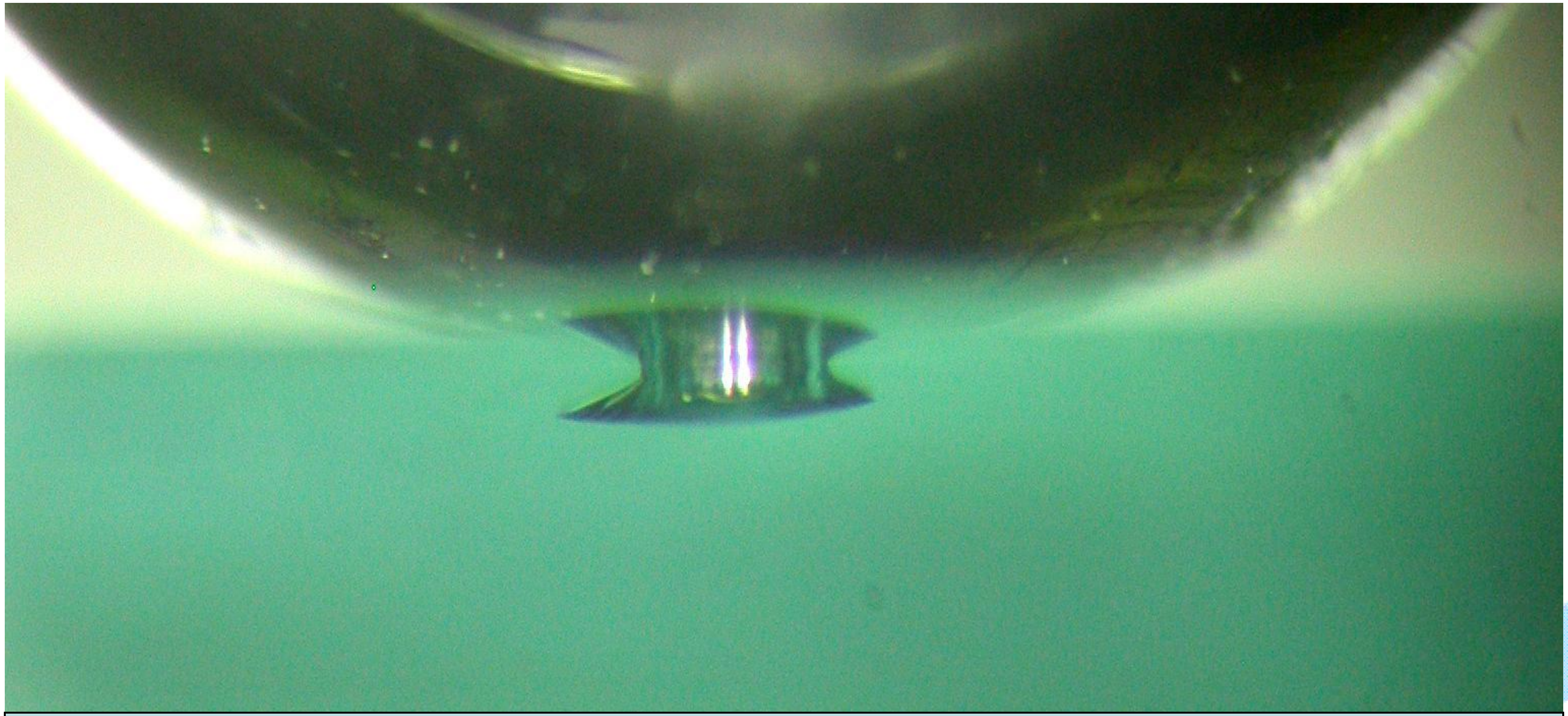
In situ observation of the initiation and extension of indentation crack in glass

ceramic ball (r=2.5 mm)



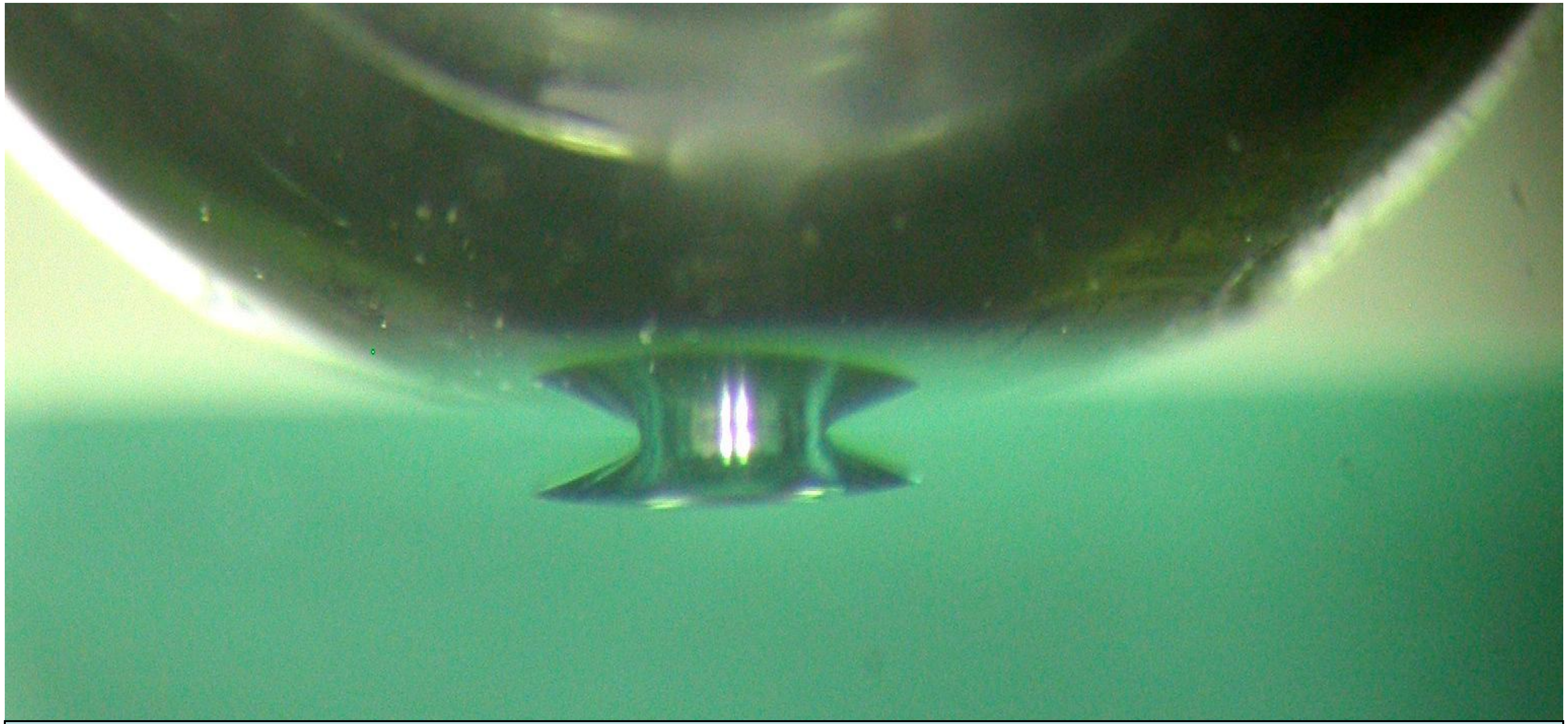
100 N

Hertzian Crack initiation

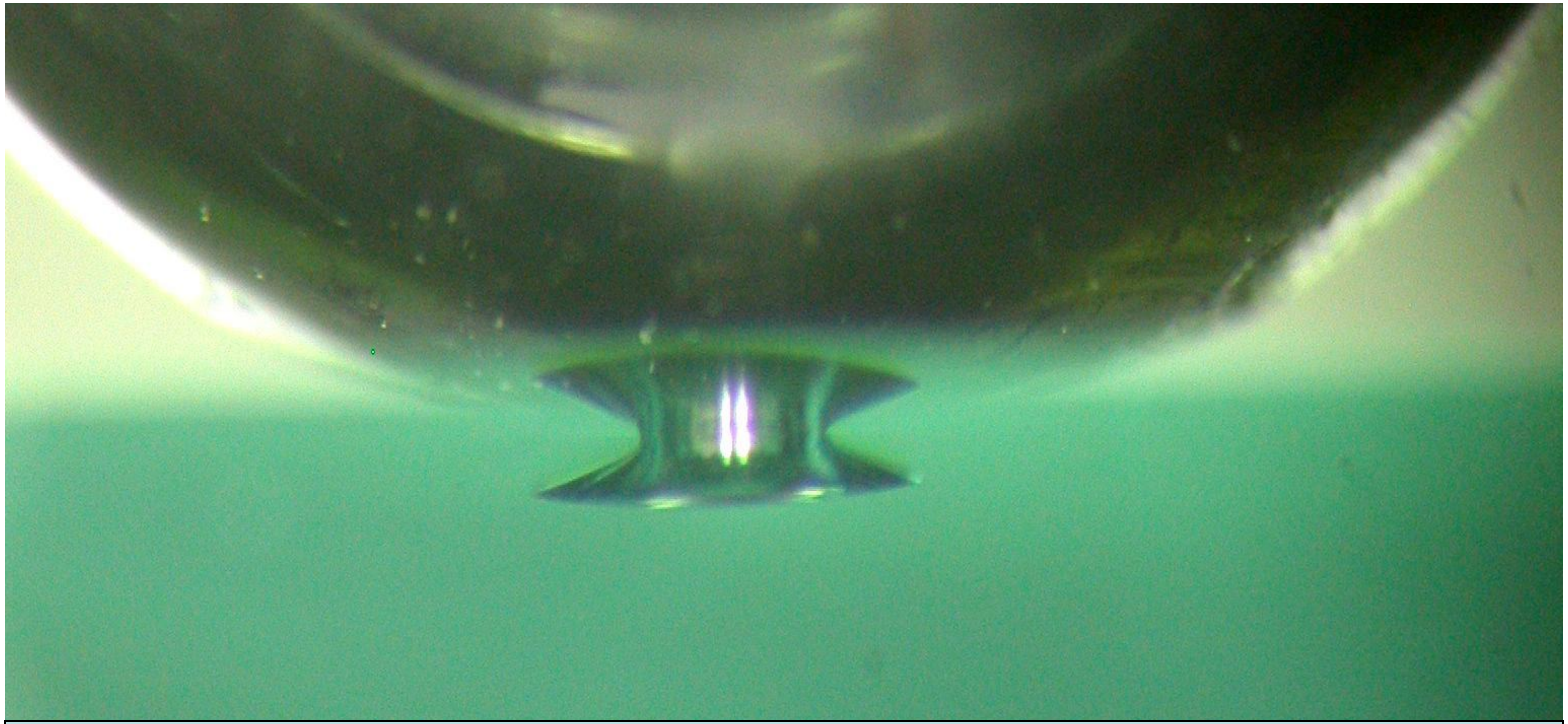


crack initiation at 180 N

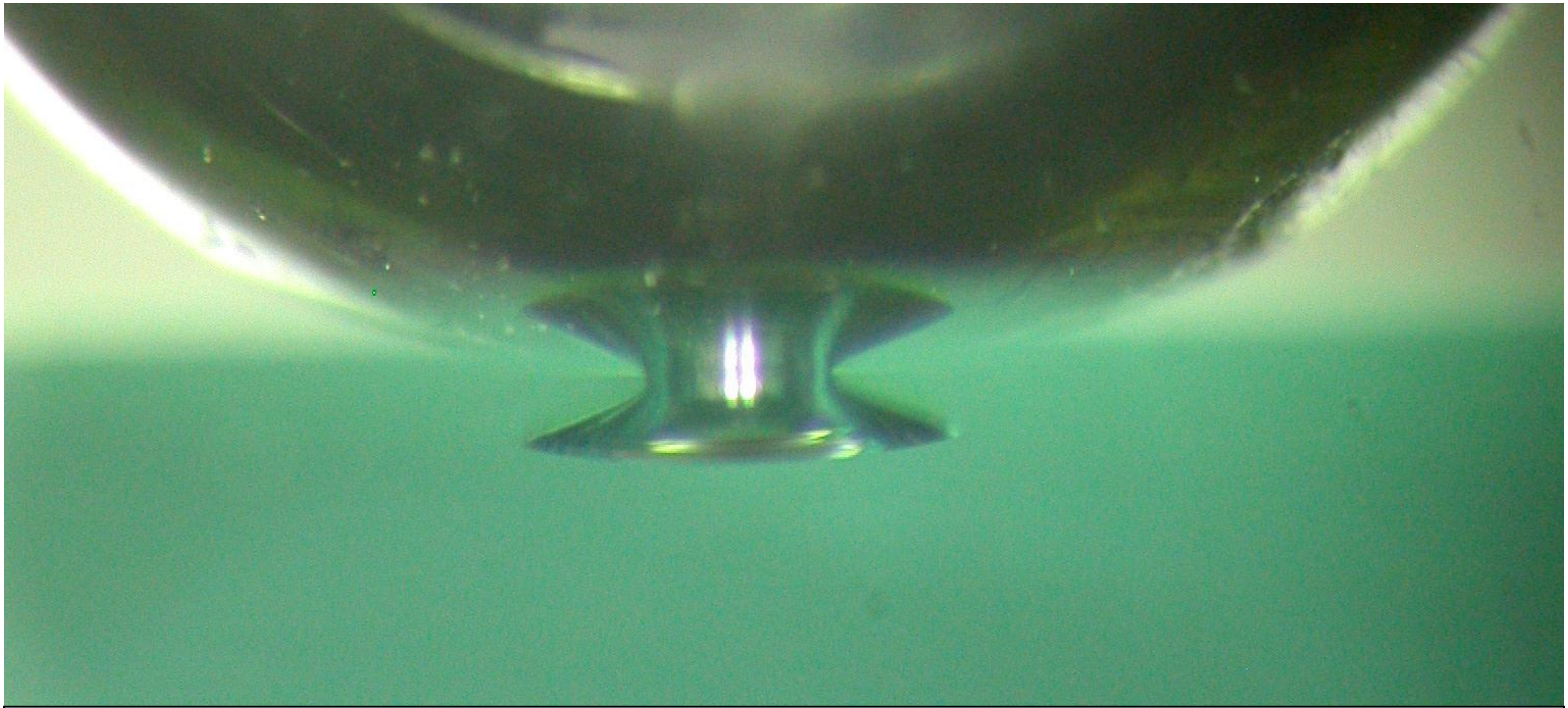
Crack extension



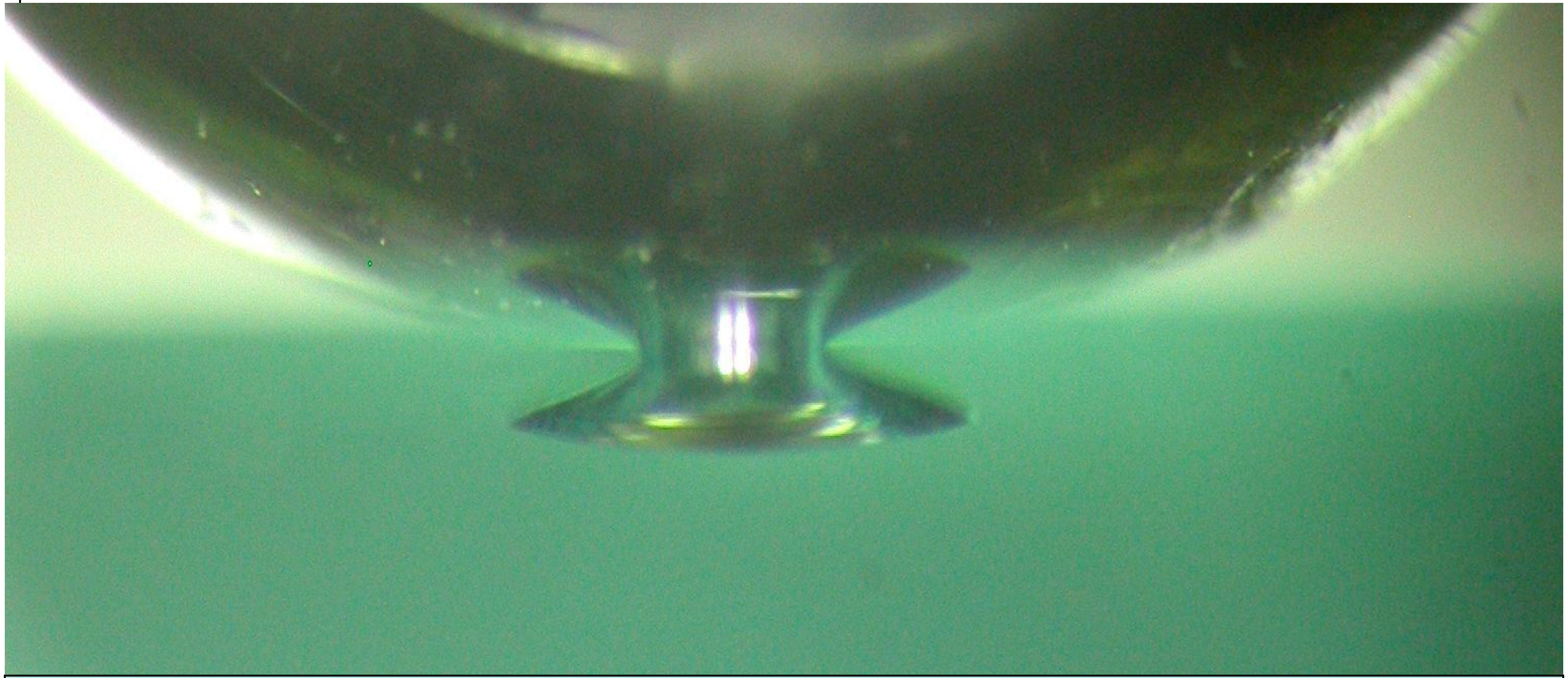
200 N



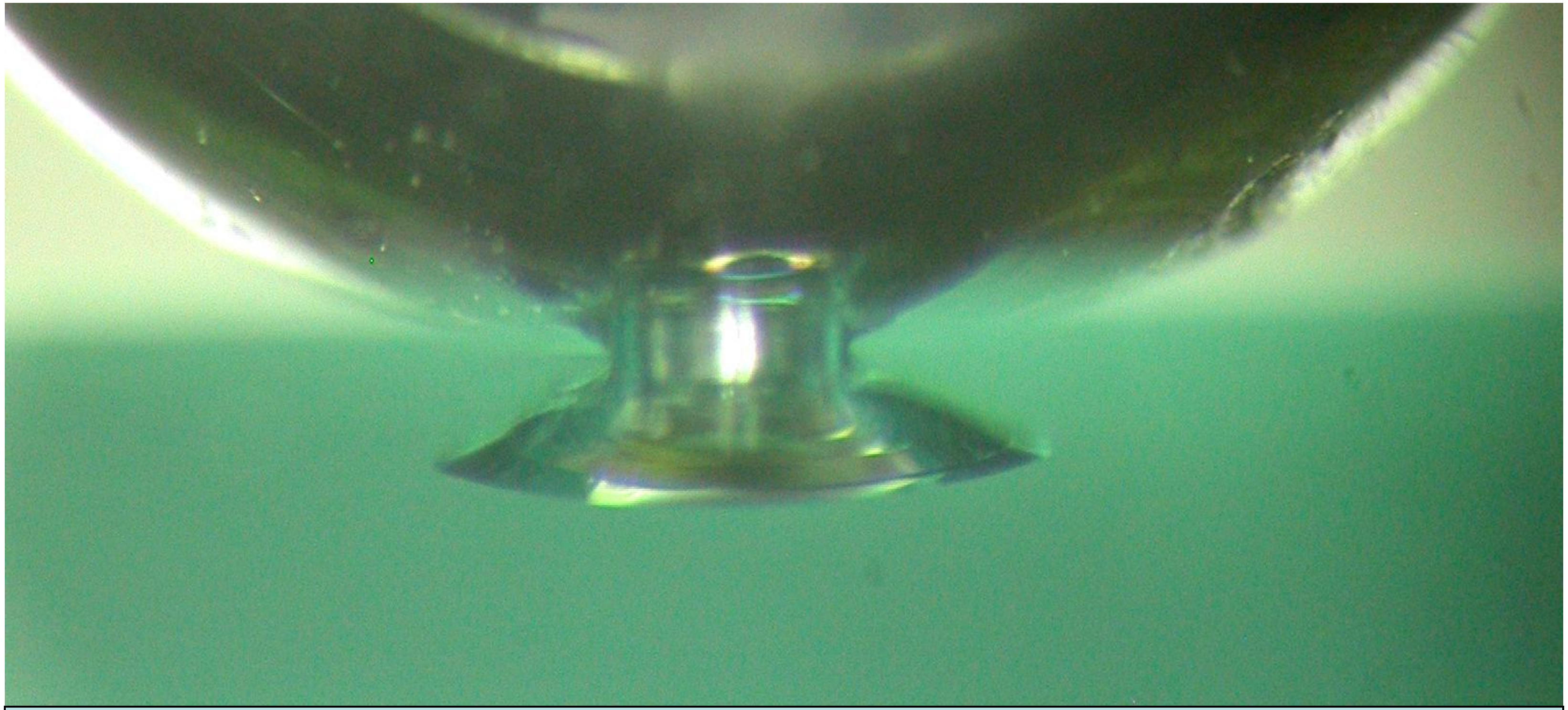
260 N



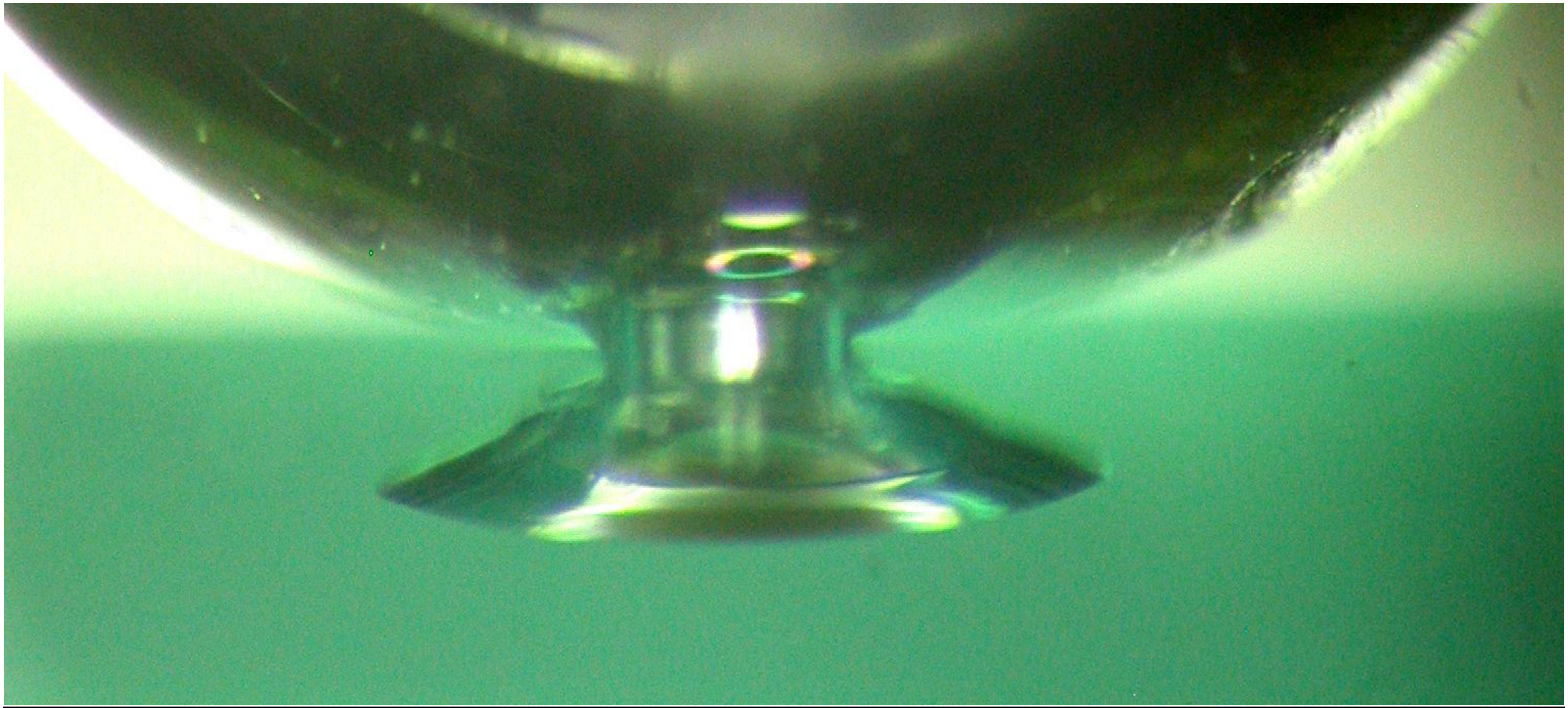
300 N



350 N

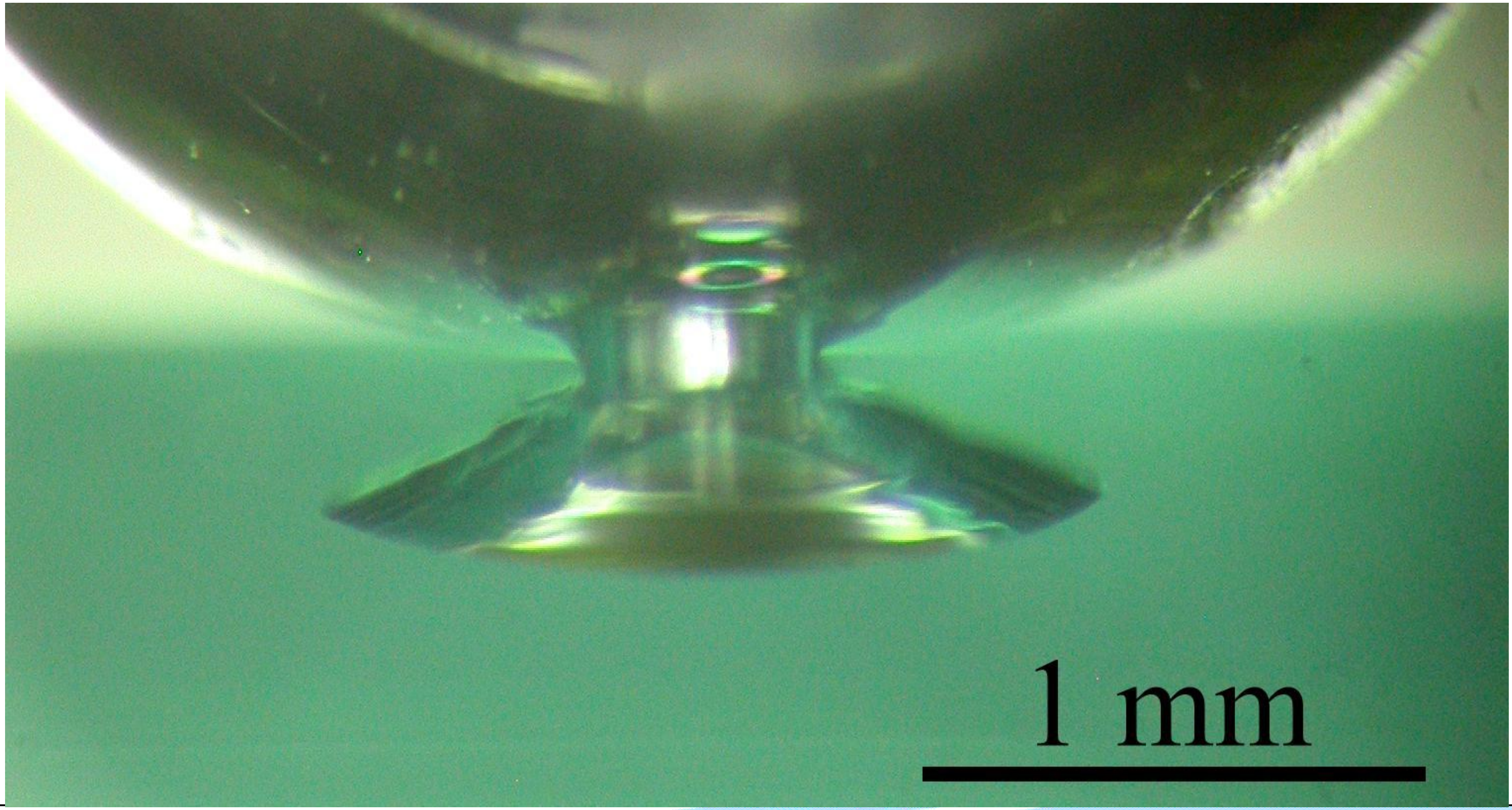


400 N



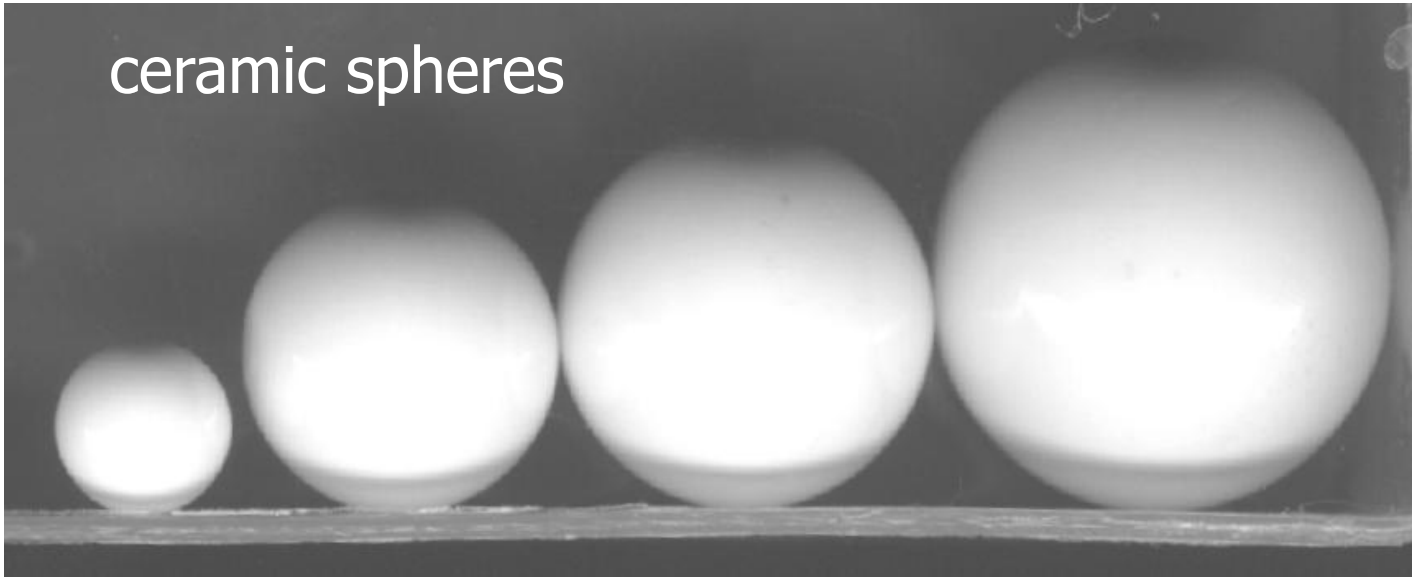
500 N

Formation of a cone crack



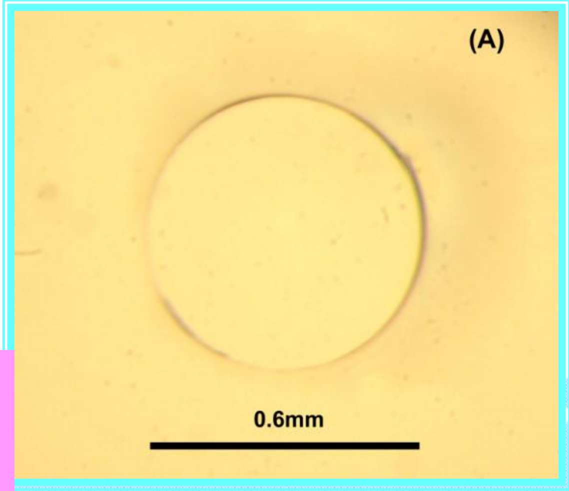
600N

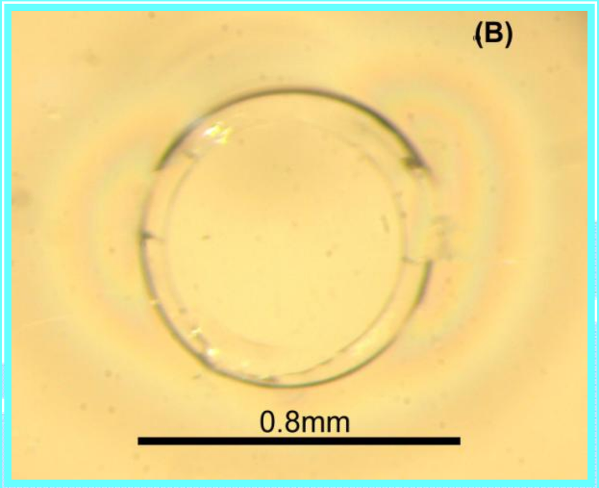
Sphere size effects on tests



Crack under critical load

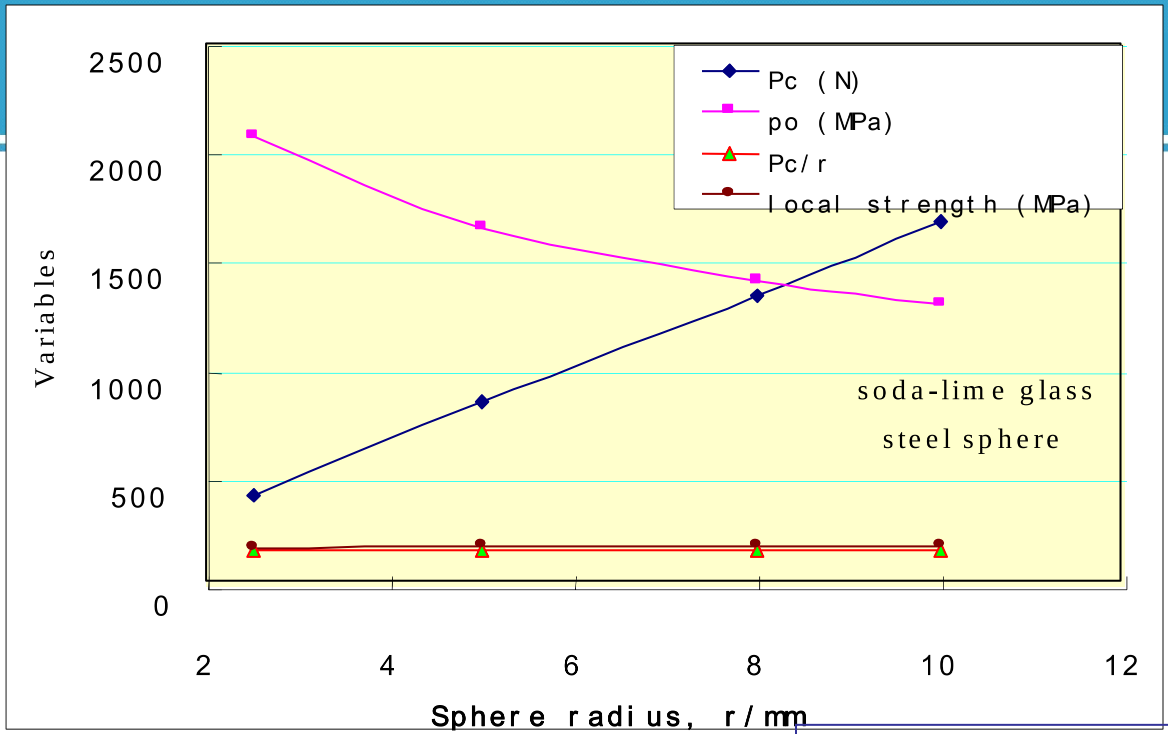
临界环形裂纹





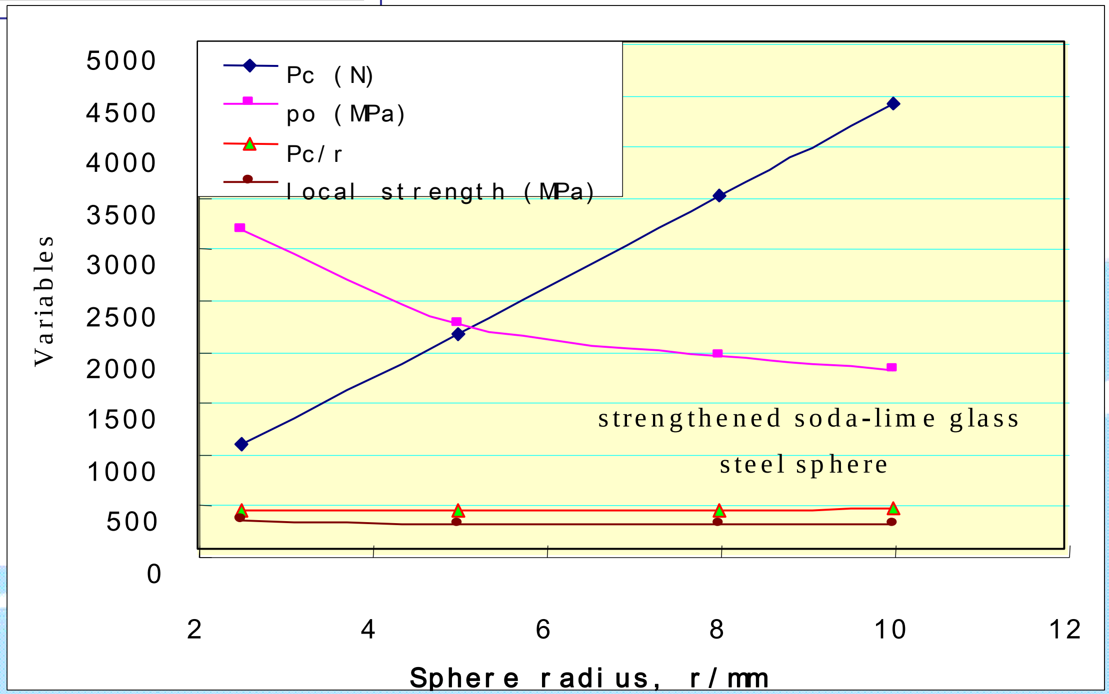
Over loaded

过载的裂纹形貌



Critical load $\mathbf{P_c}$, indentation stress P_o, ratio $\mathbf{P_c/r}$ the **local strength** varies with the sphere radius

Sphere indentation results varying with the sphere size for soda-lime glass and tempered glass



Measured local strength (at 10 points)

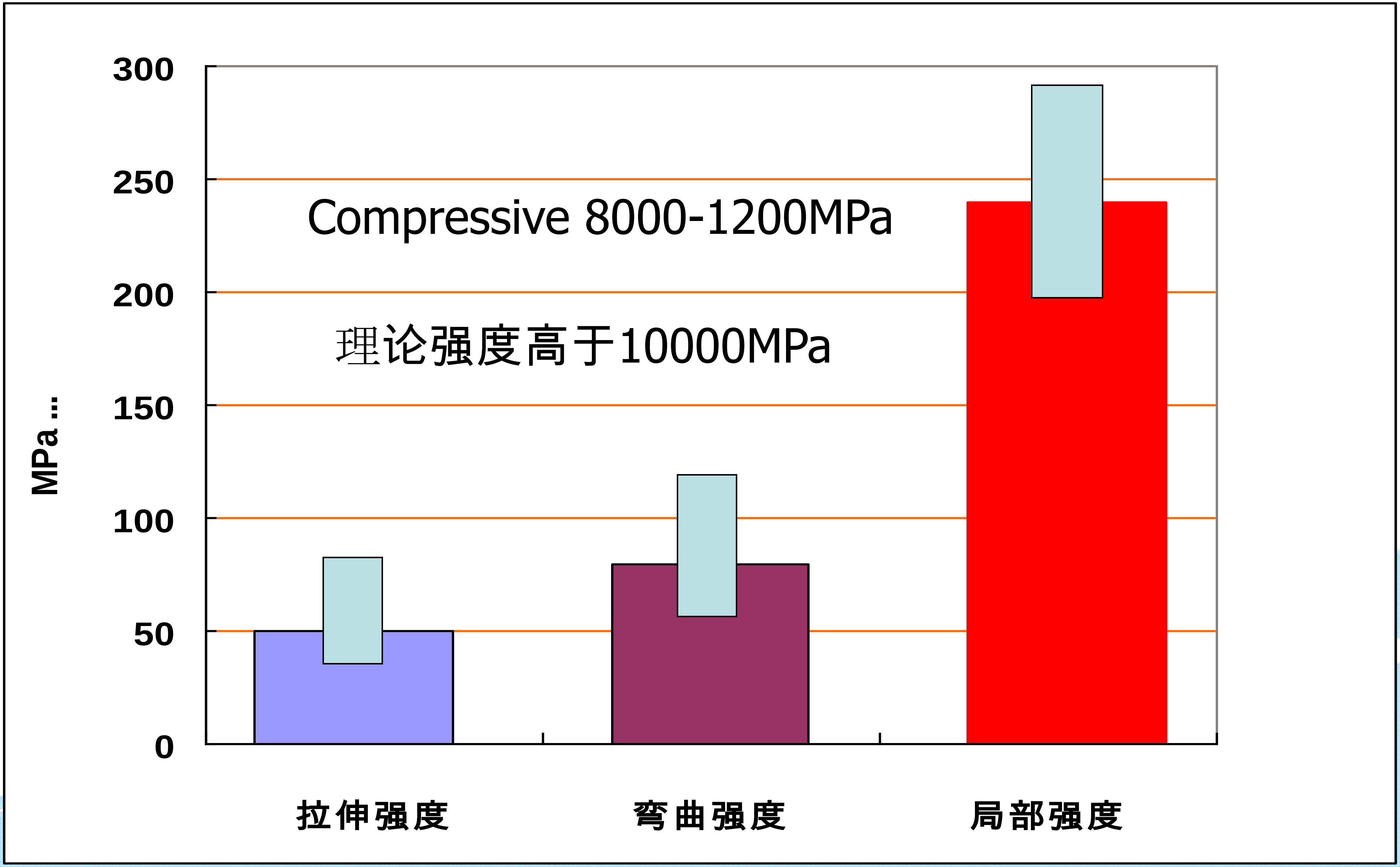
σ_0 =232MPa for soda lime glass

普通玻璃

σ_0'=348 MPa for strengthened glass

钢化玻璃

Comparison between the local strength and conventional strength



Residual stress in the surface

玻璃表面残余应力的测定

$$\sigma_r = \sigma_o' - \sigma_o$$

σ_0' is the local strength of strengthened glass

σ_0 is the strength of unstrengthened glass.

σ_r is the residual stress on the surface ,

it was 348-232=116 MPa in previous example.

Proof test for glasses by spherical indentation

Procedure

a) Given a strength requirement, σ_o

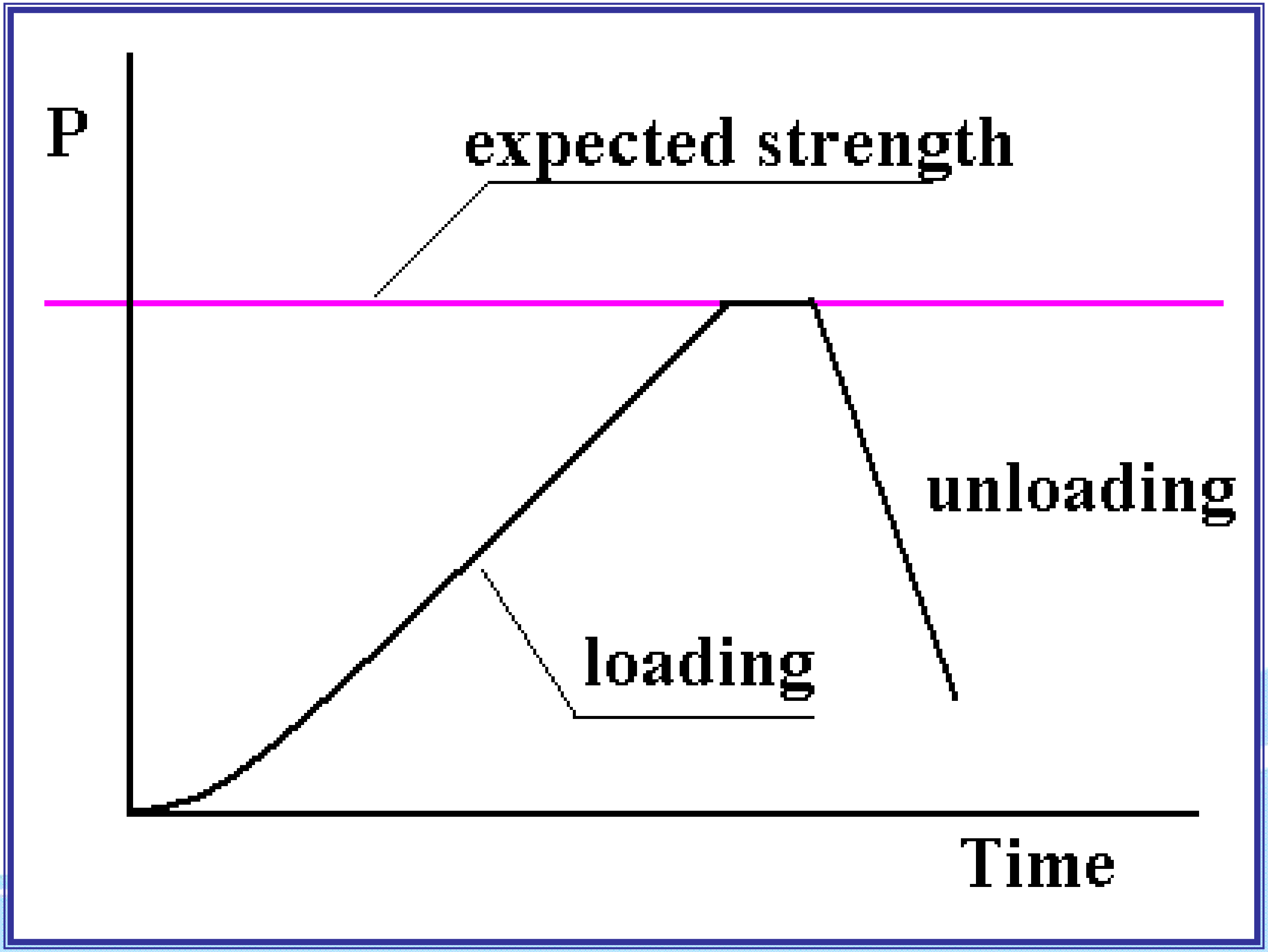
b) Indentation loading until a known value (make the maximum mean stress reaches to σ_o)

c) Check if or not a ring-crack occurs (by AE)

d) If cracked, the strength is unqualified

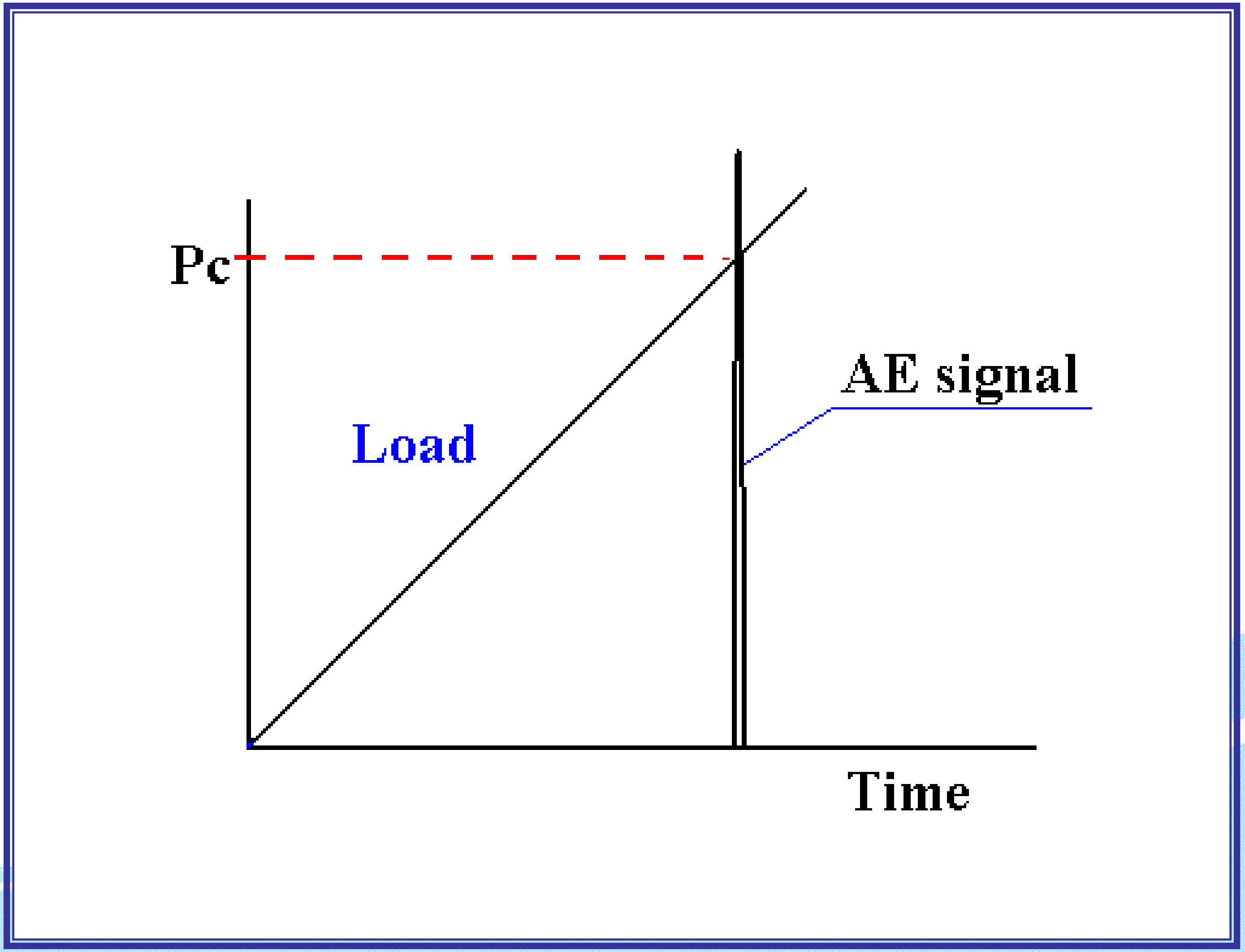
e) If no ring crack, the tempered glass is qualified.

Schematic of Proof test by using Hertzian indentation



Determining the critical load by acoustic emission

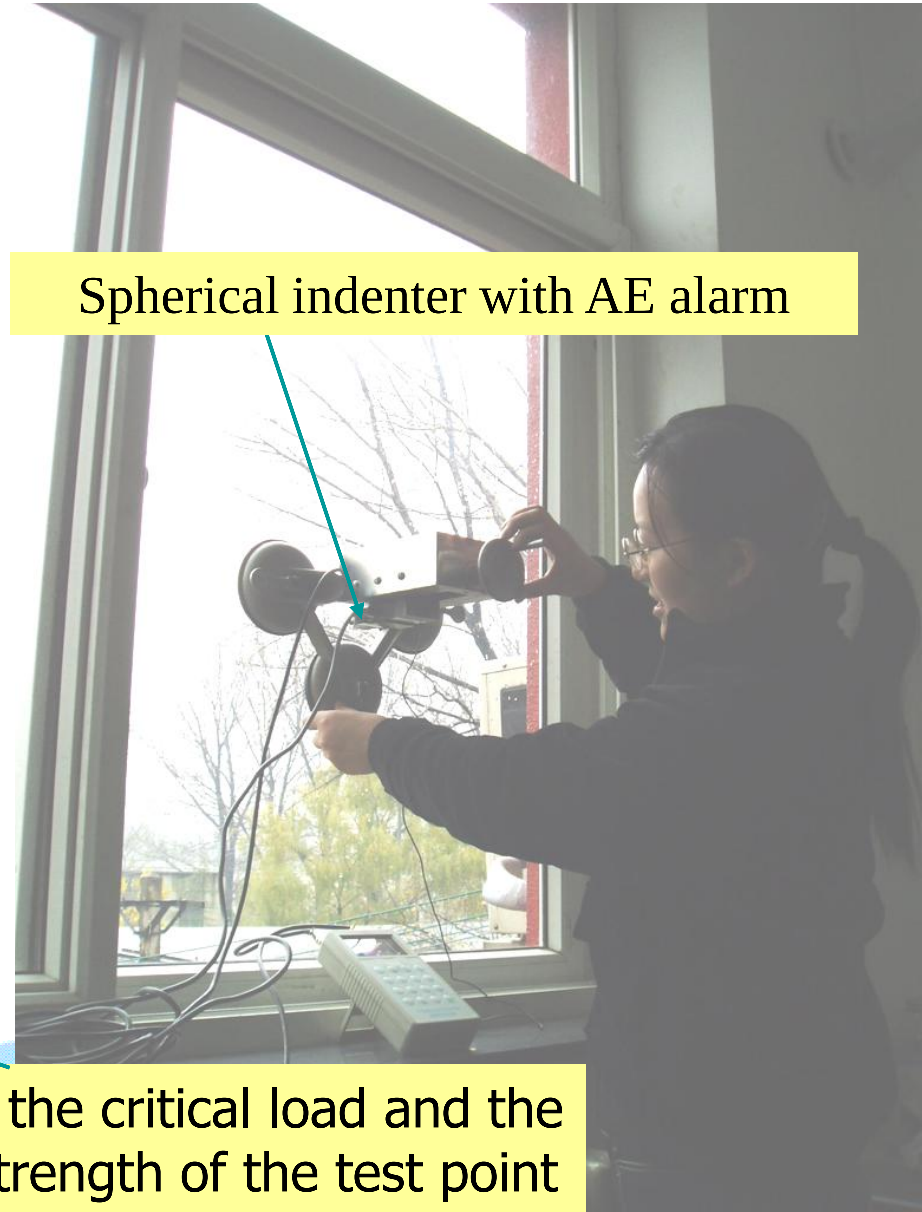
声发射确定临界载荷示意图



Results of the strength proof tests by Hertzian indentation for different requirements to chemically strengthened glasses

Required strength	**Fractured point**	**Passed rate**
200 MPa	**0**	**100%**
250 MPa	**0**	**100%**
300 MPa	**0**	**100%**
350 MPa	**3**	**84%**
370 MPa	**7**	**63%**
390 MPa	**11**	**42%**
400 MPa	**13**	**32%**
450 MPa	**15**	**21%**
500 MPa	**19**	**0%**
550 MPa	**19**	**0%**

In situ testing by using auto-fix tester



Measured local strength on tin side of float glass

局部强度

已知弹模，不测压痕 | 用测得压痕计算 | 弹模与布氏硬度

压球半径(mm) 5

压头参数

弹性模量(GPa) 320

泊松比 0.2

材料参数

弹性模量(GPa) 70

泊松比 0.22

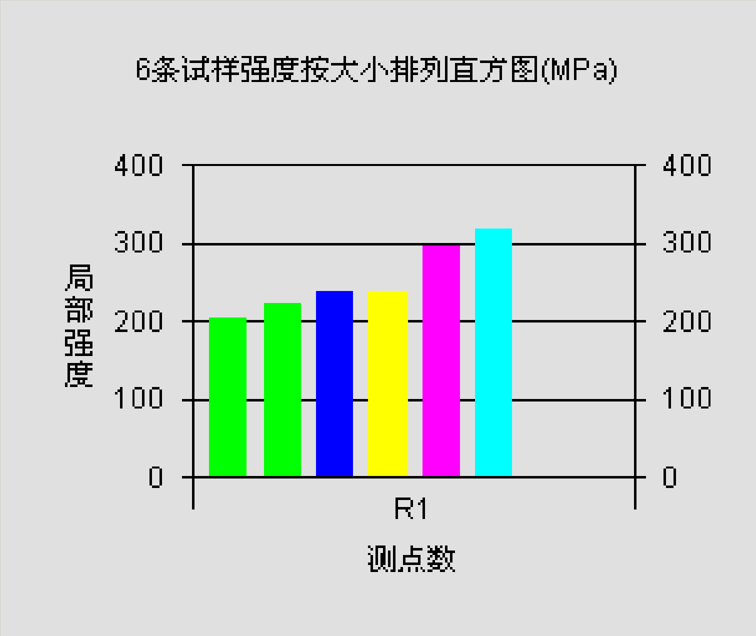
实验参数

实验点 7

临界荷载(Kg) 79

输 入

测试点	临界载荷(N)	压痕直径(mm)	强度(MPa)
1	902.52	.7659128	221.4836
2	1039.86	.8029441	238.9793
3	1020.24	.797862	236.5526
4	1765.8	.9579454	316.5021
5	1569.6	.9210643	297.4876
6	774.99	.7279906	204.0341



平均强度： 252.5065 MPa **Mean strength**

标准差： 44.4258 MPa

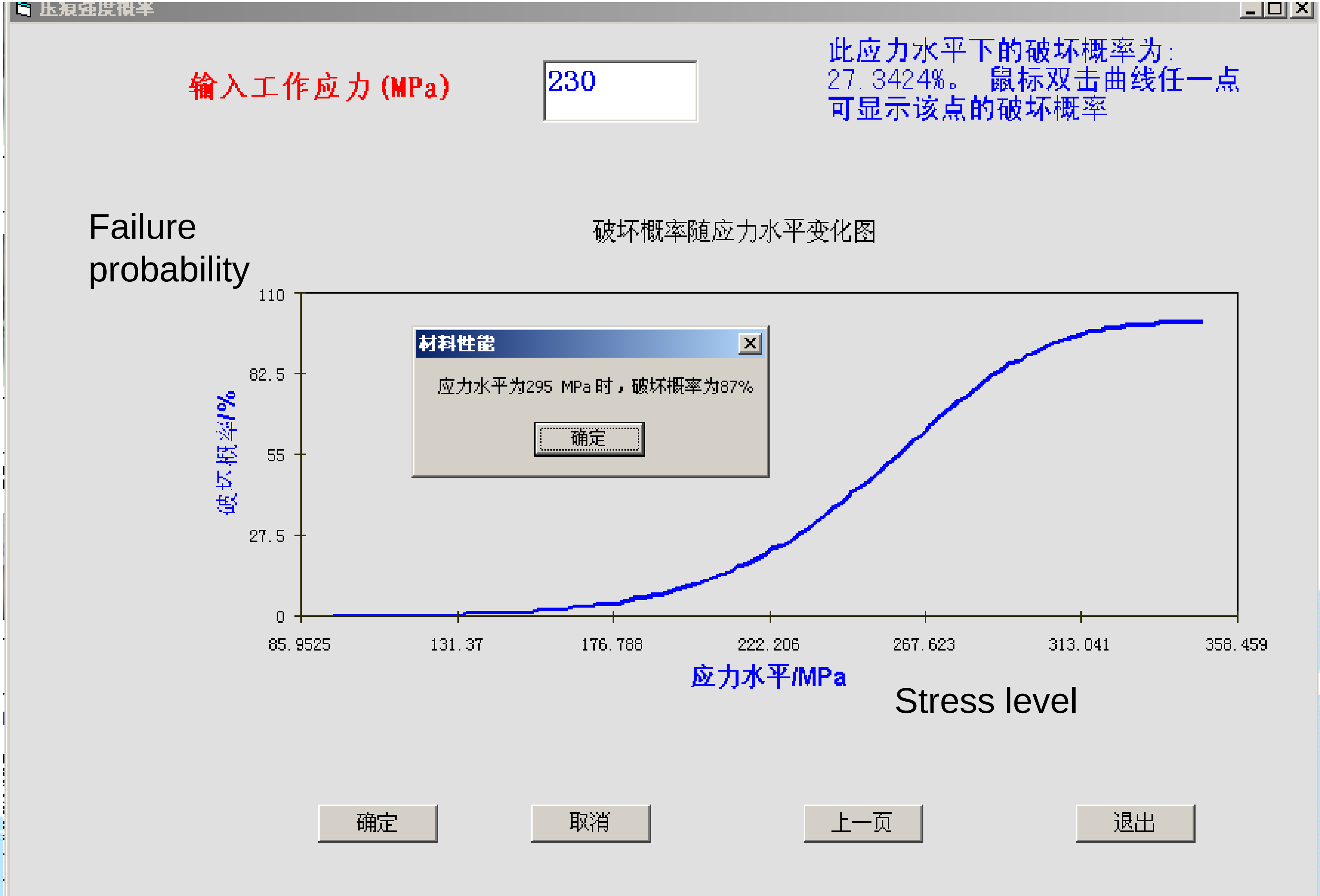
本征强度： 267.7437 MPa

Weibull 模数： 7.5108

材料类型 玻璃或细晶陶瓷

确 定 | 取 消 | 保 存 | 打 开 | 破坏概率 | 上一页

Prediction of failure probability at a given stress



Local strength measured on the tin side of strengthened glass

已知弹模，不测压痕 | 用测得压痕计算 | 弹模与布氏硬度

压球半径(mm) 5

压头参数

弹性模量(GPa) 320

泊松比 .2

材料参数

弹性模量(GPa) 70

泊松比 .22

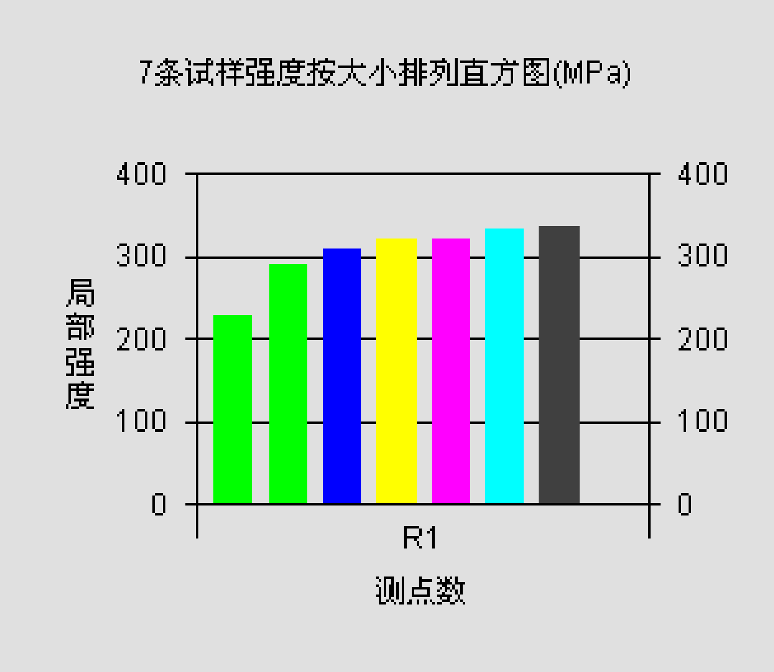
实验参数

实验点 1

临界荷载(Kg)

输 入

测试点	临界载荷(N)	压痕直径(mm)	强度(MPa)
1	1481.31	.90346	288.5282
2	1981.62	.9954827	336.1723
3	1952.19	.99053	333.5597
4	1814.85	.9667344	321.08
5	1687.32	.9435381	309.0359
6	1795.23	.9632381	319.2567
7	961.38	.7822136	229.1311



平均强度: 305.252MPa ← **Mean strength**

标准差: 37.1762MPa

本征强度= 320.6115MPa

Weibull 模数= 9.5858

材料类型 玻璃或细晶陶瓷

确 定 | 取 消 | 保 存 | 打 开 | 破坏概率 | 上一页

Local strength measured on air side of strengthened glass

局部强度

已知弹模，不测压痕 | 用测得压痕计算 | 弹模与布氏硬度

压球半径(mm) 5

压头参数

弹性模量(GPa) 320

泊松比 .2

材料参数

弹性模量(GPa) 70

泊松比 .22

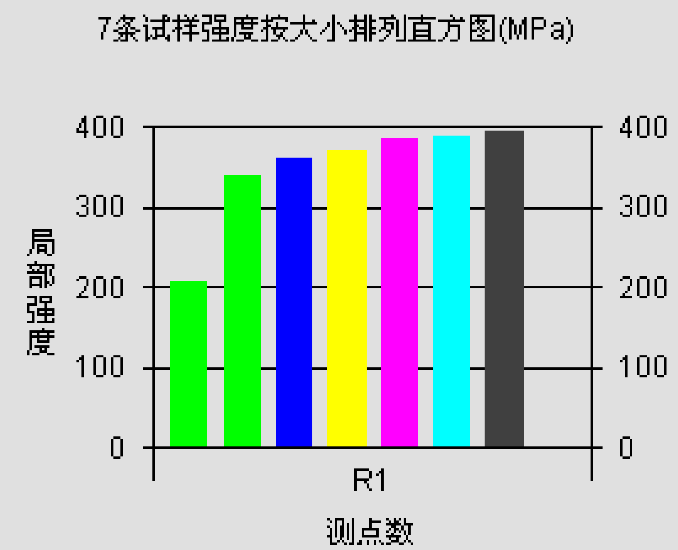
实验参数

实验点 1

临界荷载(Kg)

输 入

测试点	临界载荷(N)	压痕直径(mm)	强度(MPa)
1	2383.83	1.05873	369.9626
2	2001.24	.9987573	337.9026
3	2599.65	1.089762	386.805
4	2717.37	1.105969	395.6627
5	2570.22	1.085634	384.5556
6	2275.92	1.042508	361.2238
7	784.8	.7310494	205.4234



平均强度: 348.7908MPa ← **Mean value**

标准差: 66.0767MPa

本征强度= 374.4852MPa

Weibull 模数= 5.9228

确 定 | 取 消 | 保 存 | 打 开 | 破坏概率 | 上一页

A little higher than that of air face

for brittle materials

Weibull statistical fracture theory

$$P = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_o}\right)^m\right)$$

σ_o —— stress for failure probability 0.63

σ —— applied stress

P —— failure probability

m —— Weibull modulus

$$\sigma_0 = \bar{\sigma} / \Gamma(1 + 1/m)$$

$$m = 1.2785 \frac{\bar{\sigma}}{s_\sigma} - 0.621$$

Other requirement of glass design

- **Impact resistance（冲击阻力）**
  - Glass is brittle, so susceptible to impact breakage
  - Standard test, e.g BS EN 12600
  - Glass safety barrier
- **Post-breakage strength（破裂后强度）**
  - Robustness
  - Failure of glass shall not cause proportional failure of the whole structures;
  - Failure of glass shall not impose risk to the building user
  - Mechanism of providing the post-brakages strength

Design procedure for glass panels

① Select type of glass （玻璃种类）

② Establish design loads （设计载荷）

③ Rough sizing （尺寸和形状）

④ Structural analysis （结构分析）

⑤ Check safety and serviceability (检验安全和实用性)

⑥ Modify and recheck （修正并再检验）

⑦ Check post-breakage strength and impact resistance (usually by test)（后强度和冲击阻力）

Design strength of glass (I)

不同类型的玻璃板的强度估计

Glass type	Characteristic strength (MPa)	Standards
Annealed glass	45	BS EN 572
Thermally toughened safety glass; Heat soaked thermally toughened safety glass	120	BS EN12150
Heat strengthened glass	70	BS EN 1863
Chemically strengthened glass	150	BS EN 12337

Load bearing glass elements

Design methods

- Permissible stress design
- Design according to probability of fracture
- Limit state design

玻璃结构的三种设计思路

- **许用应力准则**
- **最小破坏概率原则**
- **极限状态准则**

1) Permissible stress design 许用应力

- A single safety factor is used
- May represent the reality inaccurately
- Relatively high safety factors are necessary (k>3)

使用一个安全系数

可能在反映安全性方面不够准确（因为玻璃强度的离散性）

需要用相对比较高的安全系数

2) Limit state design （极限状态）

- The limit states are the states beyond which the structure becomes unfit for its intended use.
- Two limit states are considered:
  – Ultimate limit state (ULS)（基于最终状态）
  – Serviceability limit state (SLS)（服役状态）

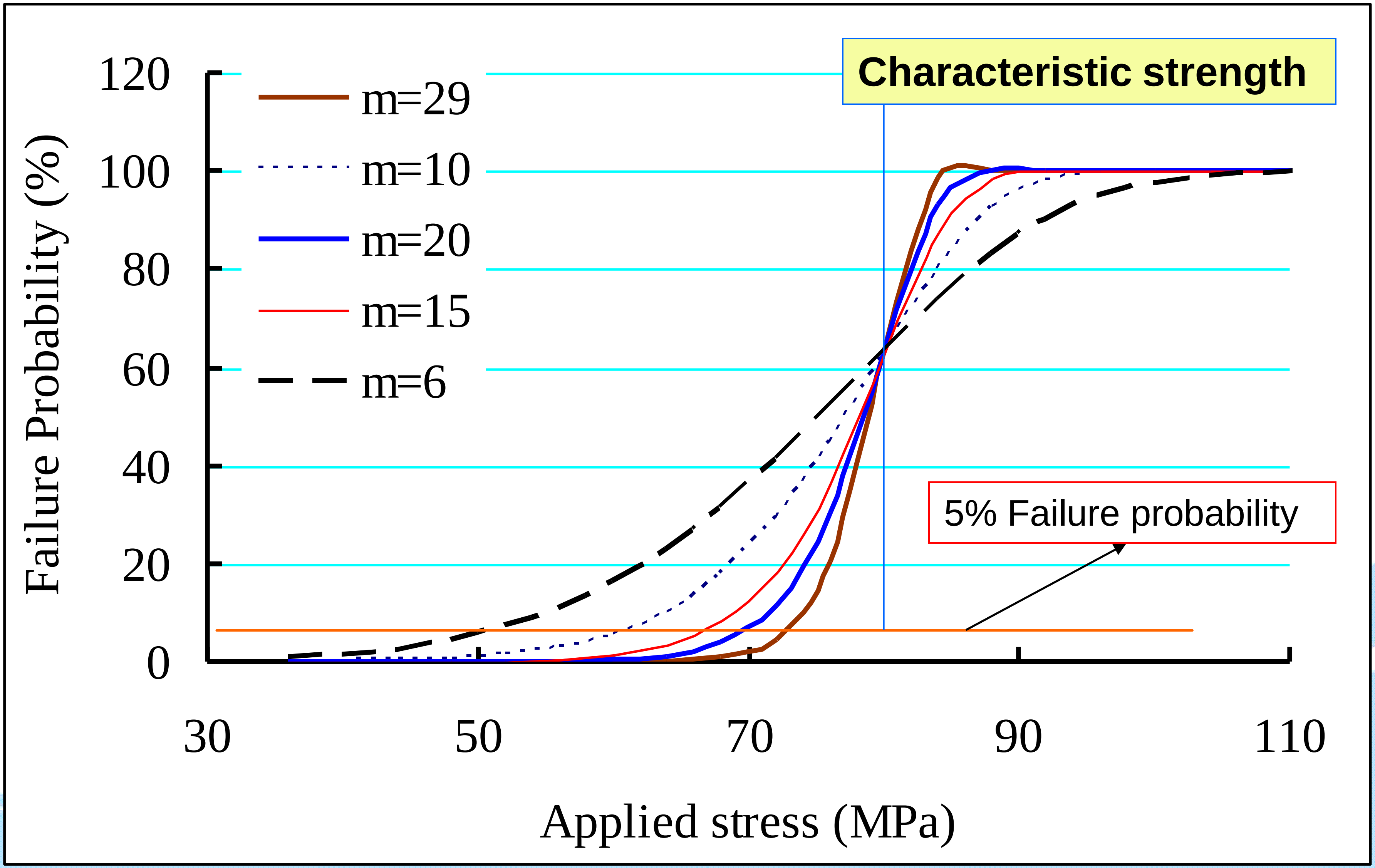
准则：变形或载荷不能超过某一种极限状态

3) Design according to probability of fracture 破坏概率准则

- Based on fracture mechanics and statistical theory
- Load duration, size effect
- More accurate than the permissible stress design but complicated

准则：发生破坏的概率不超过某一个微小值

Design based on Weibull statistical method



Conclusions

- Glass strength depends on surface defect size
- ----Approaches for Improving the strength: residual compressive stress; less defects.
- Robustness related to: strength, post-breakage strength, damage tolerance, durability.
- Spontaneous breakage of tempered stress is due to various impurities and defects in the glass.
- Nondestructive test for strength and proof test can be performed via spherical indentation
- Safe design of glass structures involve three design mode: Permissible stress design， Failure probability， Limit state

Thank you for your attention