- 5 cours Michel Andrieux
- 5 cours Vincent Ji

  (03/02 à 13h30, 07/02 à 10h30, 10/02 à 13h30, 14/02 à 10h30, 17/02 à 13h30)

Contrôle en écrit le 22/02 14h

+

Oral mécanique le 21/02 à 8h30

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Residual stresses analysis:

1) RS generation dues to process
2) RS influence on properties
3) RS determination and relaxation
4) Surface mechanical traitments
5) Industrial applications

Residual stresses analysis:
Generation, influence (1)

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outline

- Bibliographic References
- Residual Stress: definition, 3 orders of RS
- RS origins
- RS and materials process (plastic deformation, rolling, heat treatment, welding, surface treatment and surface coating, machining)

Residual Stress

- References:

1) Residual Stress Measurement by Diffraction and Interpretation, Noyan, I. C., Cohen, J.B. Springer Verlag (1987)
2) Handbook of measurement of residual stresses, ed J. Lu, SEM Inc. The Fairmont Press (1996)
3) Handbook of Residual Stress and Deformation of Steel, eds G. Totten, M. Howes and T. Inoue, ASM Inter., Materials Park, (2002)

Residual Stress

Definition:

Residual stresses or locked-in stresses can be defined as those stresses existing within a body in the absence of external loading or thermal gradients.

In other words residual stresses in a structural material or component are those stresses which exsist in the object without the application of any service or other external loads.

Residual Stress

Role of residual stresses

<u>Residual stresses</u> have the same role in a structure's strength as common mechanical stresses.

<u>Residual stresses</u> can play a significant role in explaining or preventing failure of a component at times.

<u>Tensile residual</u> stresses may reduce the performance or cause failure of manufactured products.

<u>Compressive residual</u> stresses are beneficial. It must be kept in mind that the internal stresses are balanced in a component.

Tensile residual stresses are counter balanced by compressive residual stresses. Residual stresses are three-dimensional.

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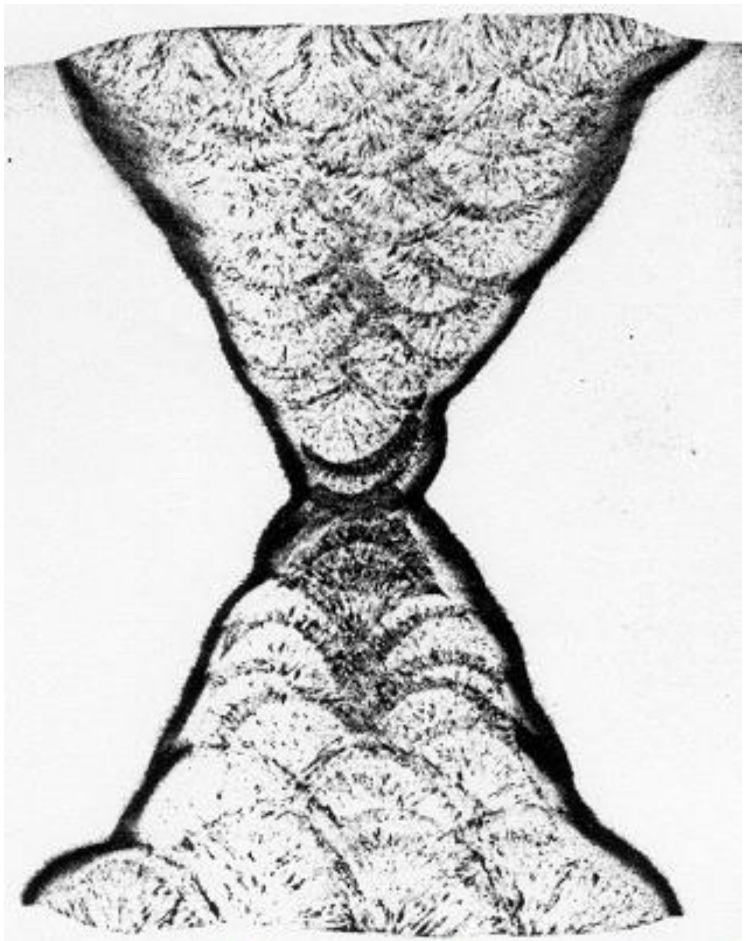
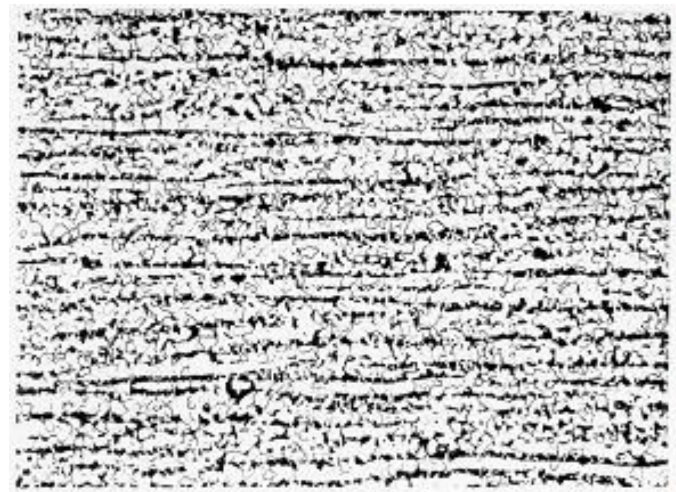
Multiscale material study (1)



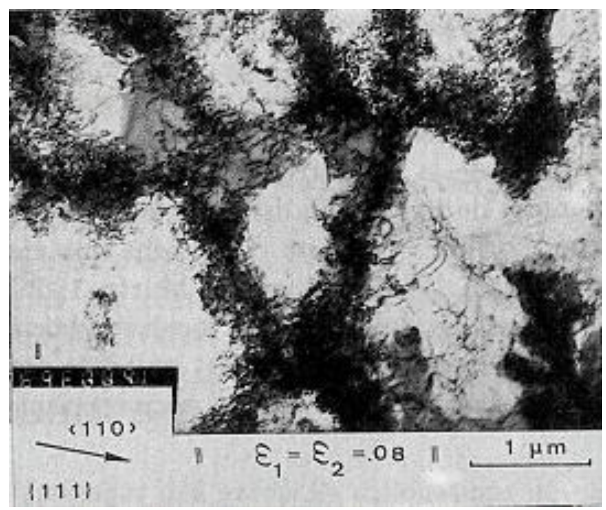
X sharp multi-pass welding joint

1 cm



Carbon steel, structure in strip

2.5 mm



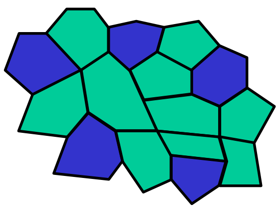
Dislocations cells

1 µm

Multiscale material study (2)

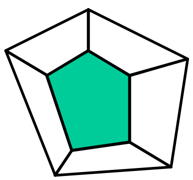
Macroscopic scale (≈ cm)
Mechanical scale

- chemical composition
- massive/surface
- fabrication process



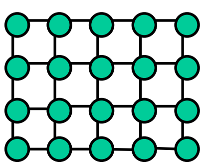
Phases (≈ few tens µm)
Metallurgy scale

- chemical composition
- proportion
- crystalline structure
- interphase joint



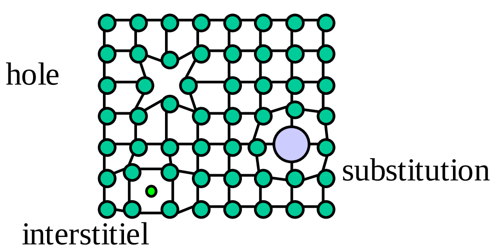
Grain (few µm)
Crystallographic scale

- size
- morphology
- orientation
- grain boundry



Coherent domaine (few nm)
Diffraction scale

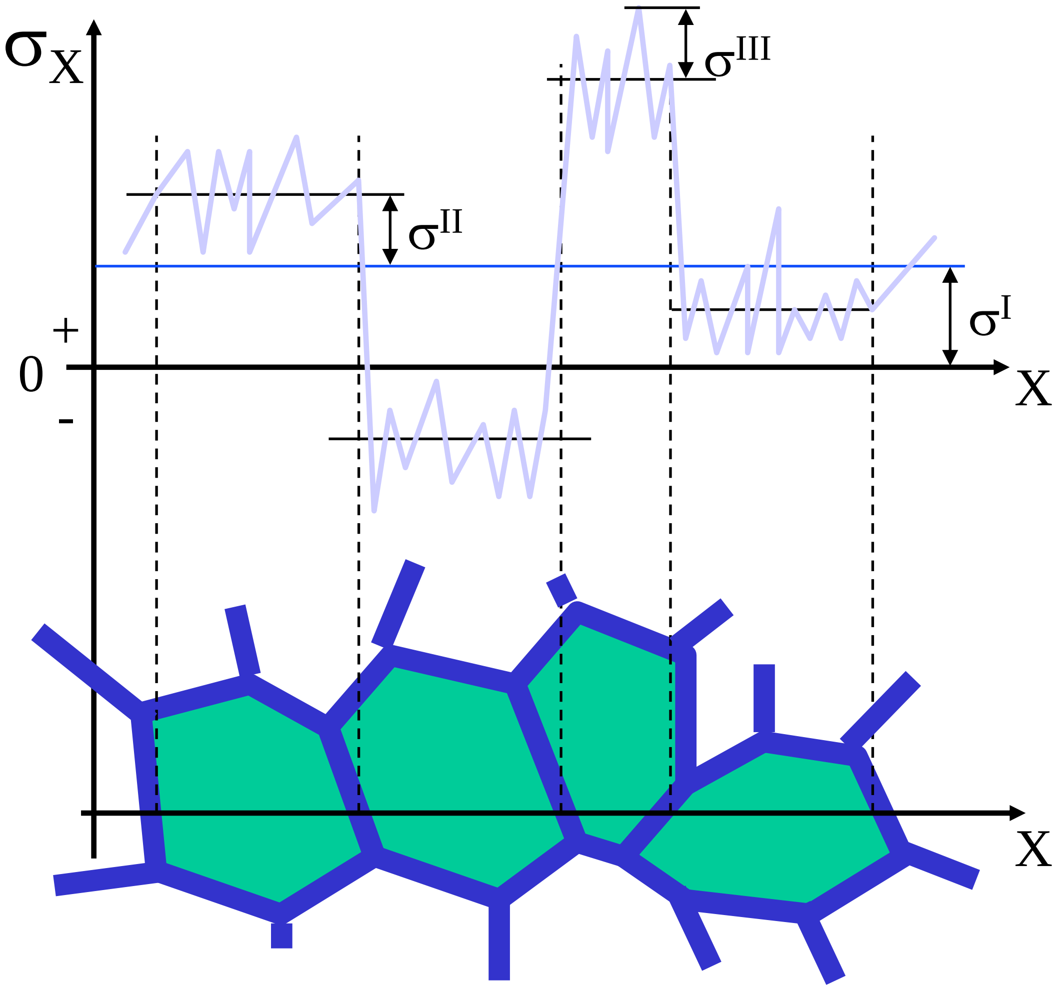
- size
- distorsion
- dislocations



Crystalline lattice (few Å)
TEM scale

- crystalline planes
- point defects

Multiscale material study (3)



Ordre I (σ^I)

Average stress in observed zone

Ordre II (σ^{II})

Average stress in a grain or in a phase

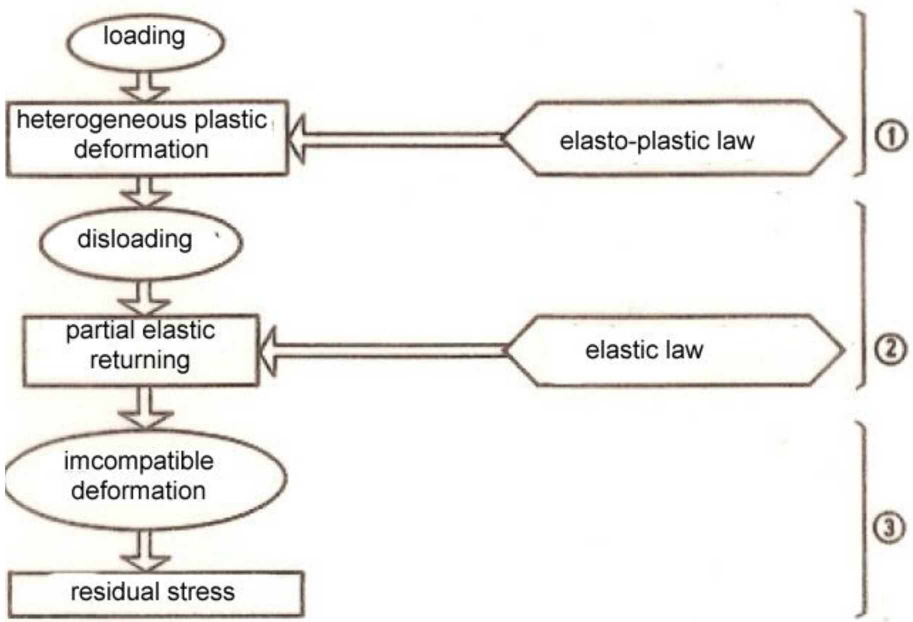
Ordre III (σ^{III})

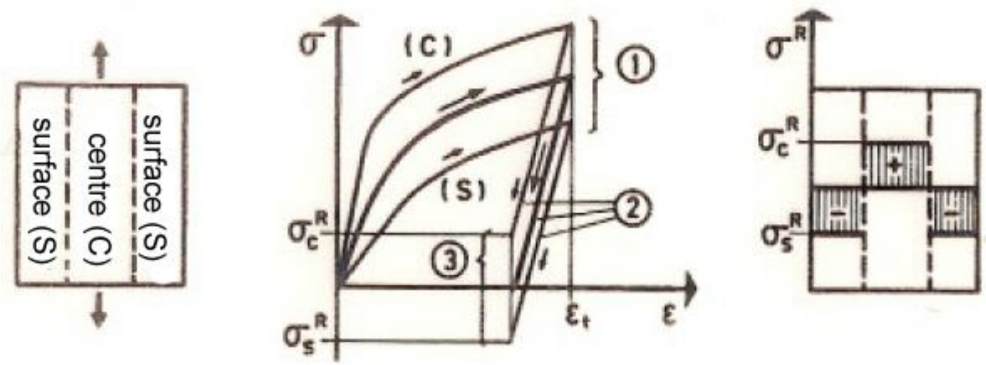
stress in a grain

σ_R origin

- Mechanical
- Thermal
- Chemical (microstructural)

Material forming – plastic deformation (1)

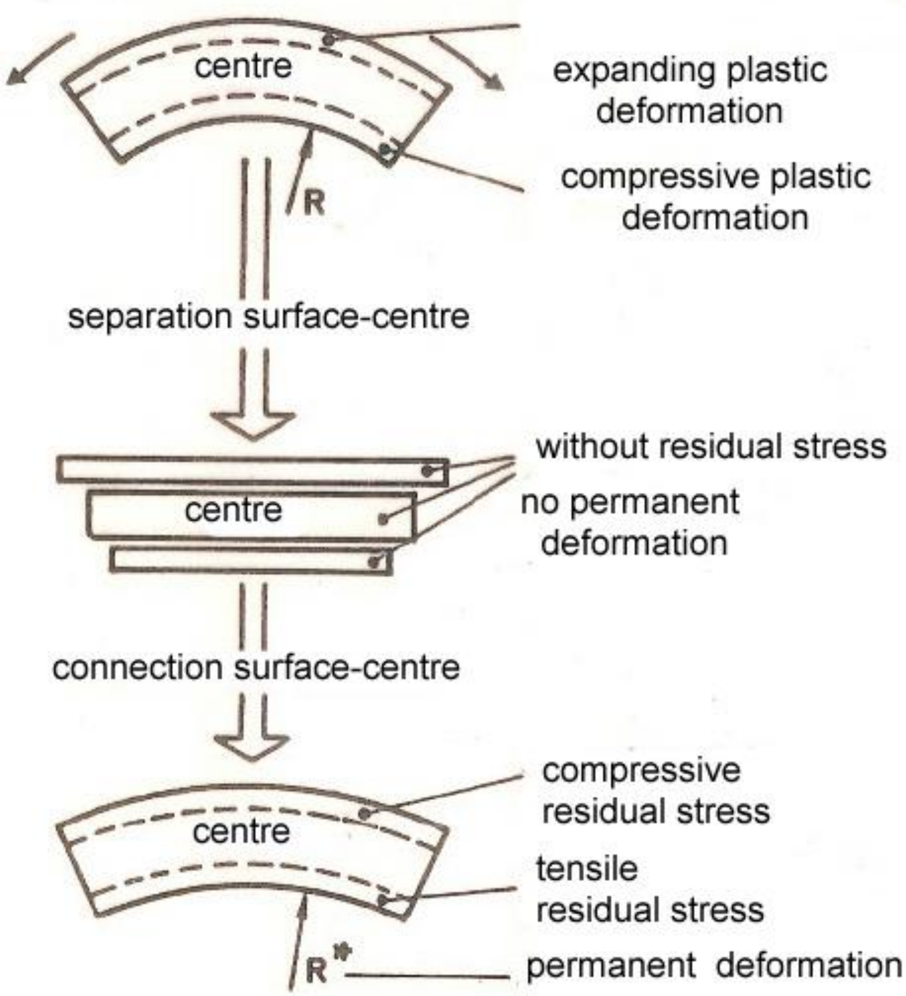




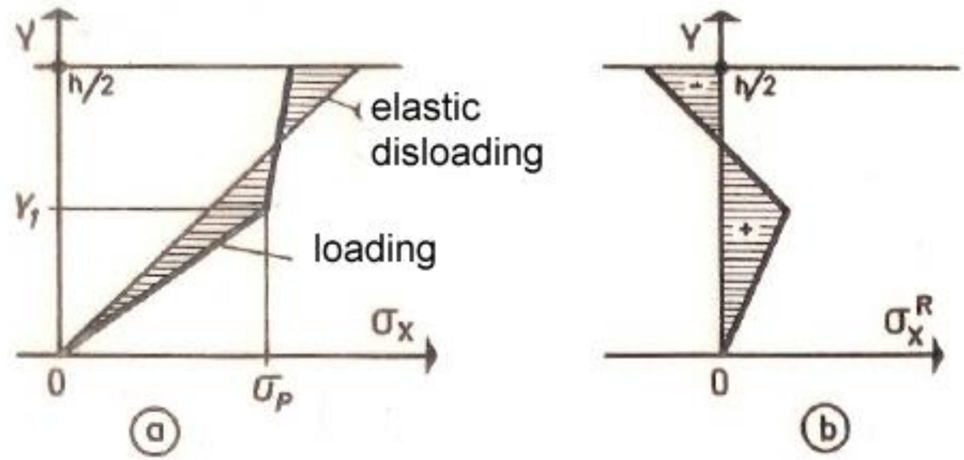
Case of tensile test for a surface treated specimen

Residual stress introduction by plastic deformation

Material forming – plastic deformation (2)

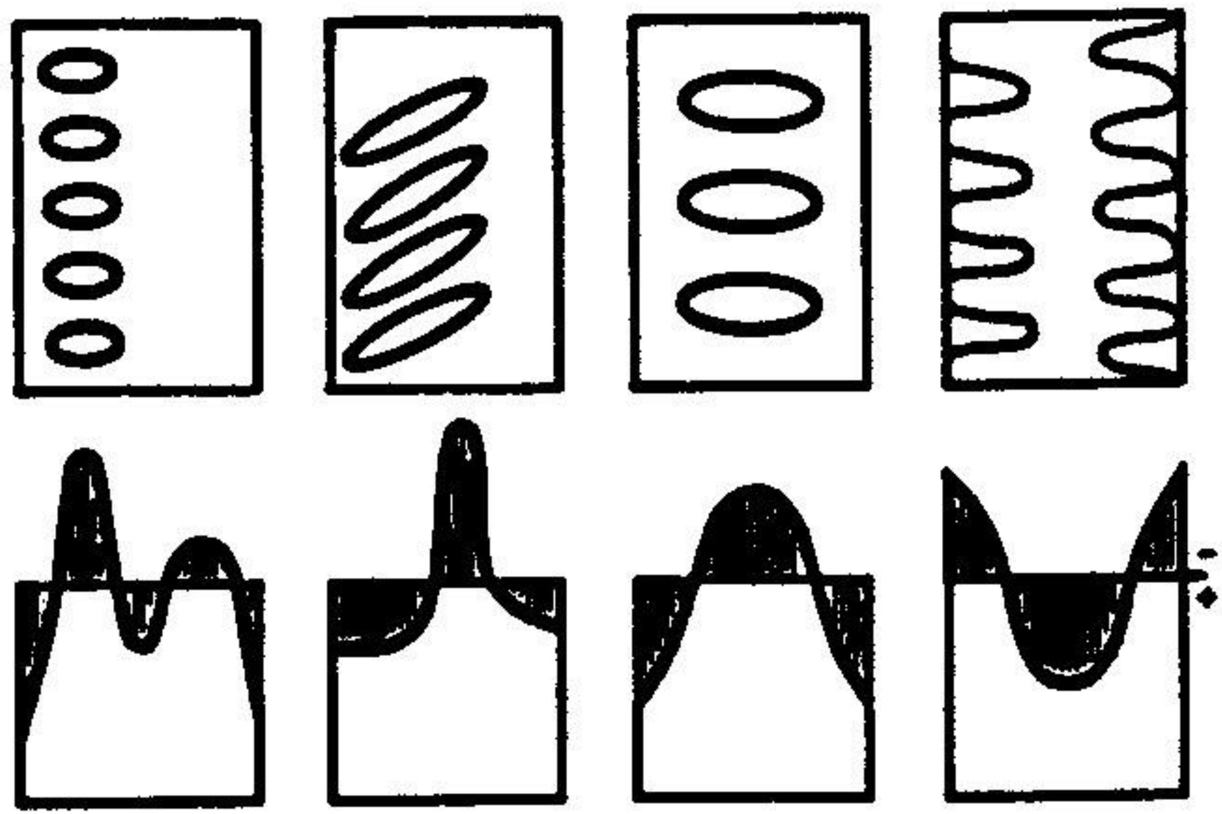


Residual stress generation in case of material forming by plastic bending



Stress profile in section in case of elasto-plastic bending
(a) Applied stress
(b) Residual stress

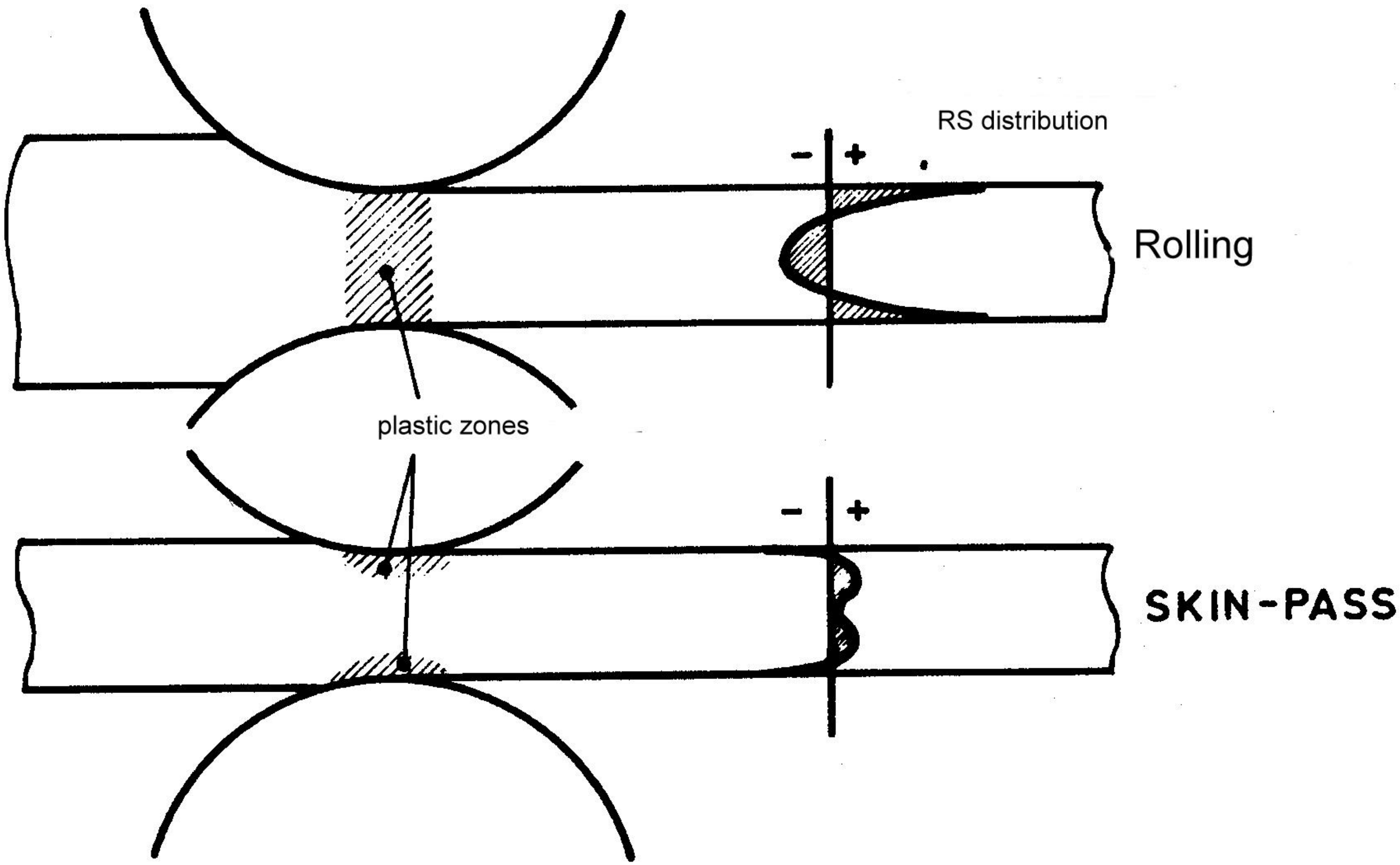
Material forming – rolling (1)



<u>Example:</u> rolling

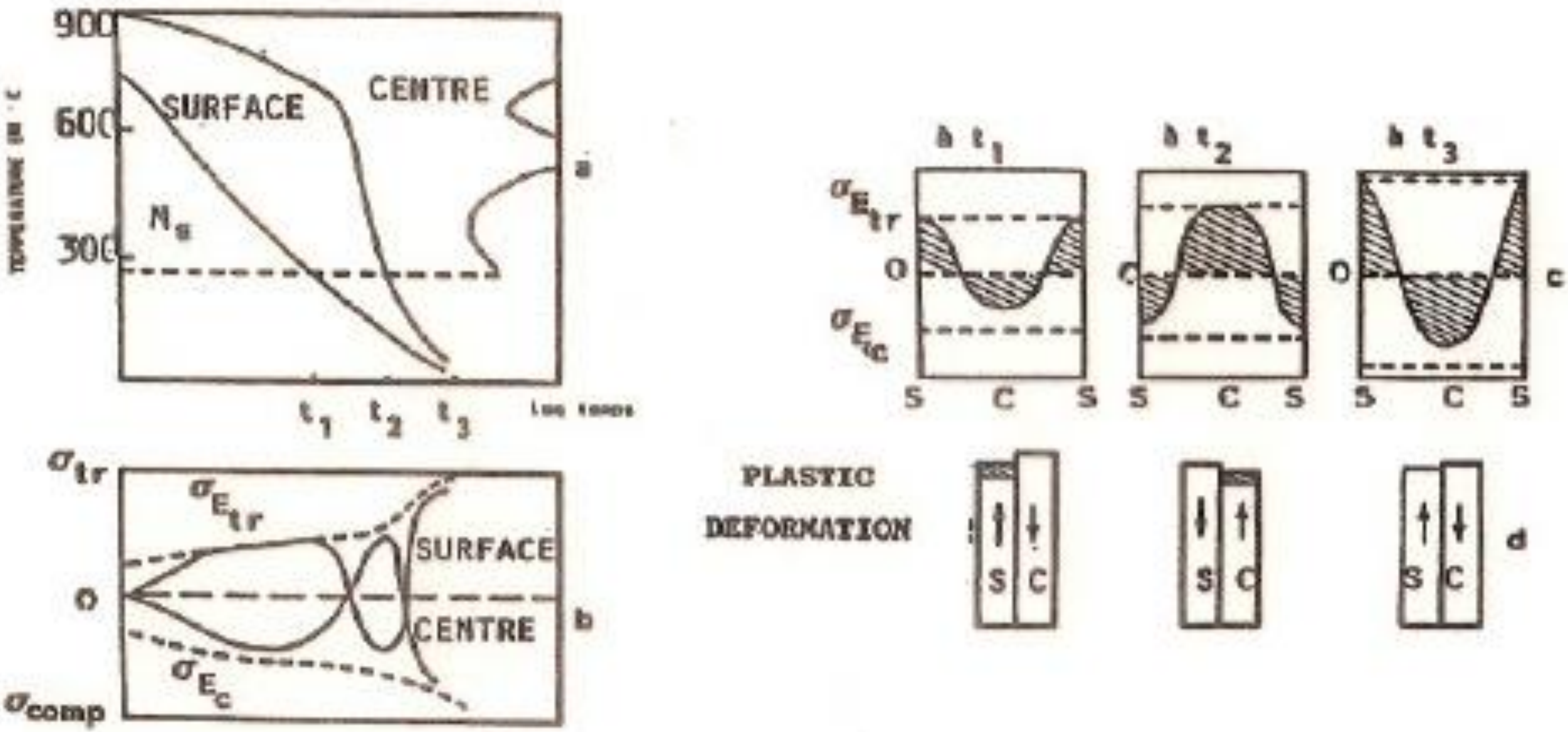
Residual stress distribution and associated geometrical modification (blisters, edge longs, bucklings ...)

Material forming – rolling (2)



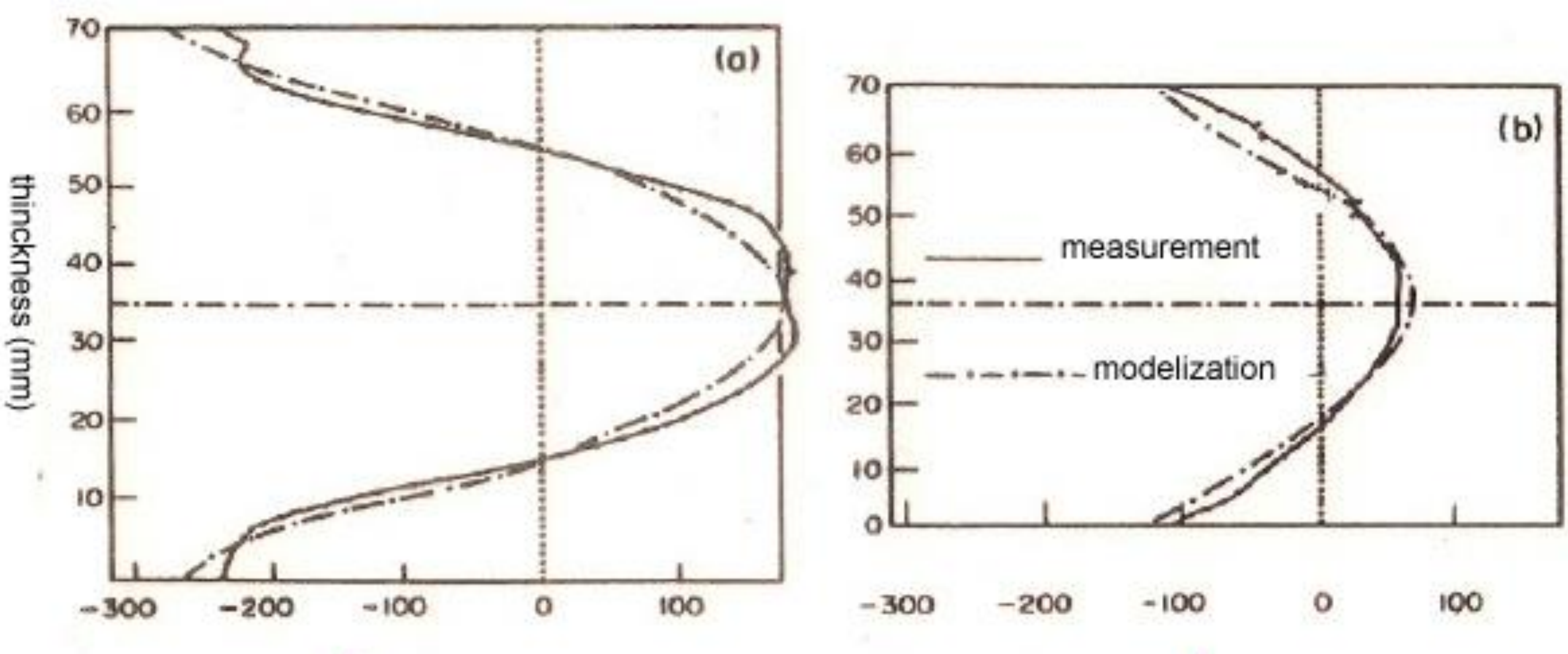
Residual stress gradient in depth of rolled sheet

Heat treatment (quench 1)



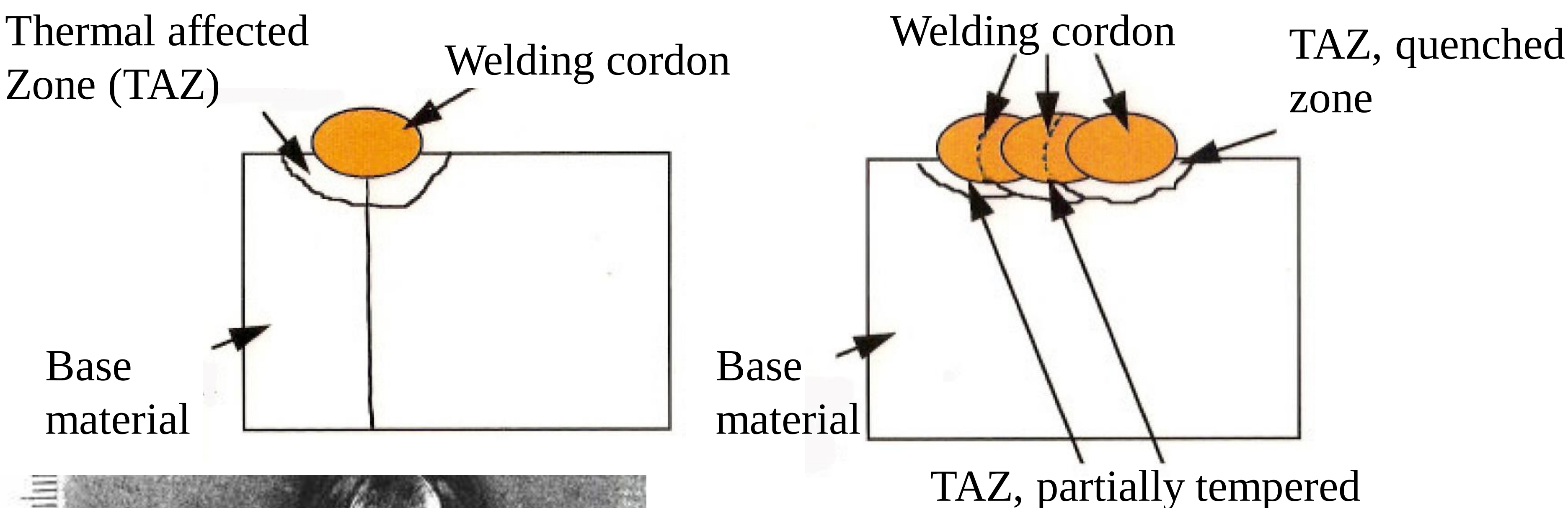
stress profile (in long direction σ_L and in transverse direction σ_T)
after quench in cold water for Aluminium alloy 7075 – thickness of sheet: 70 mm

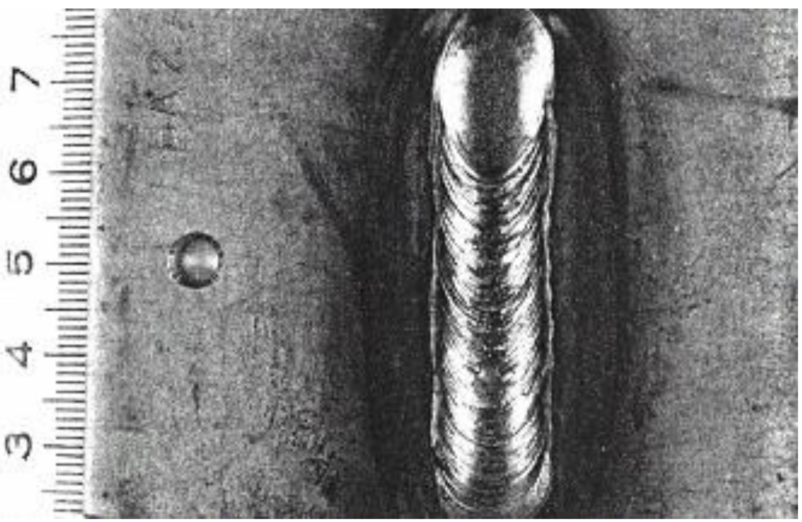
Heat treatment (quench 2)



Residual stress distribution for quench specimen with phase change (a) high speed (b) low speed

Welding (1)

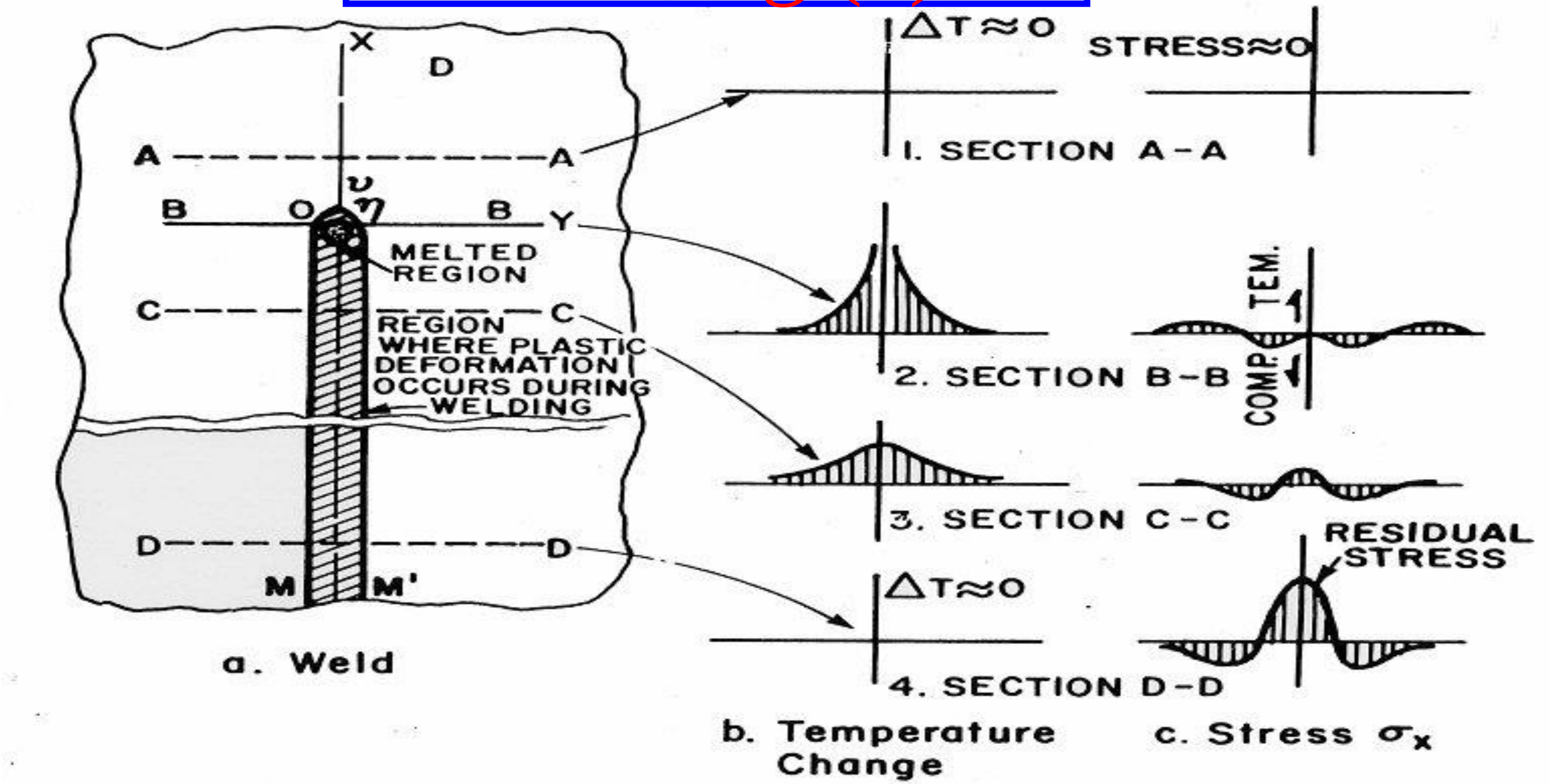




Residual stress:
Residual strain
Structure heterogeneities
Crack apparition de risk…

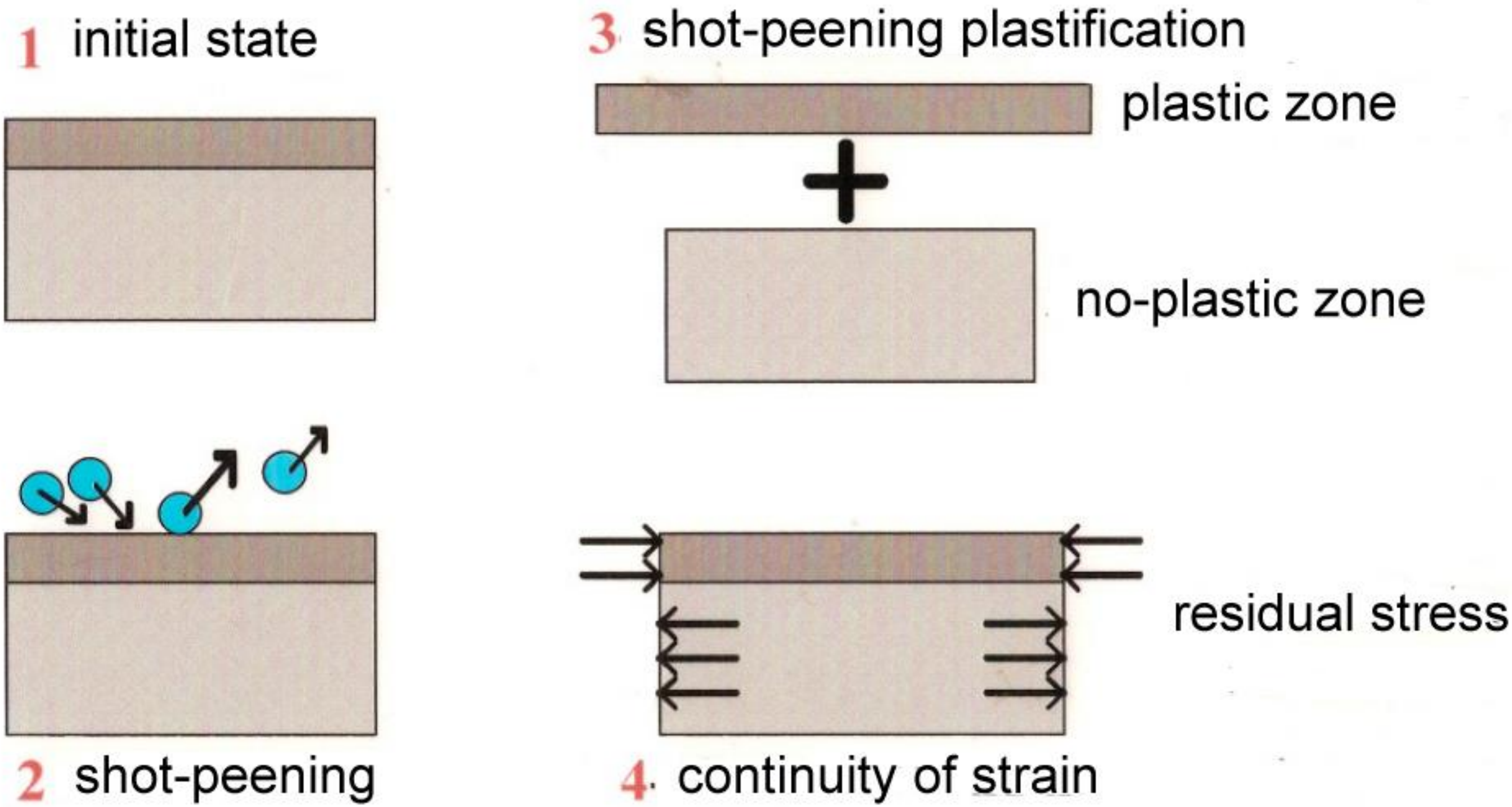
Welding cordon (austenitic steel)

Welding (2)



Schematic representation of residual stress generation during welding without phase change

Surface treatment



Case of shot-peening

Coatings (1)

-Utilisation under extreme loading conditons (corrossive atmosphrres, vaccum, high temperature…)
-High hardness (TiN, TiC, TiCN)
-Aims:
- increasing corrosion resistance,
- decreasing wear dommage
- modification of tribological properties for tools and mechanical

Techniques for coatings elaboration :

- CVD
  high T° C (600° C to 1050° C) and corrosive atmosphere
- PVD
  Evaporation under vacuum / Cathodique Pulverisation / Ionique deposition
  relatively low T° C (100° C to 500° C)
- Thermal Projection (at high temperature, plasma)
- Electrolytic deposition

Coatings (2)

CVD coating

-thermal origin of RS
-(difference of thermal dilatation coefficient between Substrat and coating)
- RS level and nature depend on substrat (hard metal or steel)

PVD coating

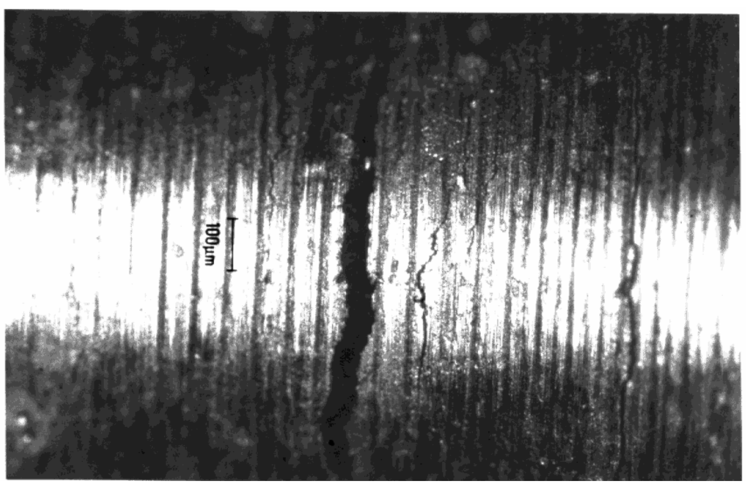
- origin of RS is thermal and microstructural (defects of growth)
- RS are generally in compression

Machining (1)

Processing of material remove induce:

- great plastic deformations on surface layer
- generation of heats
- metallurgical transformations

➔ Source of residual stress apparition
➔ Influence on utilisation properties of components (fatigue, stress corrosion cracking, fissuration …)

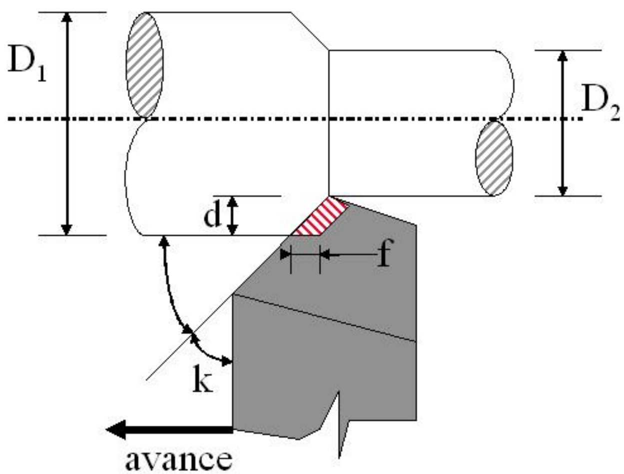


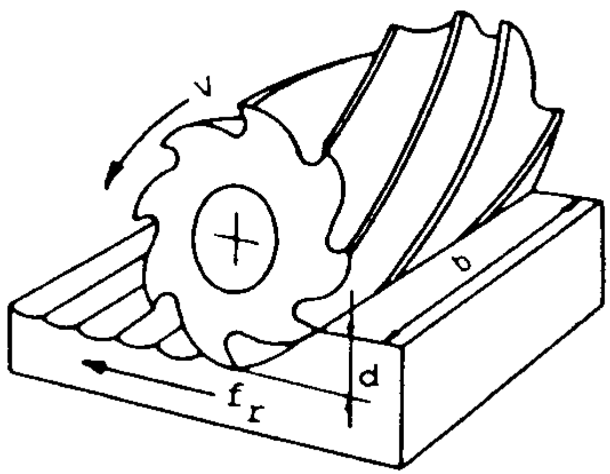
crack on specimen surface prepared by turning on 316L steel

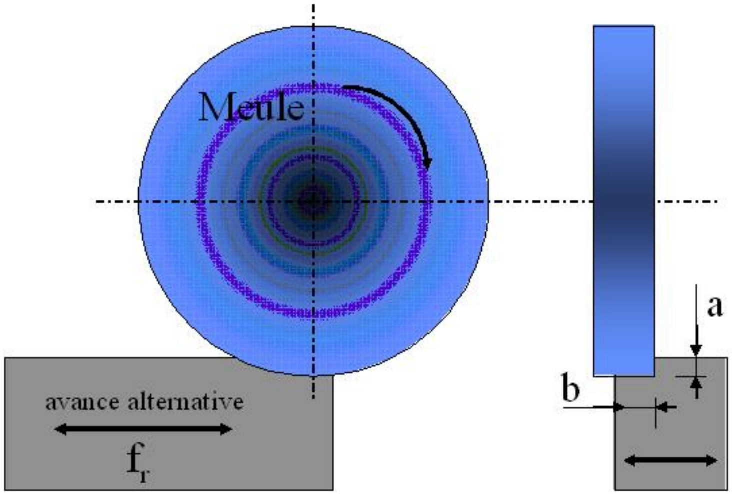
Machining (2)

Main maching processing

Turning | Milling | Grinding







Machining (grinding 1)

generation mechanism of RS in case of grinding

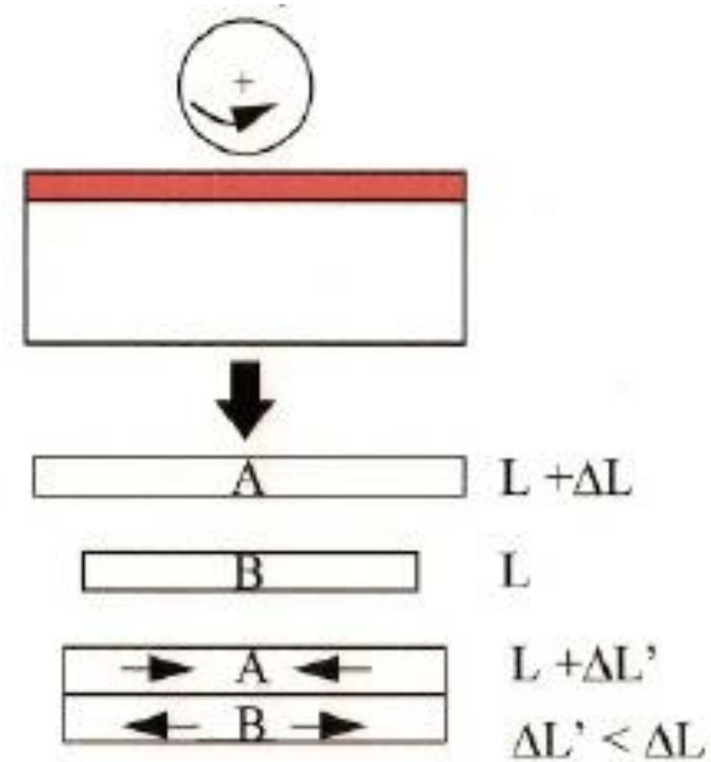
Simultaneous 3 actions :

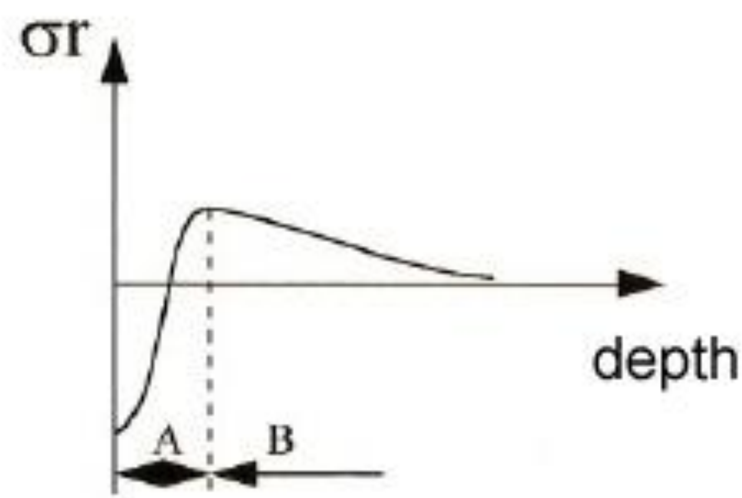
1) Heterogeneous plastic deformation in surface layer due to cutting force

2) Thermal dilatation of surface layer engendered by surface heating due to the friction bewteen tool/ piece and the associated thermal gradient

3) Volume change because of metallurgical transformations (phase change)

Machining (grinding 2)

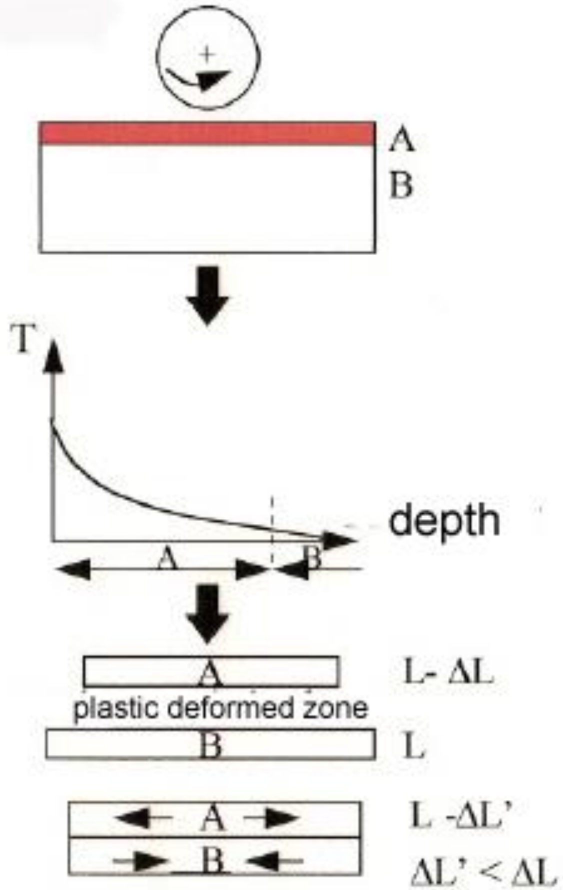


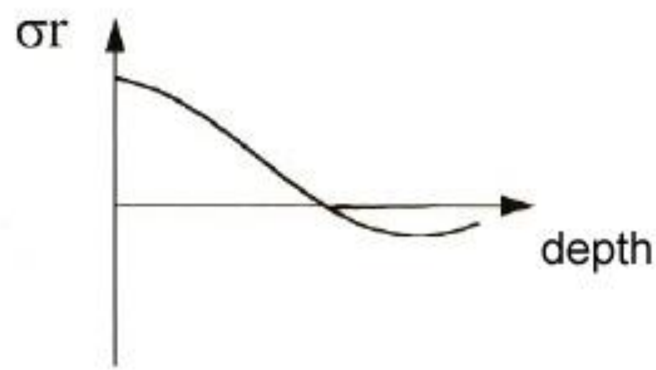


A: plastically deformed layer
B: base material

1) Residual stress gererated by plastic plastique without thermal grdient

Machining (grinding 3)



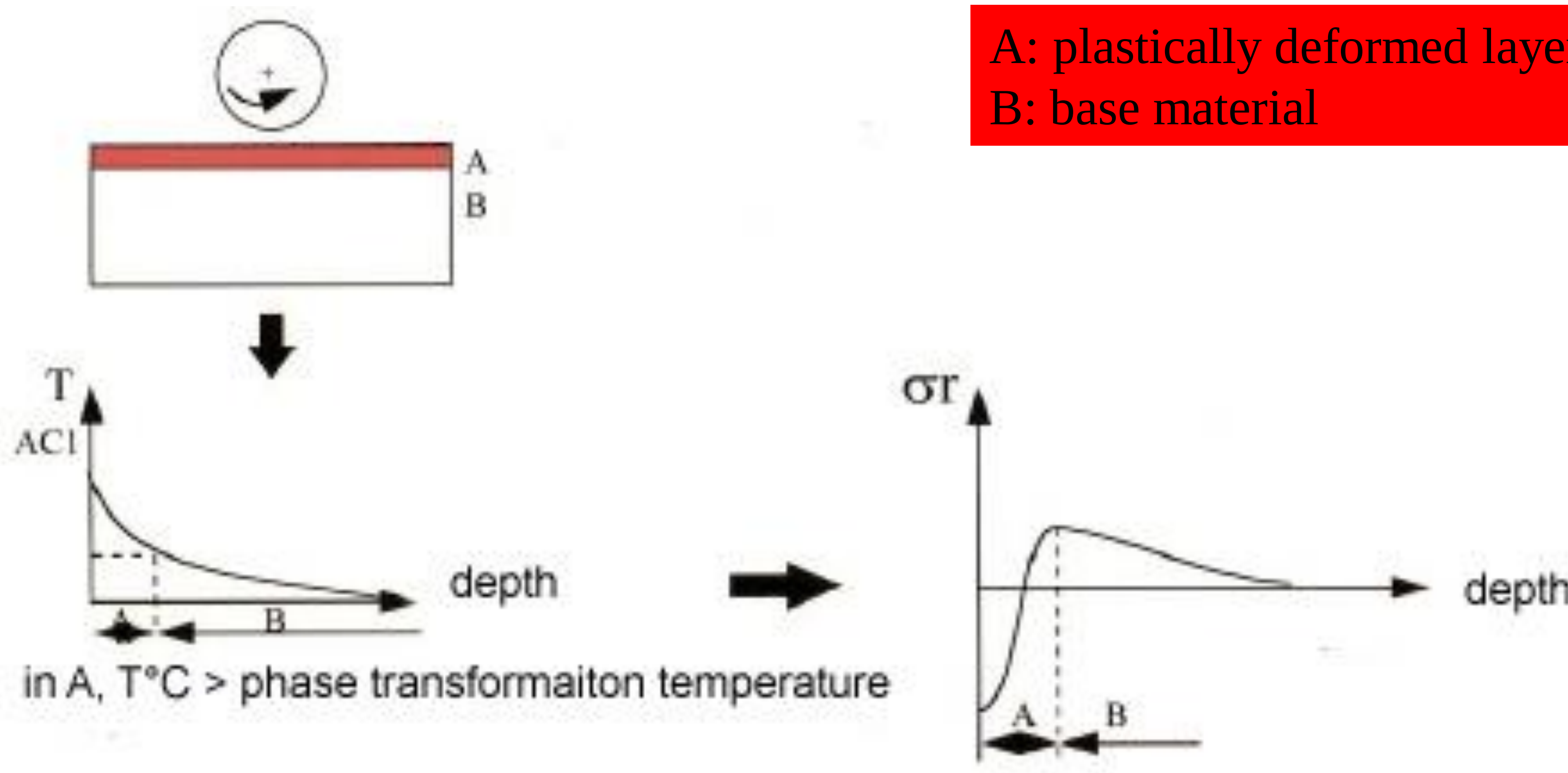


A: plastically deformed layer
B: base material

2) Residual stress gererated by exceeding of elastic limit of material because of presence of a thermal gradient

Machining (grinding 4)

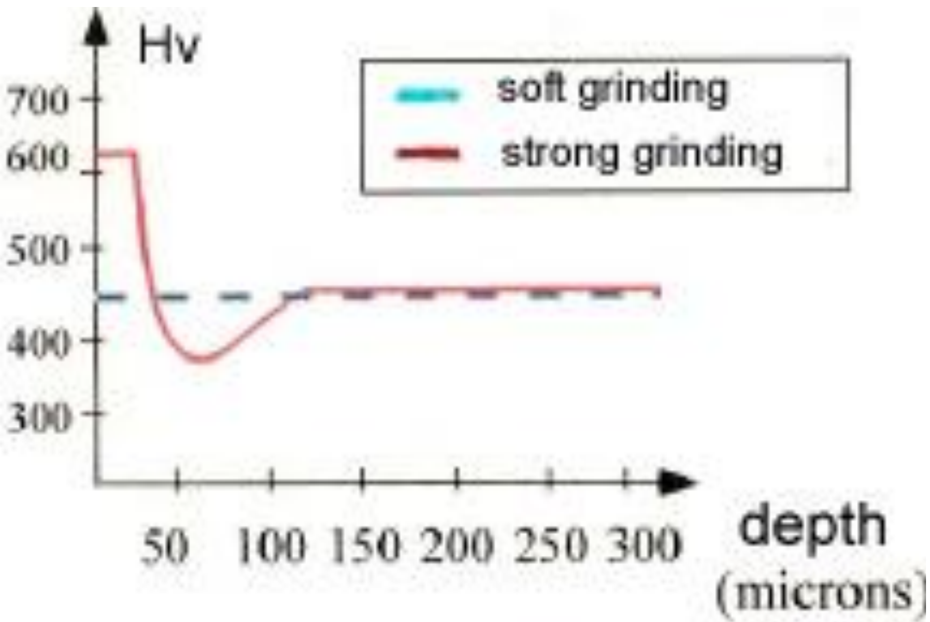
A: plastically deformed layer
B: base material

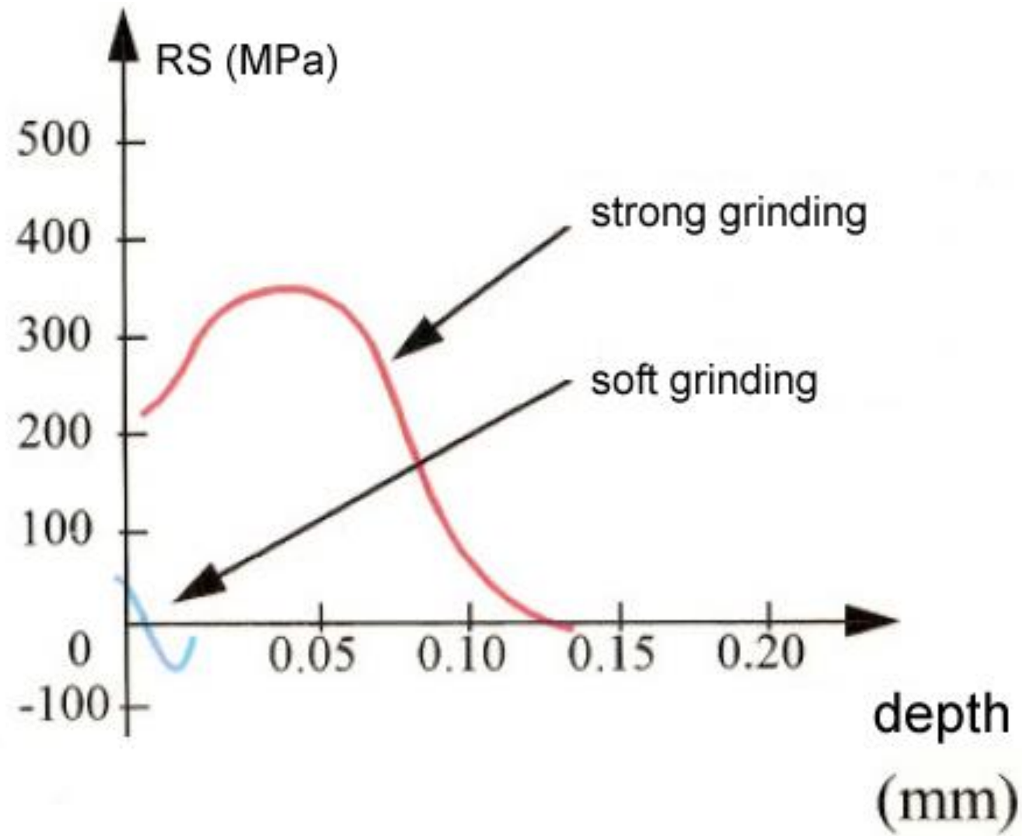


3) Residual stress generated by volume change after a metallurgical change

Machining (grinding 5)

Vickers hardness (under 100g)





Study example: Influence of grinding conditions on residual stress distribution on a steel 42CD4

process	mechanical	thermal	metallurgical
Cold rolling	+++		
Hot rolling	+++	+++	
Forging	+++	+++	
Wire drawing	+++		
Quenching	+++	+++	+++
Welding	+++	+++	+++
Coating CVD-PVD	++	+++	++
Shot-peening	+++		++
Machining	+++	+++	++
Press-forming	+++	++	
Additive fabrication	++	+++	++

Residual stress generation for different process

Residual stresses analysis: generation, influence (2)

outline

Influences of residual stresses on materials properties

- Physical properties
- Geometrical deformation
- Static mechcanical properties
- Contact and erosion
- Stress corrosion cracking
- Fatigue properties
- Cracking characteristics
- Microstructure modification

σ_R & utilistion properties

Residual stresses

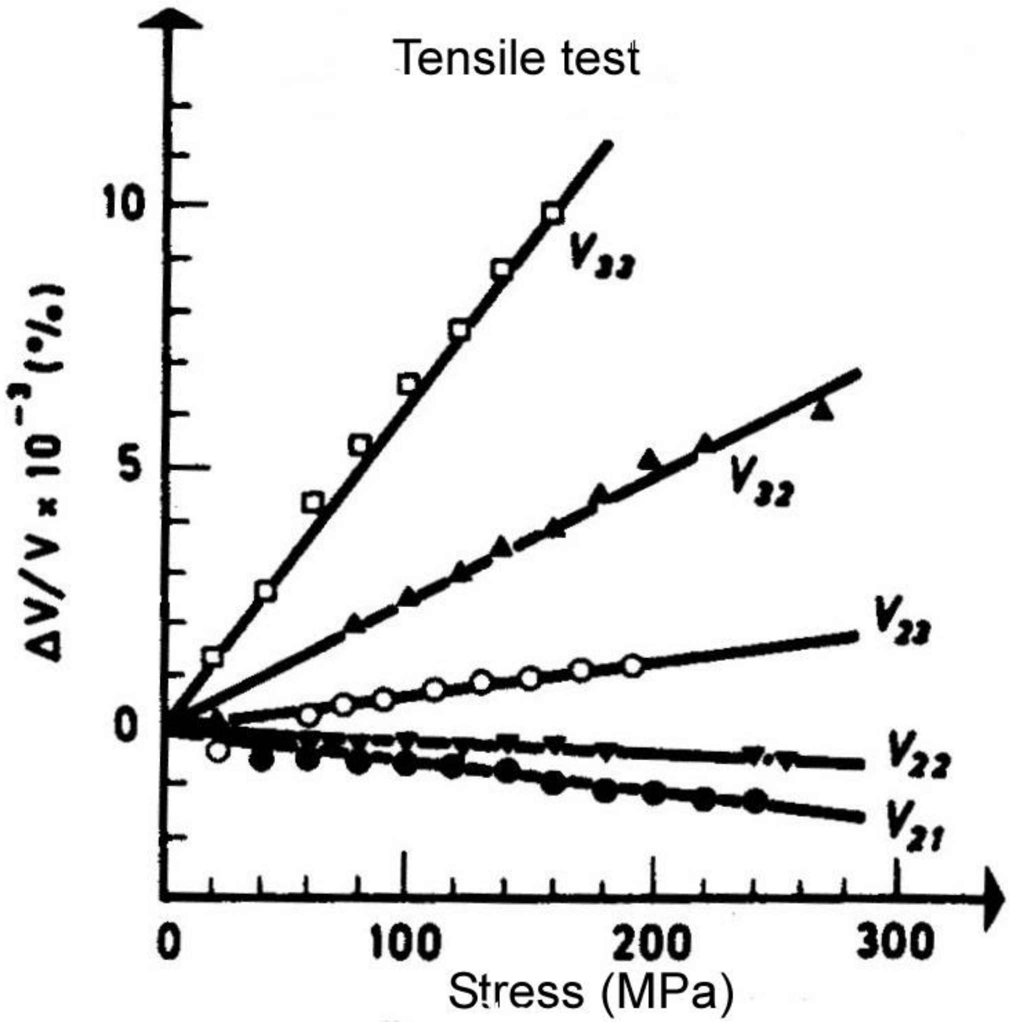
- Contact Erosion
- Corrosion and cracking
- Physical Properties
- Micro-structure
- Fatigue
- Dynamique Resistance
- Statique Resistance
- Geometrical Deformation

Physical Properties (1)

<u>Acoustical effect :</u>

speed of ultrasonic wave propagation V varies in function of stress level in material

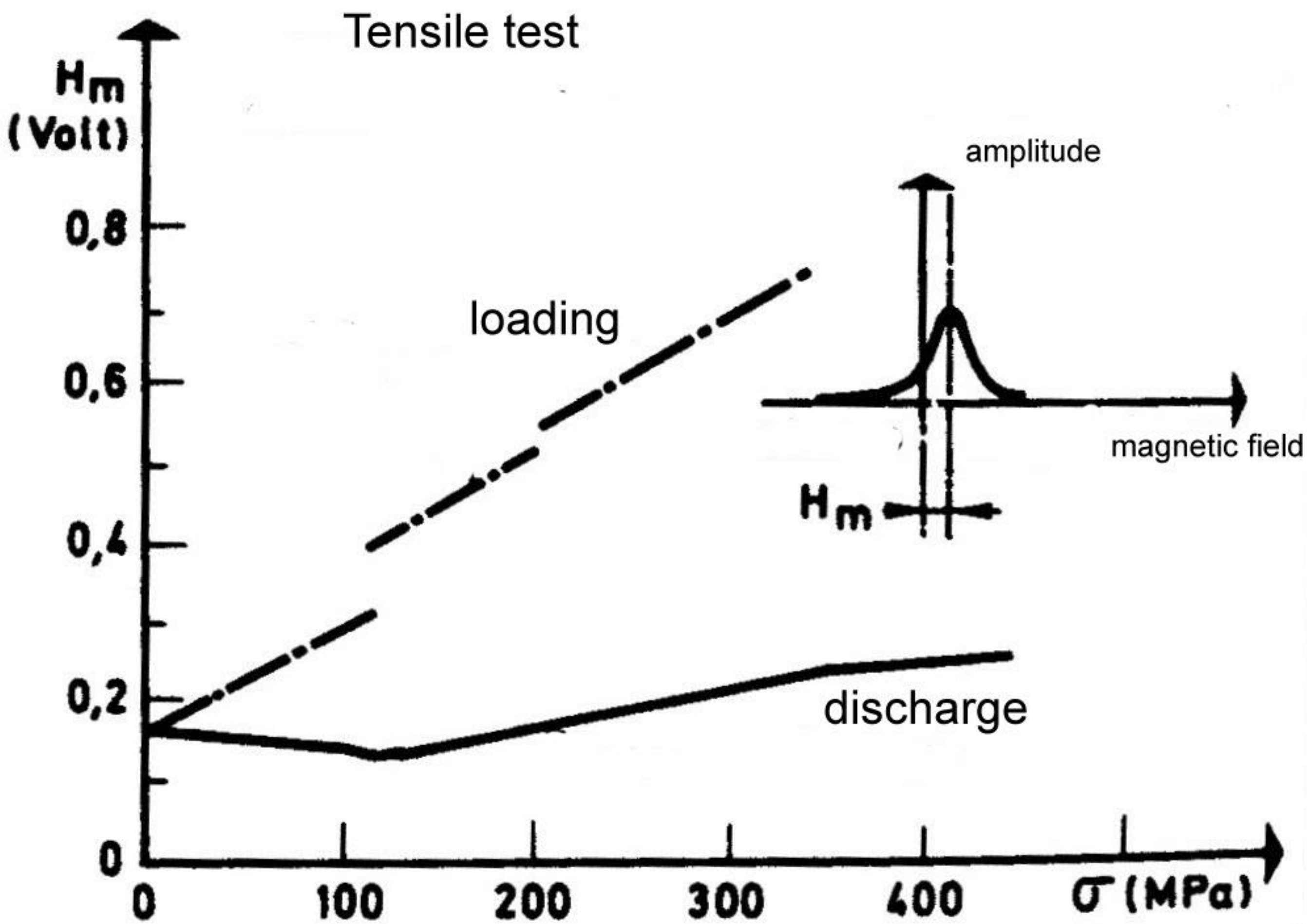
Example : Measurement of propagation speed on a specimen in Al based alloy AU4G under monotonic tensile loading



Physical Properties (2)

<u>Magnetic effect:</u>

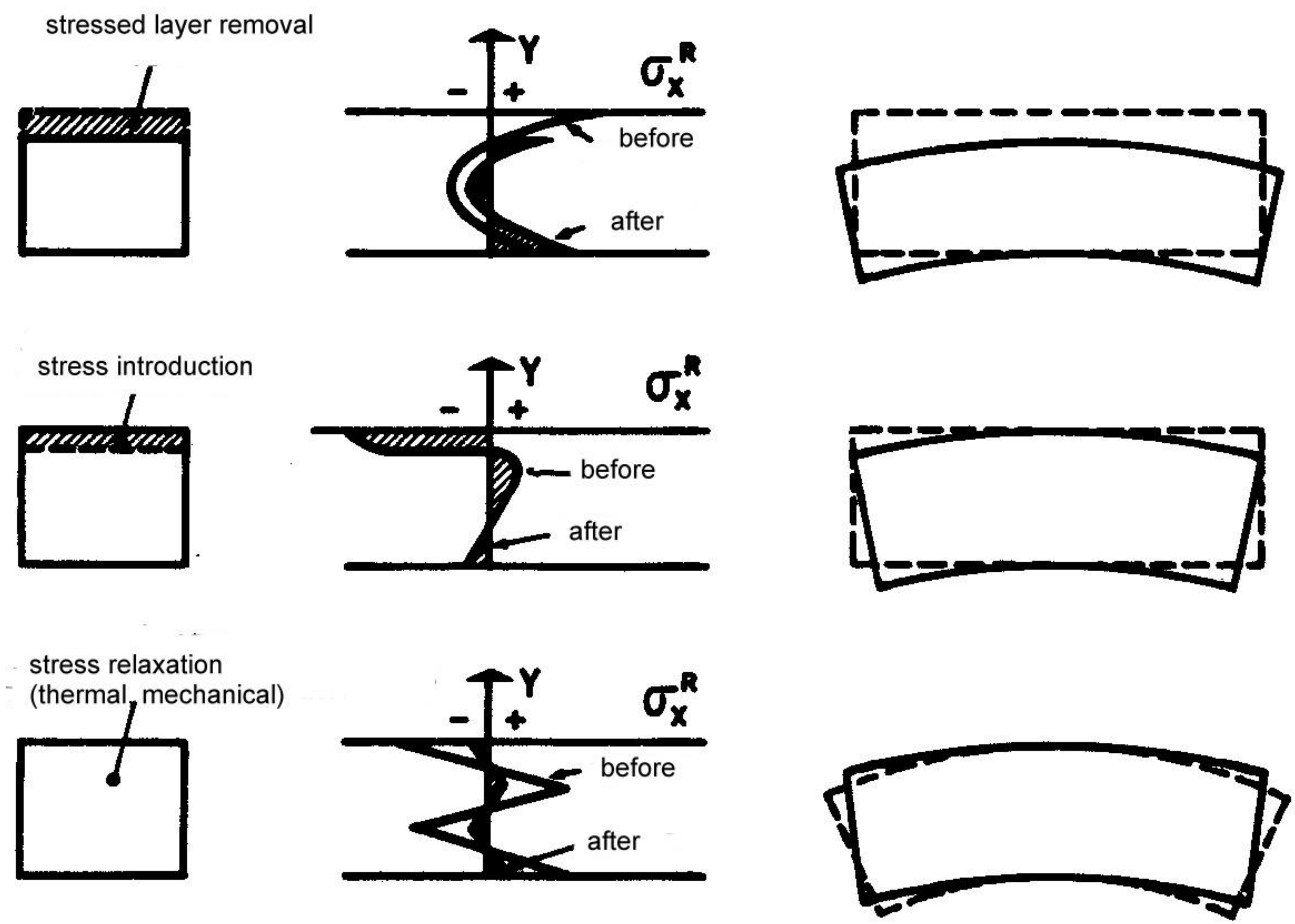
coercitif field of Barkhausen effect is modified in function of stress in material



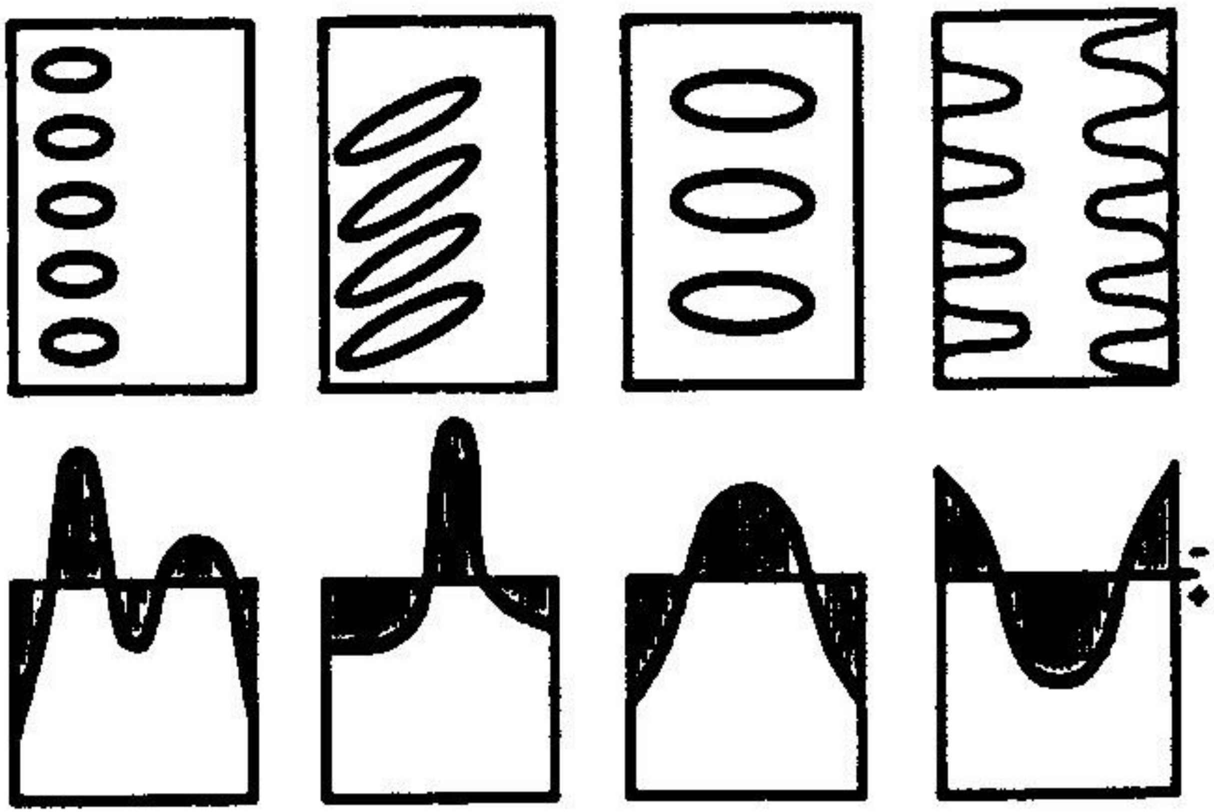
Example : Evaluation of Barkhausen effect Hm on Nickel specimen under monotonic tensile loading

Geometrical deformation (1)

<u>Cutting :</u>



Geometrical deformation (2)

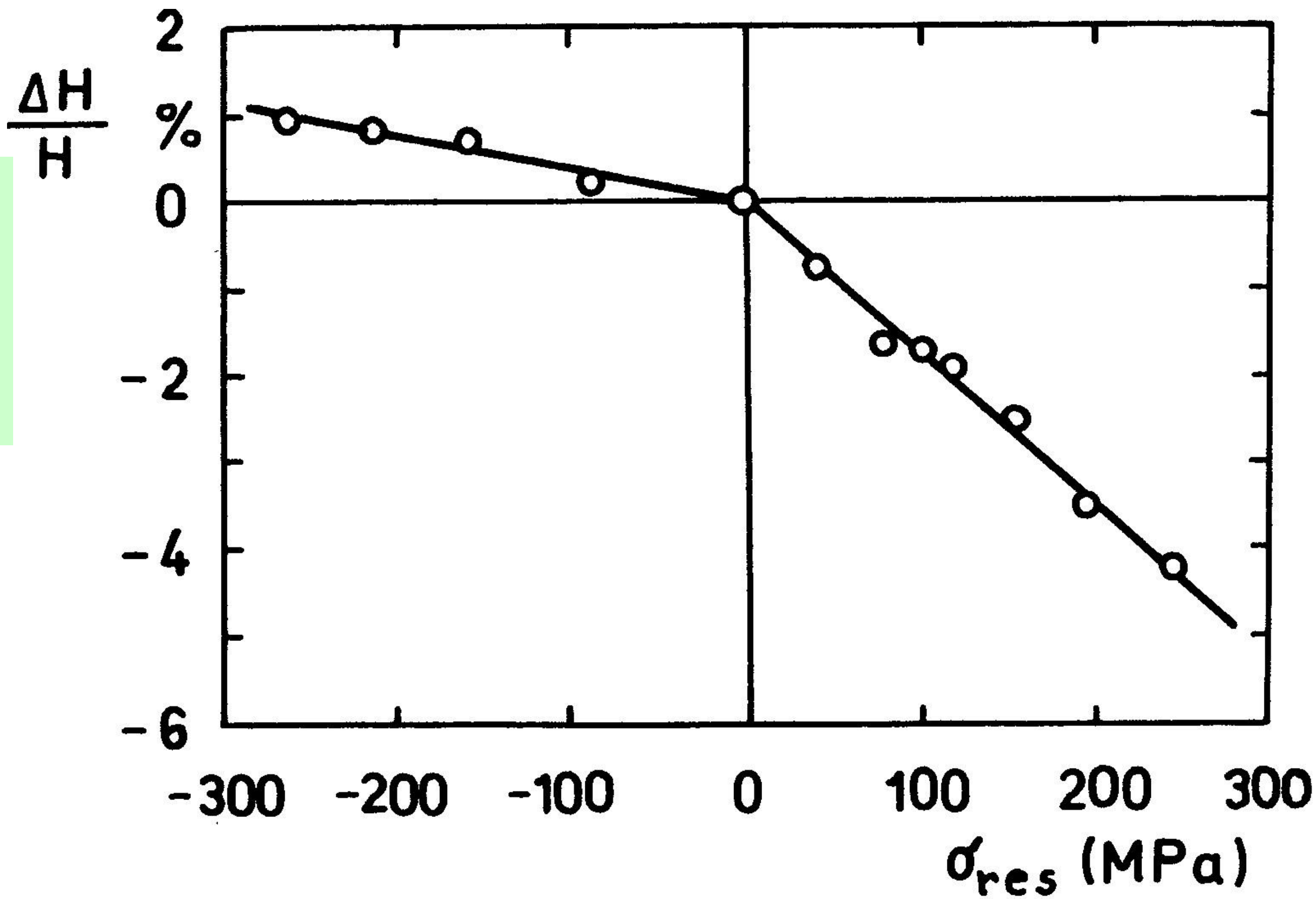


<u>Example:</u> rolling

Residual stress distribution and associated geometrical modification (blisters, edge longs, bucklings ...)

Static mechcanical properties (1)

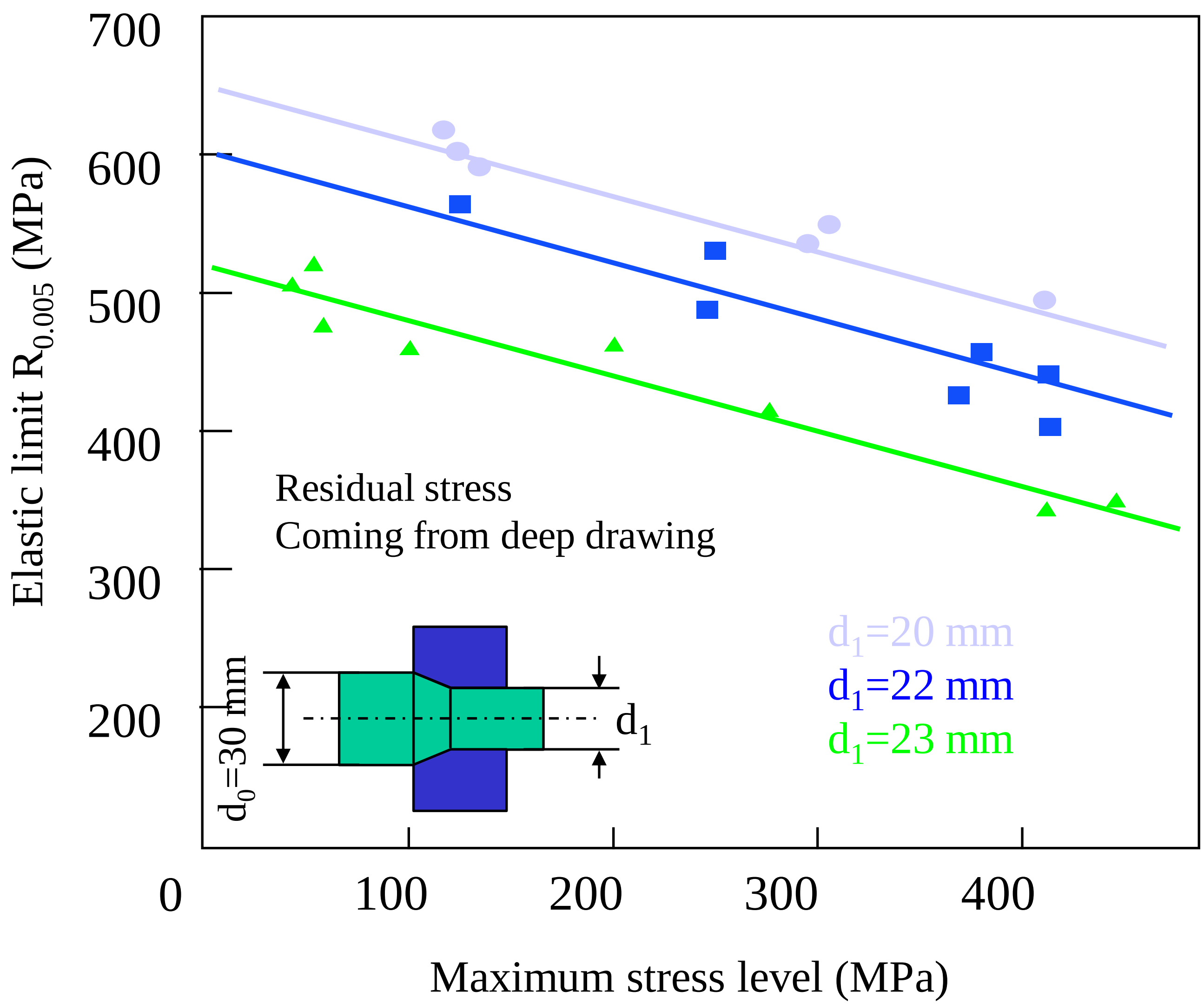
<u>Example :</u> Hardness variation in function of level and sense of residual stress on surface of carbon steel



Static mechcanical properties (2)

Elastic limits

Example 1 : decease of elastic limits of steel wire by drawing in function of stress level under tensile test



Static mechcanical properties (3)

Coating Adhesion:

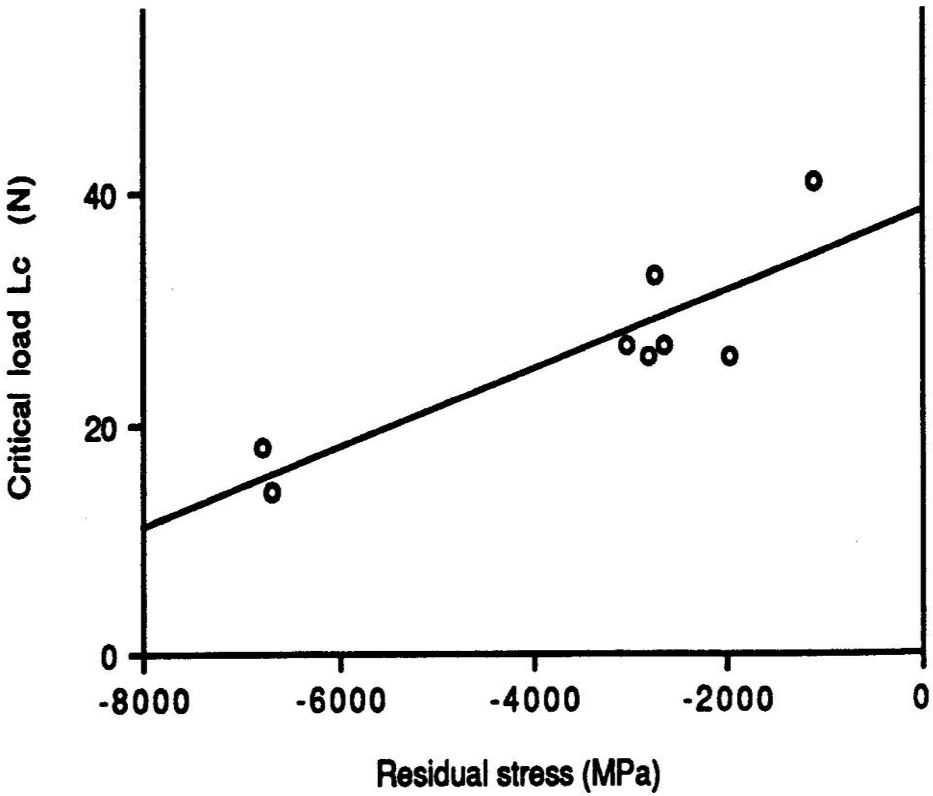


Table 2. Characteristics of the TiN coatings

Substrate No.	Thickness µm	-σ MPa	Lc N	Deposition	H2:N2
1	3,9	6775	18	CVD	1:1
1	3,3	6686	14	CVD	4:1
2	4,6	3040	27	CVD	1:1
2	4,2	2815	26	CVD	4:1
3	4,3	2740	33	CVD	1:1
3	3,5	2655	27	CVD	4:1
4	4,4	1970	26	CVD	1:1
4	4,6	1122	41	CVD	4:1
1	13,8	3475	24	CVD	1:1
1	13,8	3140	21	CVD	1:1
2	17,1	776	61	CVD	1:1
2	17,1	756	57	CVD	1:1
3	15,3	870	57	CVD	1:1
3	15,3	882	55	CVD	1:1
4	14,4	700	57	CVD	1:1
4	14,4	692	52	CVD	1:1
1	3	11825	14	PVD	-
2	3	7392	20	PVD	-
3	3,2	8912	17	PVD	-

TiN coating on cutting tools

Contact and erosion (1)

TABLE 1
Levels of residual macrostresses in specimens of steel XBГ

Batch No.	After thermal treatment		After additional DC pulse treatment	
	$(\sigma_1 + \sigma_2)$ (MPa)	σ_φ (MPa)	$(\sigma_1 + \sigma_2)$ (MPa)	σ_φ (MPa)
1	471	333	not treated	
2	520	392	not treated	
3	490	275	3	1
4	559	353	7	2

TABLE 2
Wear stability parameters of hardened steel XBГ

Batch number	Load kgf	Specimen wear mm^3	f
1	24	0.041	0.0969
2	54	0.116	0.0898
3	24	0.027	0.0813
4	54	0.045	0.0755

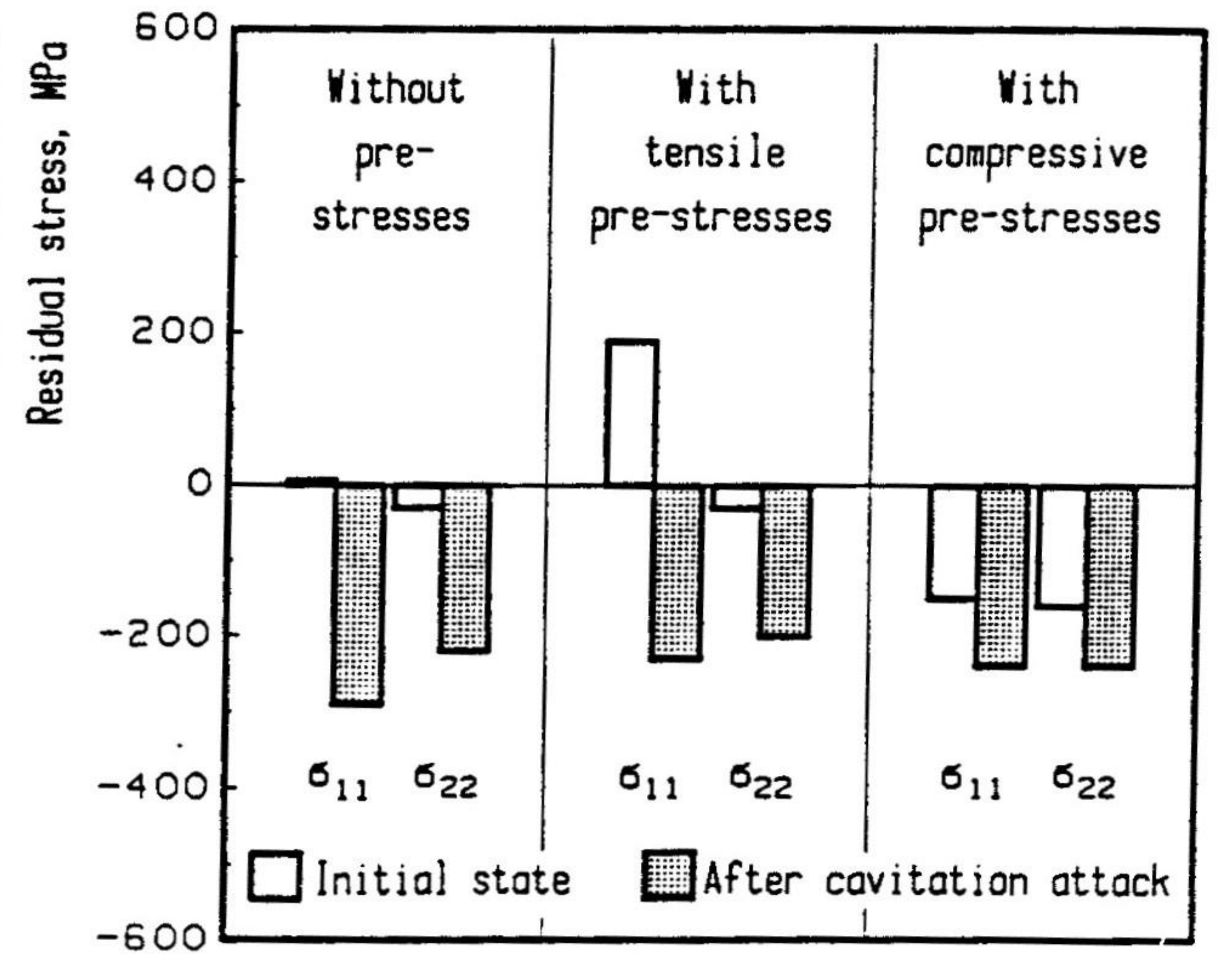
<u>Wear :</u>

piece wear of treated steel will increase if residual stress in surface will be in tension

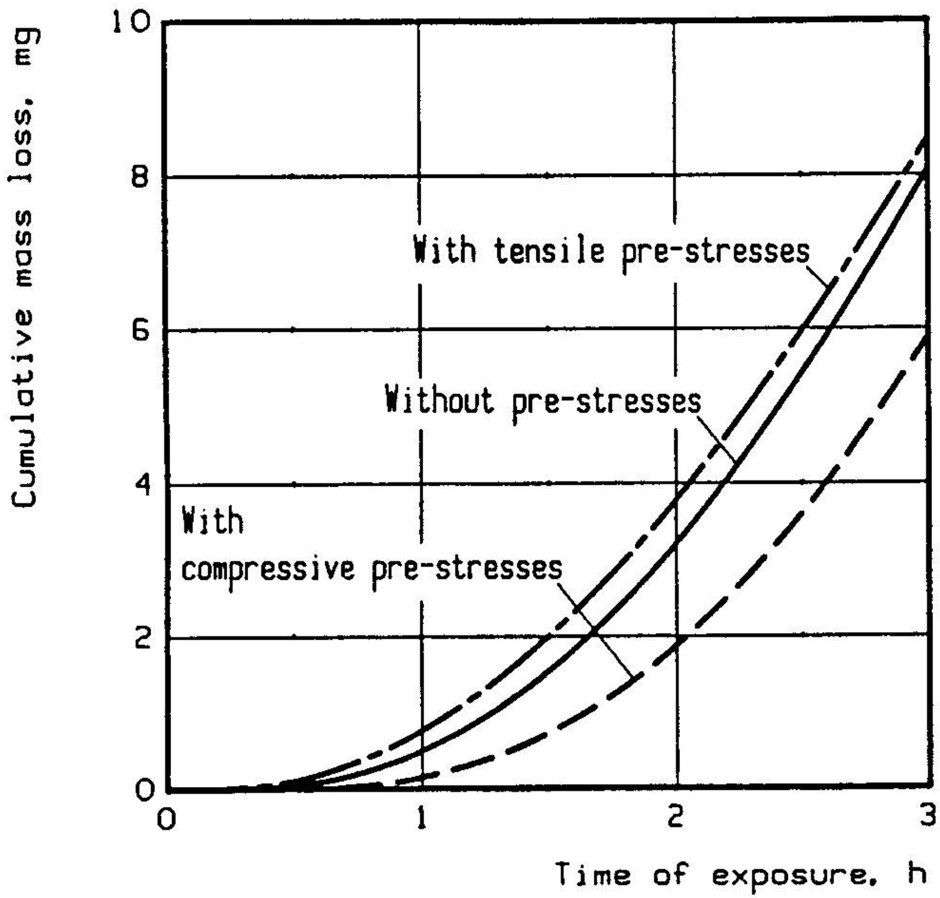
Contact and erosion (2)

Erosion :

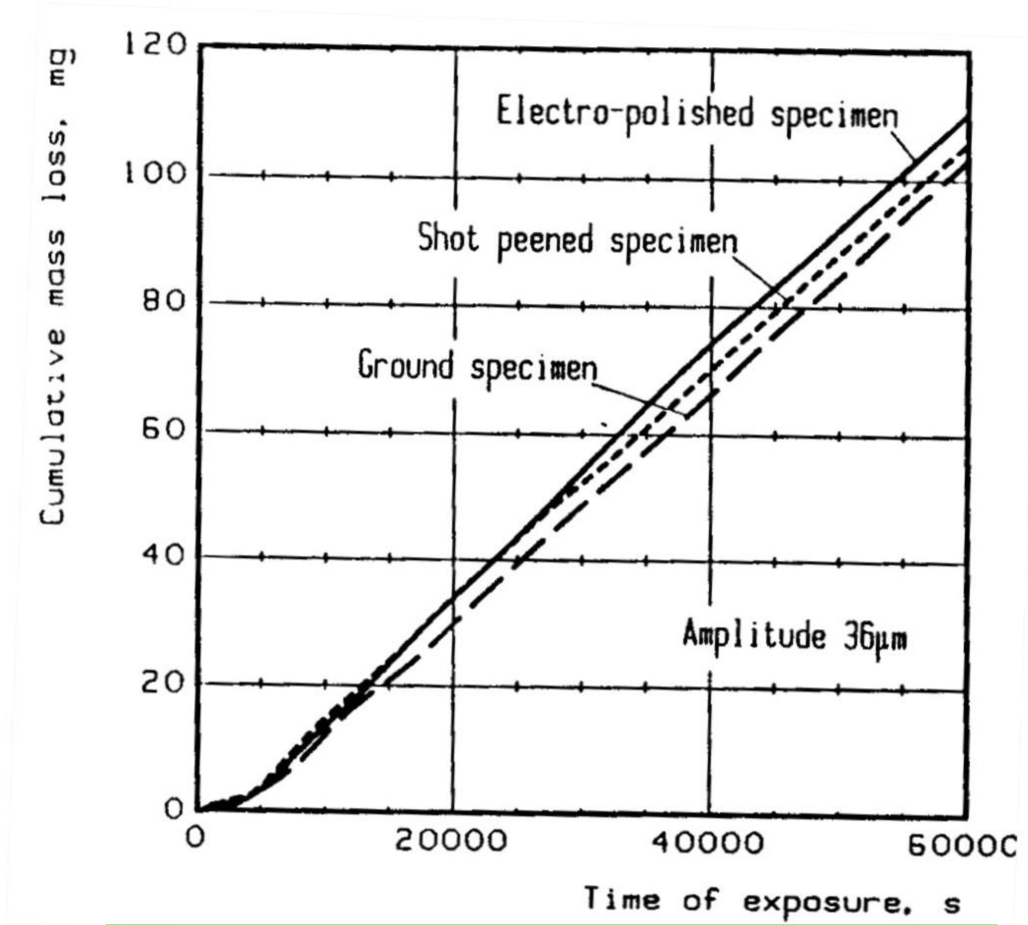
Surface Residual Stress in the initial state and after a short cavitation time



Contact and erosion (3)



Influence of prestress on erosion mecanism

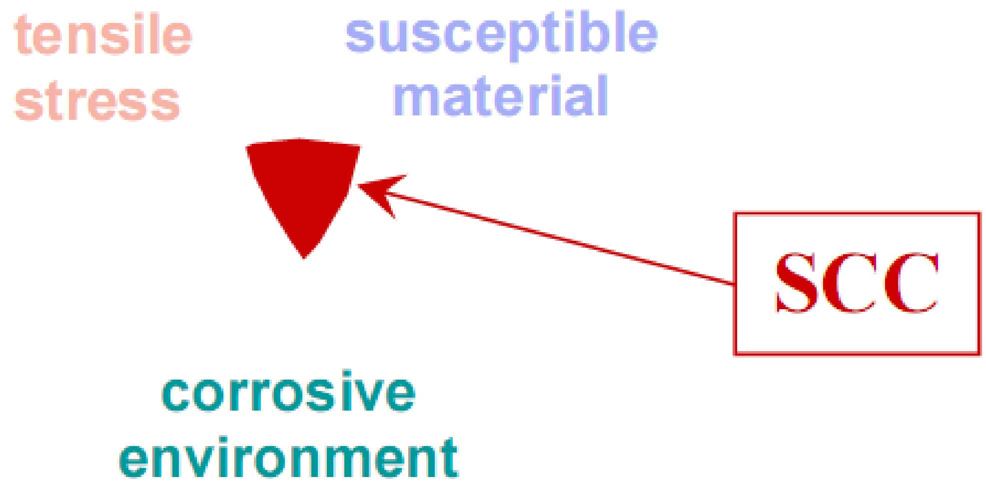


Influence of surface preparation on erosion property

Stress corrosion cracking (1)

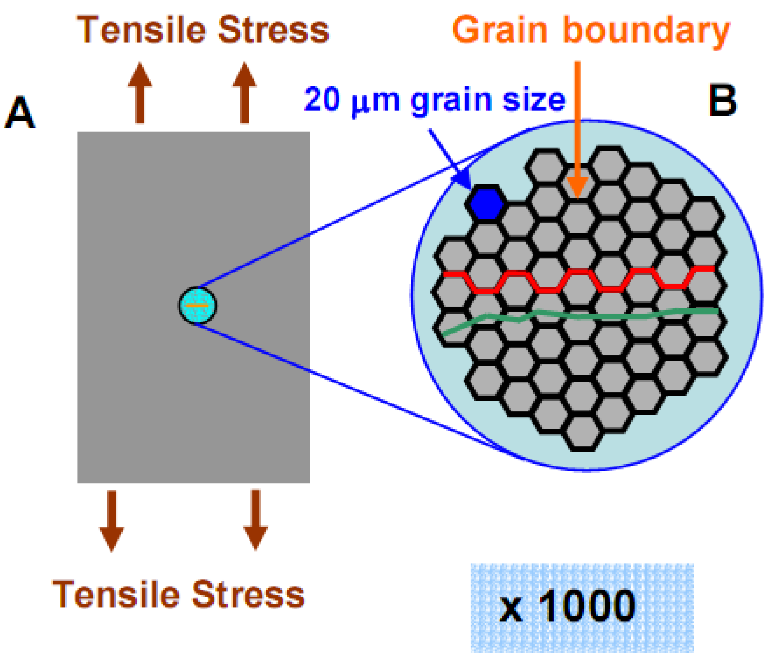
SCC is the conjoint action of stress and a corrosive environment leading to the formation of brittle cracks

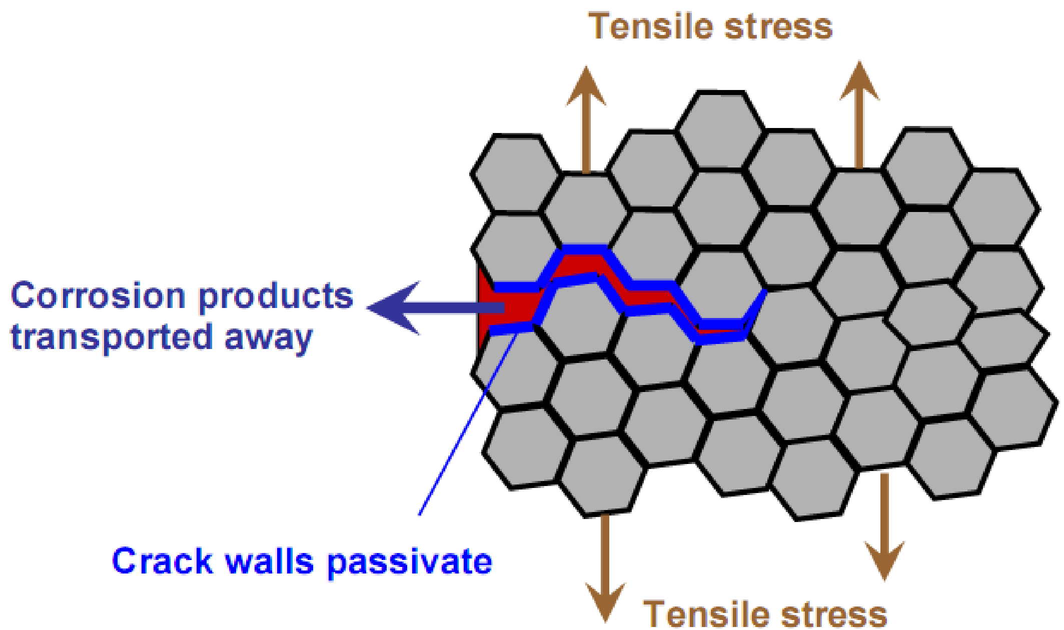
Typical SCC failures are seen in
- pressure vessels,
- pipework,
- highly stressed components
- an excursion from normal operating conditions or the environment occurs.



Stress corrosion cracking (2)

The required tensile stresses may be in the form of applied stresses or residual stresses.

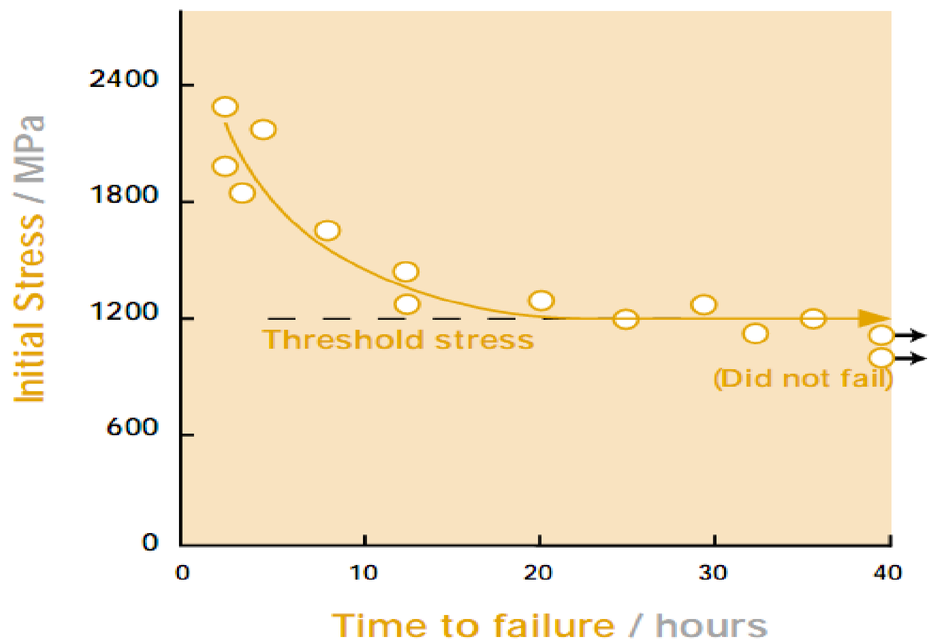




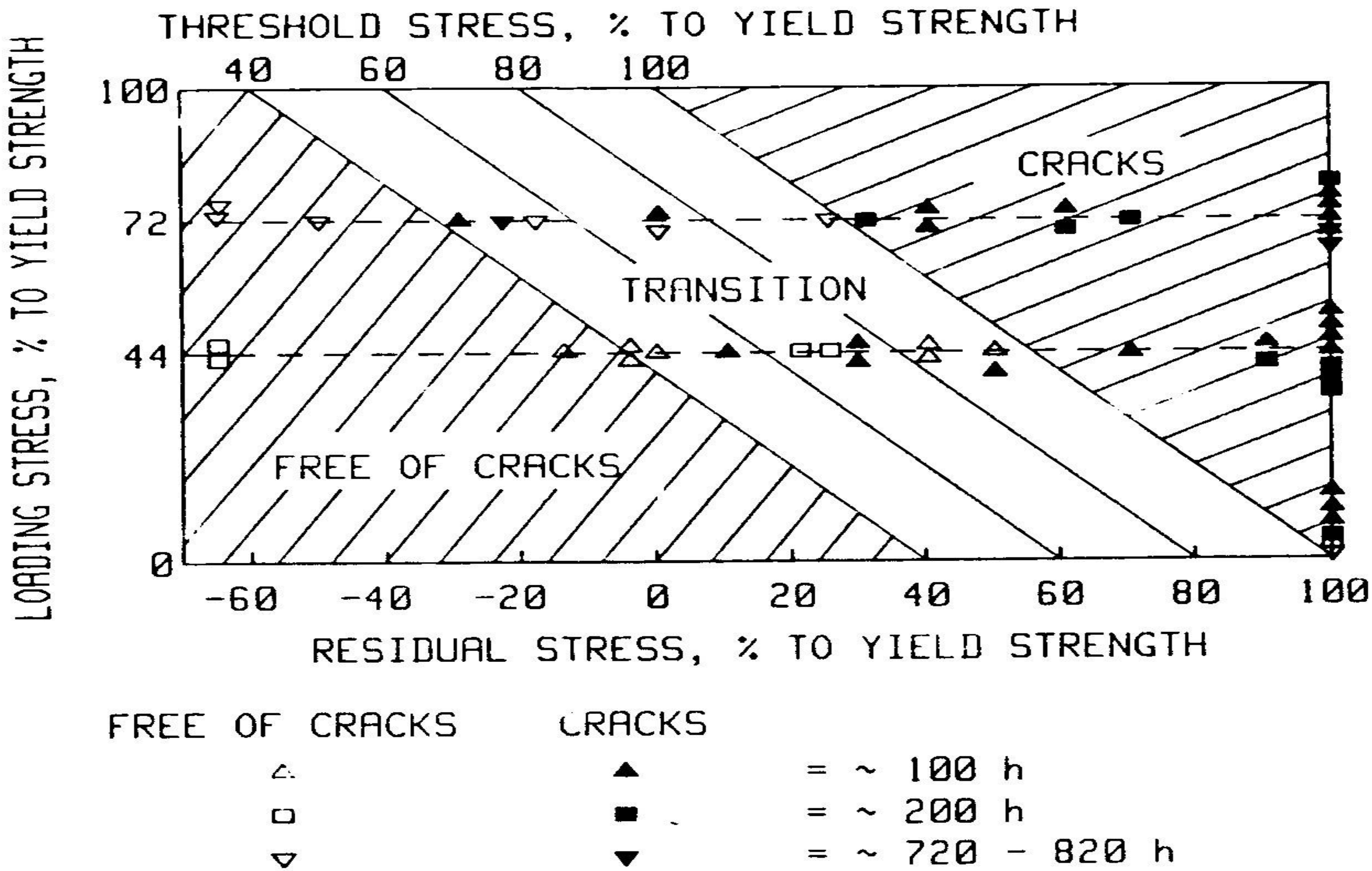
Stress corrosion cracking (3)

The environment is
- either the permanent service environment i.e. sea water
- or a temporary one caused by operations such as cleaning of the system which can leave a residue,
- or if the stress is applied during the operation initiate cracking.

SCC is a corrosion mechanism that requires the pairing of a material with a very particular environment and the application of a tensile stress above a critical value.

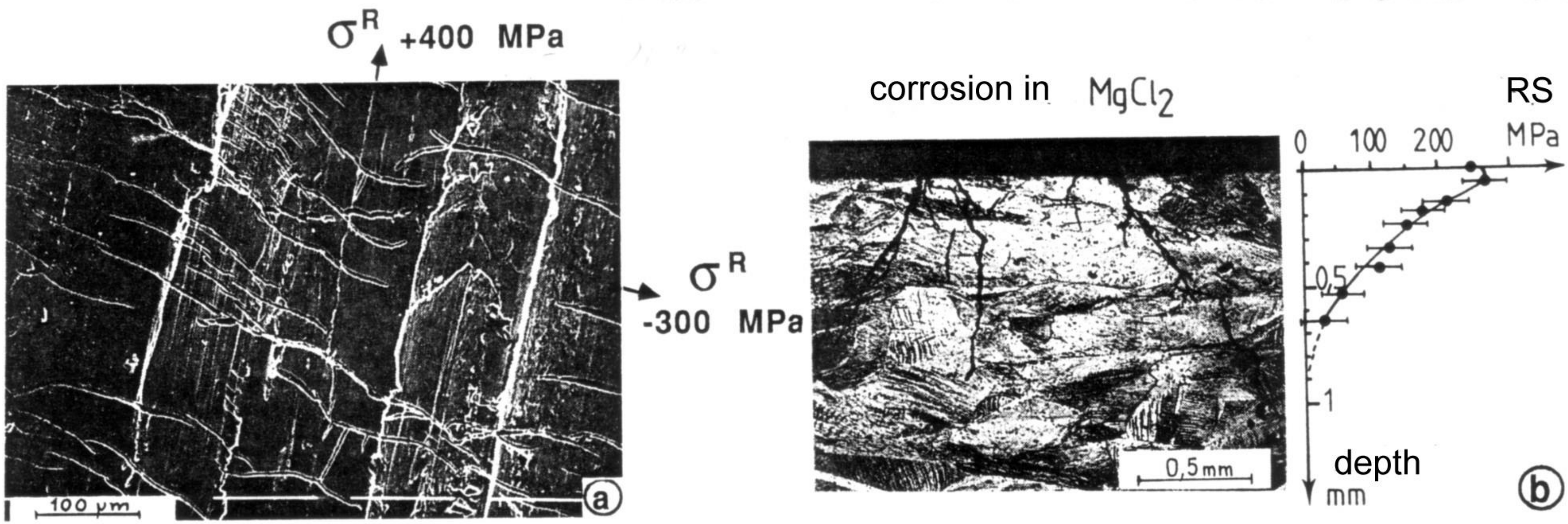


Stress corrosion cracking (4)



<u>Example 2 :</u> Influence of level and sign of residual stress on critical cracking stress of a stainless steel

Stress corrosion cracking (5)



Example 3 : residual stress influence on stress corrosion cracking of an austenitic stainless steel under $MgCl_2$ environment
(a) after milling (b) after rolling

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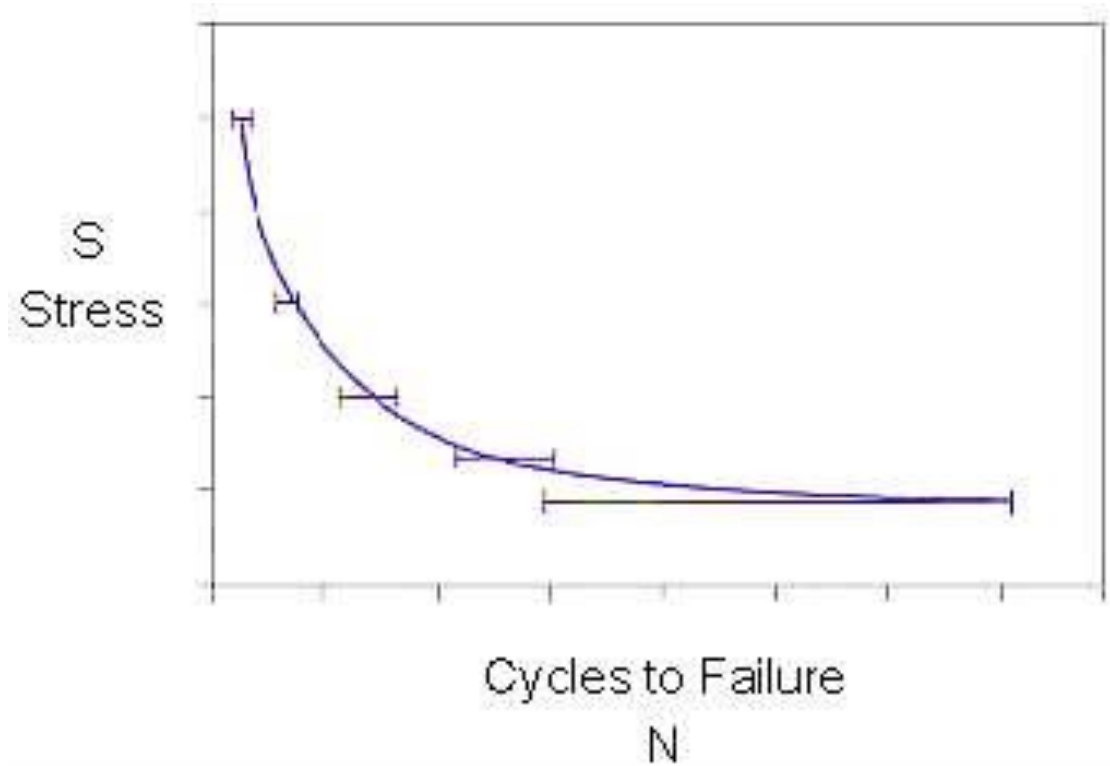
Fatigue properties (1)

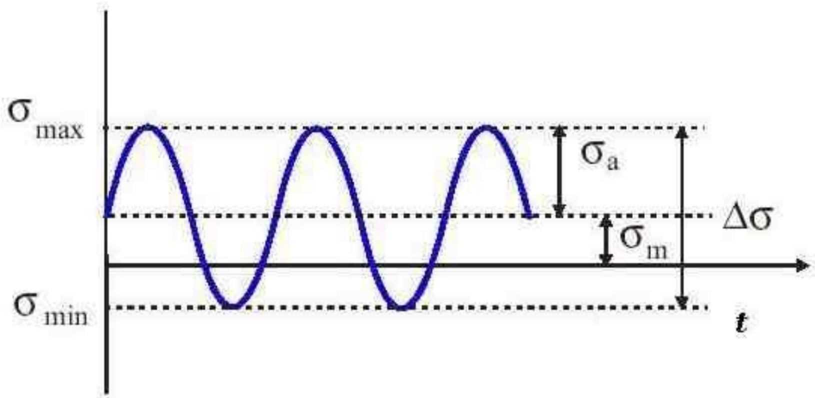
fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading;

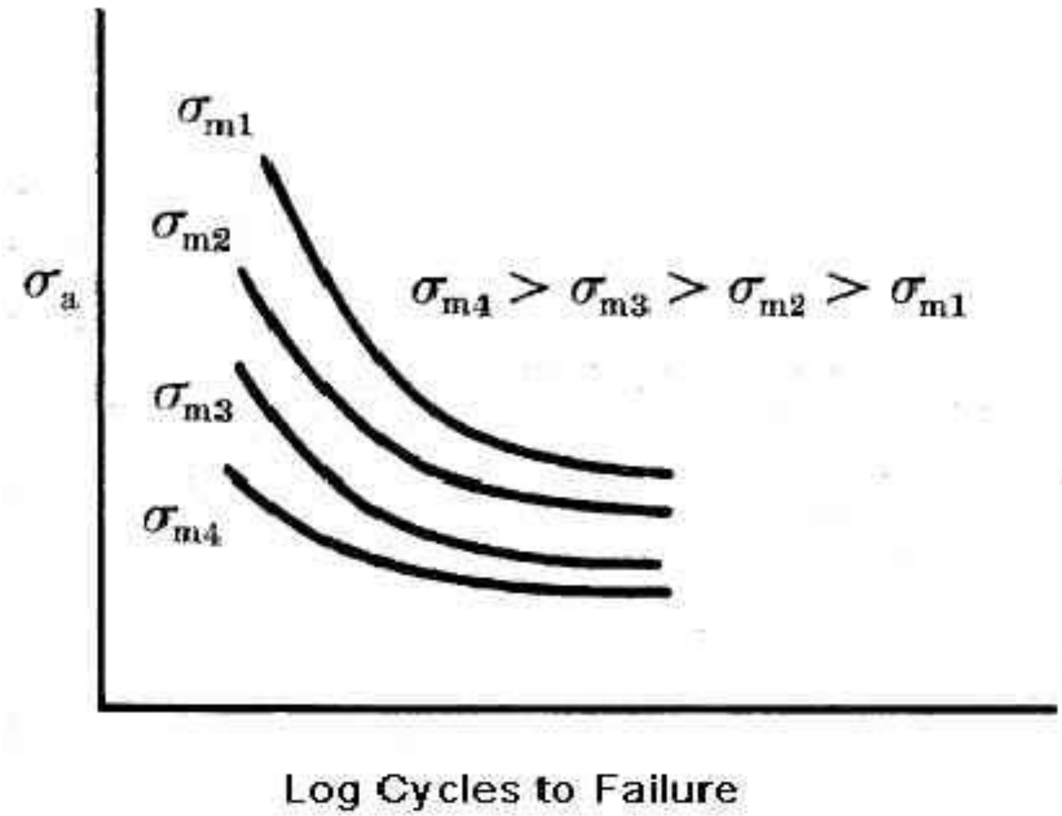
It is a progressive localized damage due to fluctuating stresses and strains on the material. Metal fatigue cracks initiate and propagate in regions where the strain is most severe.



Fatigue properties (2)

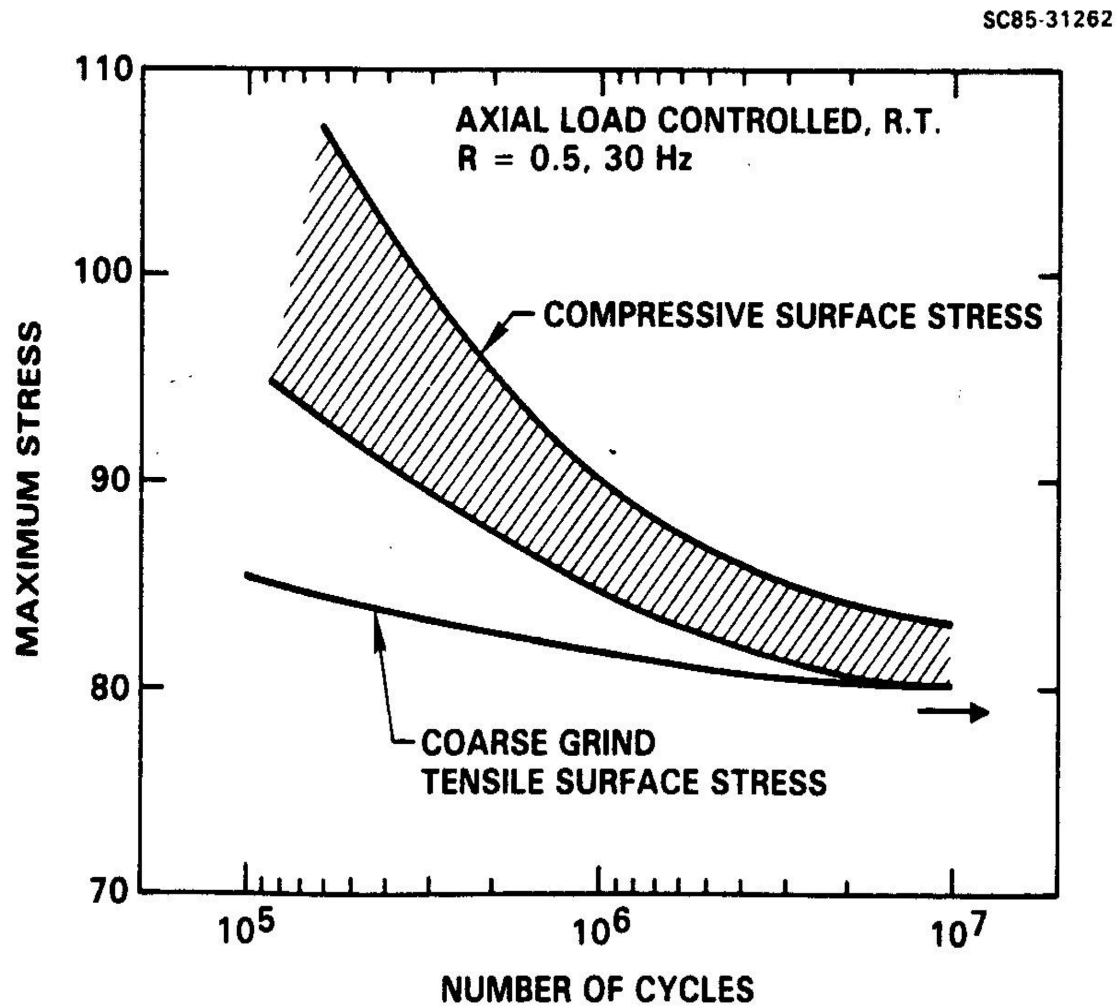
The most commonly used stress ratio is R, the ratio of the minimum stress to the maximum stress (σmin/σmax).





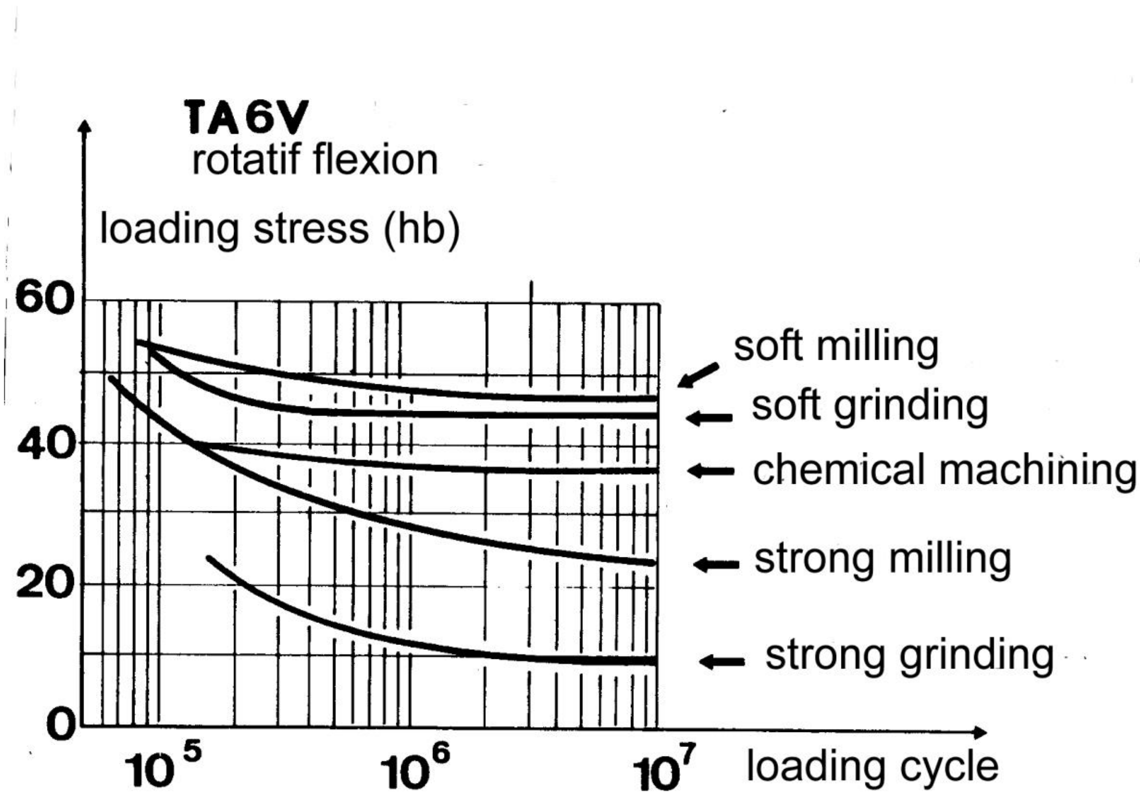
Fatigue properties (3)

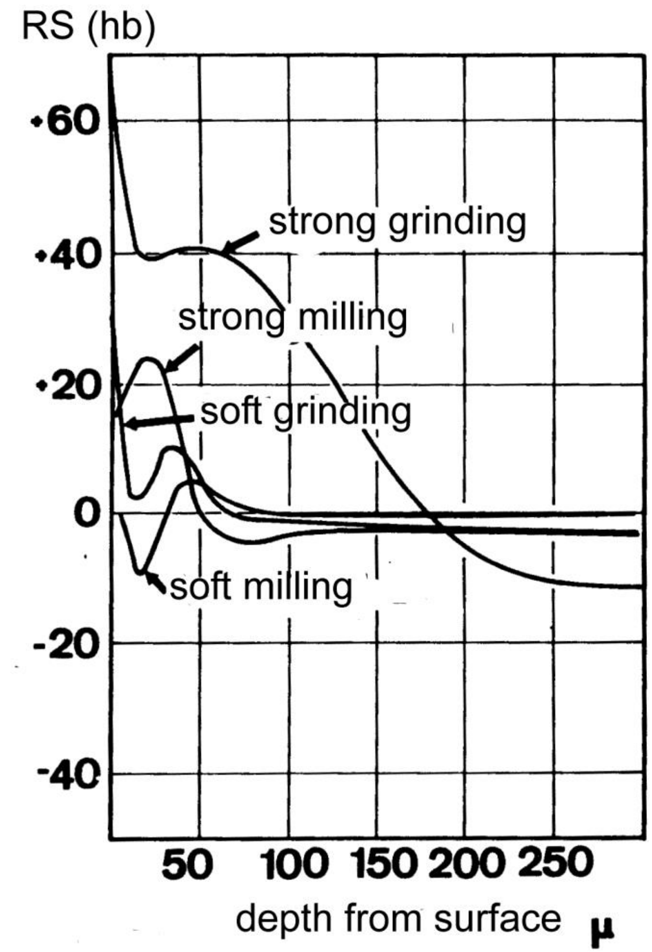
Coarse Grinding	+190 MPa
Gentle Grinding	-200 MPa
Form Tool Finish	-380 MPa
Single Point Tool	-275 MPa
Shot Peen	-700 MPa



Evolution of fatigue limits according surface residual stress

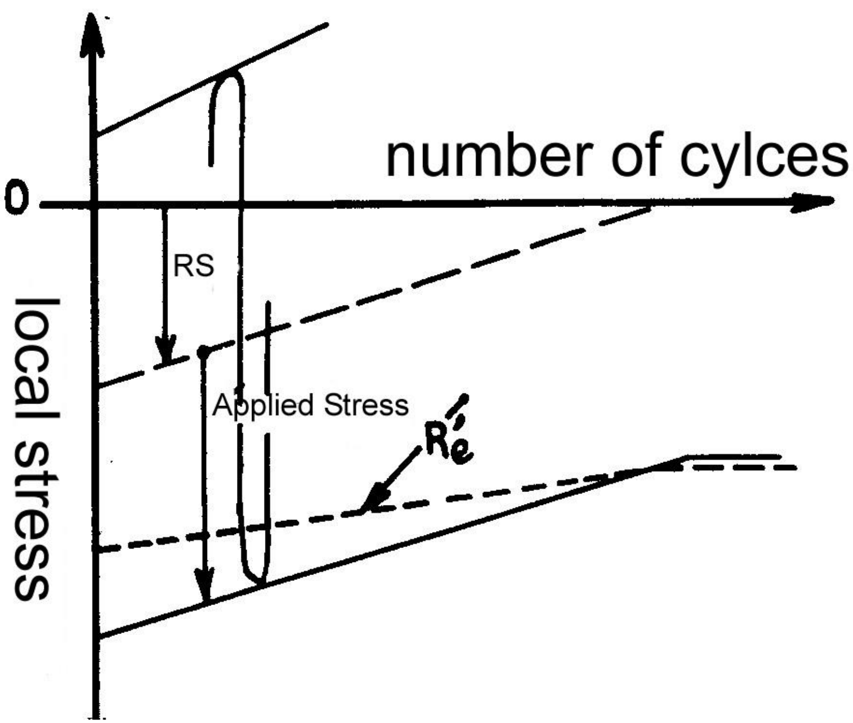
Fatigue properties (4)



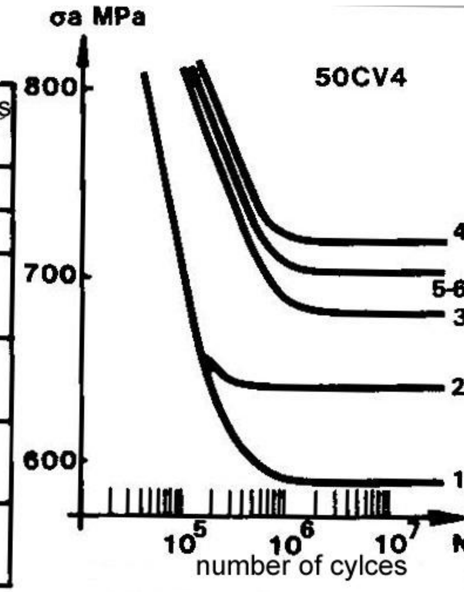


<u>Example 3 :</u> Influence of machining modes on residual stress distribution and on fatigue resistance with rotative bending tests for rolled TA6Vspecimens

Fatigue properties (5)

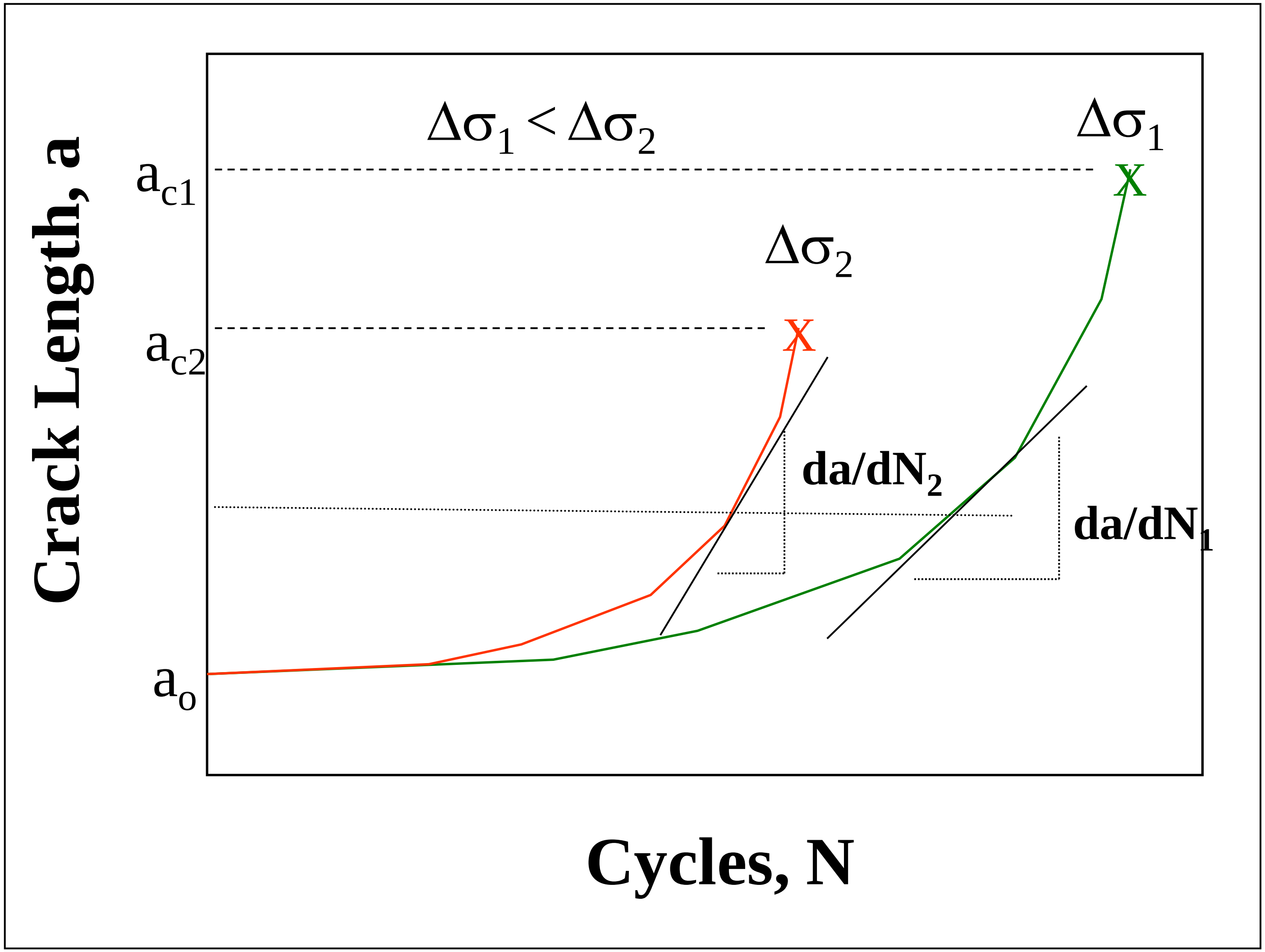


sample	surface preparation	roughness Ra µm
1	raw turning	4,3
2	raw grinding	1,4
3	turning + soft shot-peening (S110, 0.36 A)	2,2
4	grinding + soft shot-peening (S110, 0.36 A)	2,7
5	turning + strong shot-peening (S330-0,61 A)	4,4
6	grinding + strong shot-peening (S330-0,61 A)	4,3



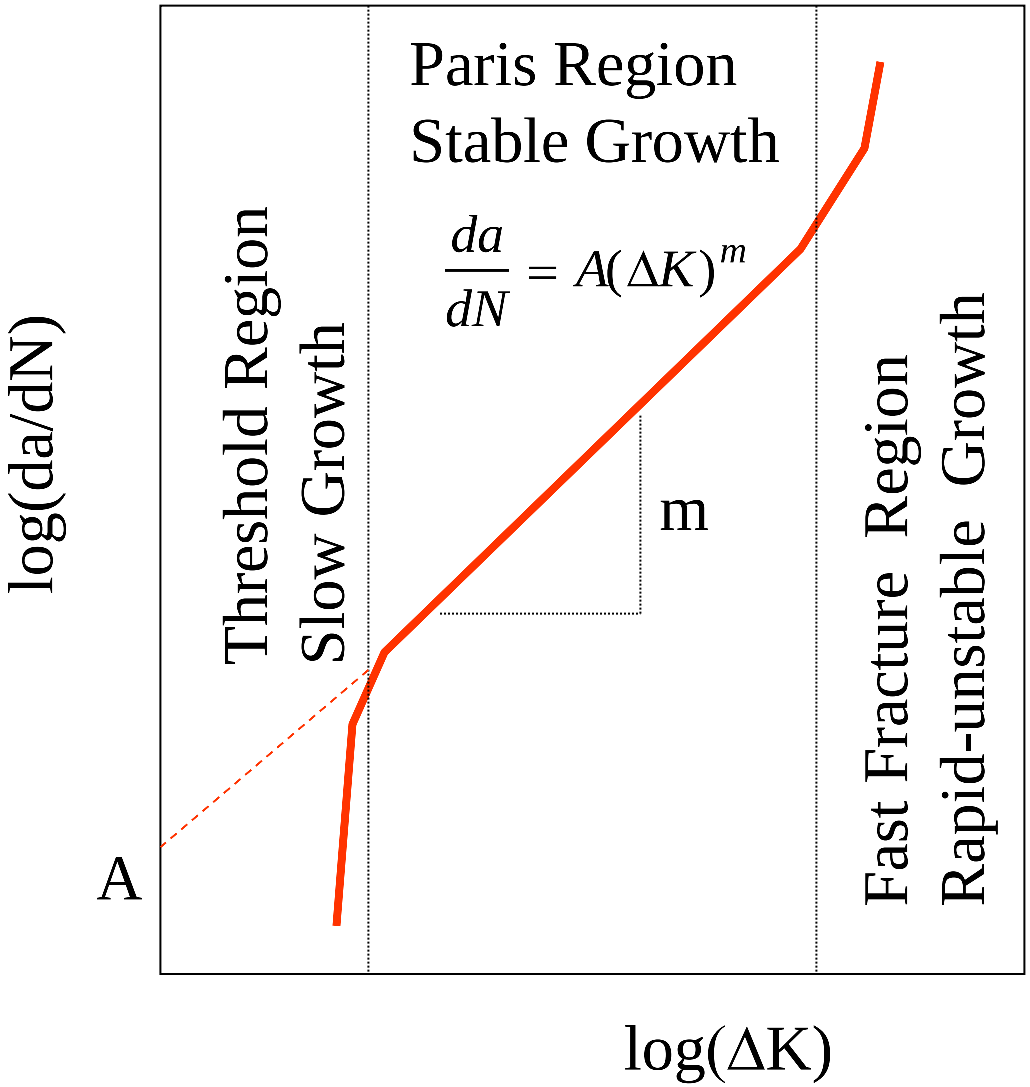
<u>Example 4</u> : Effect of shot-peening on fatigue resistance of 50CV4 steel (spring steel)

Cracking characteristics (1)



Crack Growth Rate, da/dN

Cracking characteristics (2)



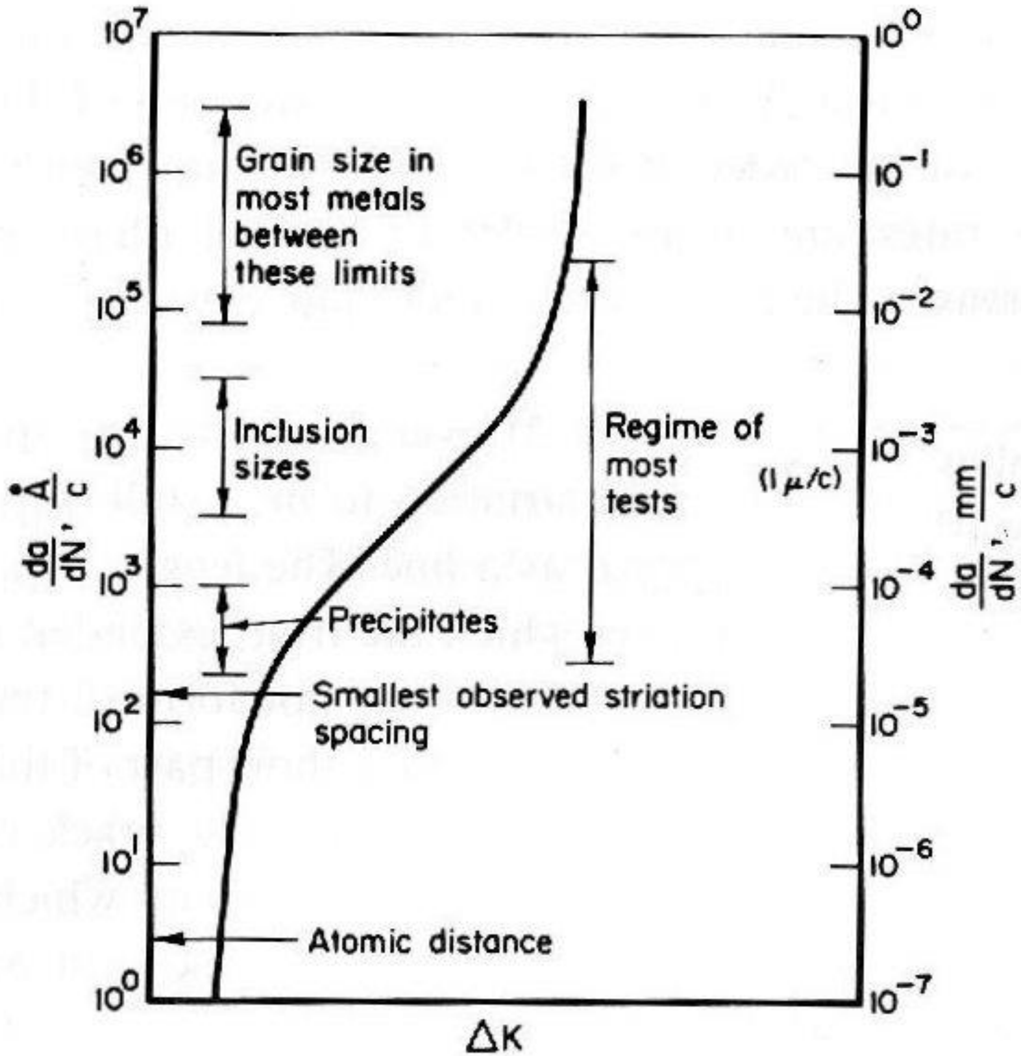
•The driving force for crack growth is the **range** in the stress intensity factor during cycling.

$$\Delta K = f\,(a/W)\Delta\sigma\sqrt{\pi a}$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad \text{for } R \geq 0$$

$$\Delta\sigma = \sigma_{max} \quad \text{for } R < 0$$

Cracking characteristics (3)

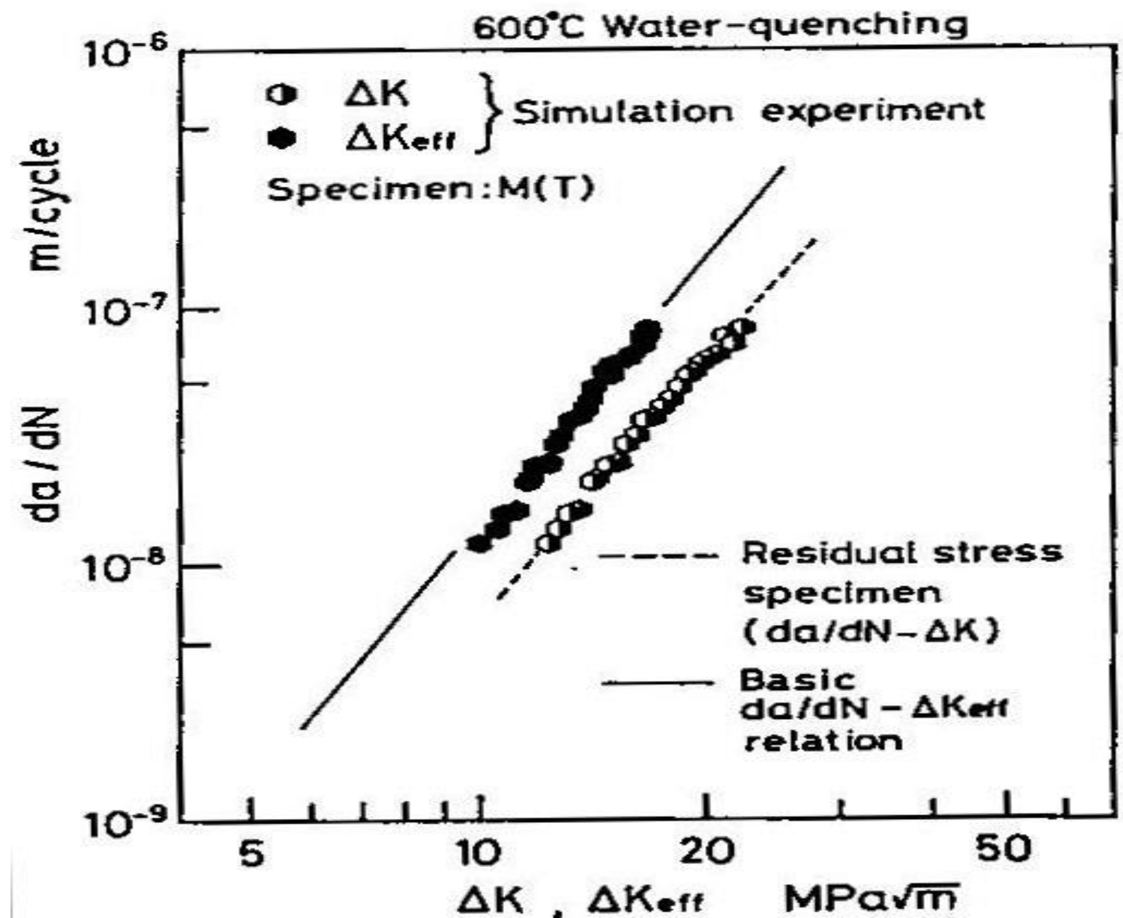


Crack Growth Rates
and
Microstructural
Features

Cracking characteristics (4)

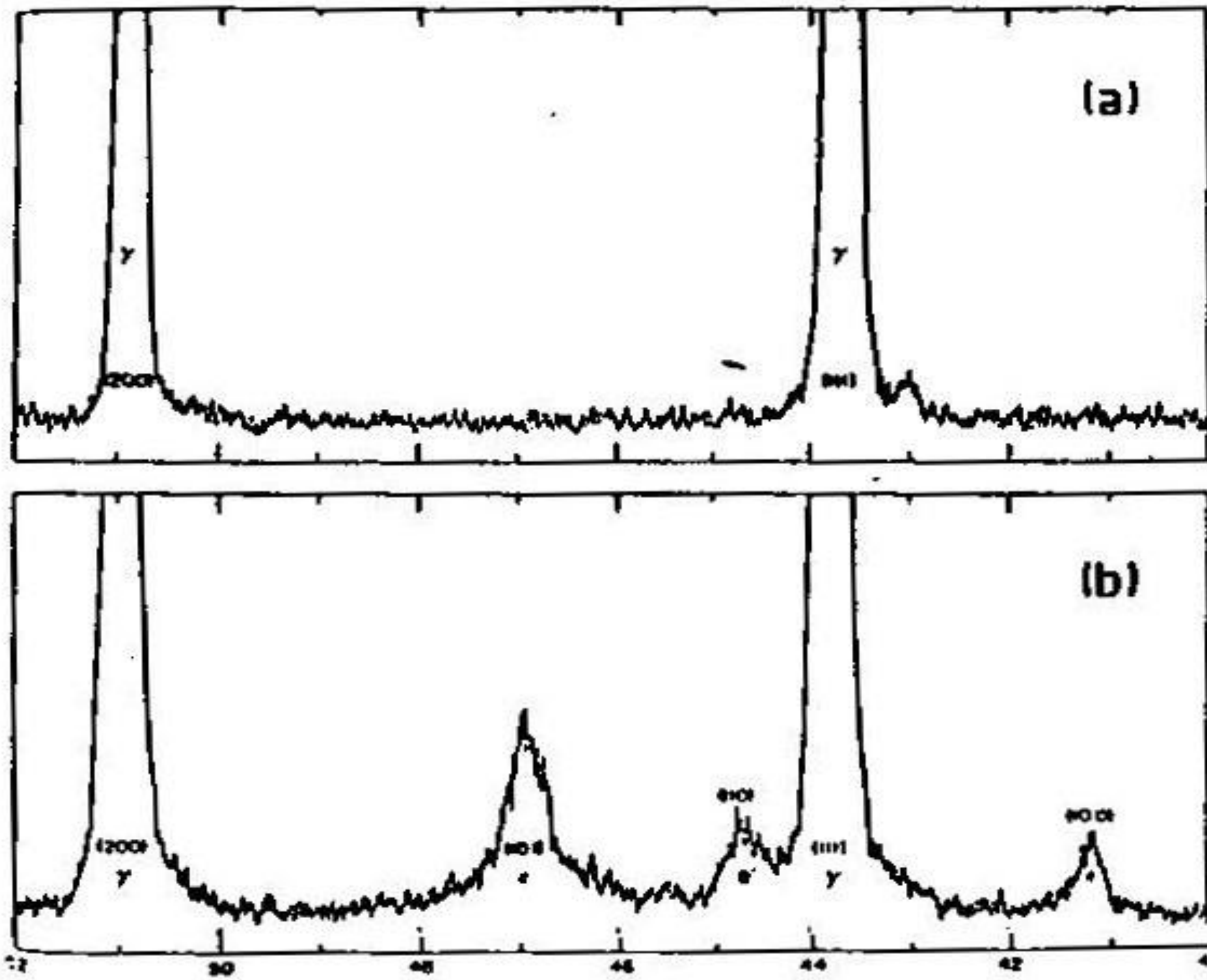
Speed of crack propagation is influenced by the presence of residual stress in materials

<u>Example 1 :</u> reducing of crack propagation spped da/dN due to the compressive residual stress

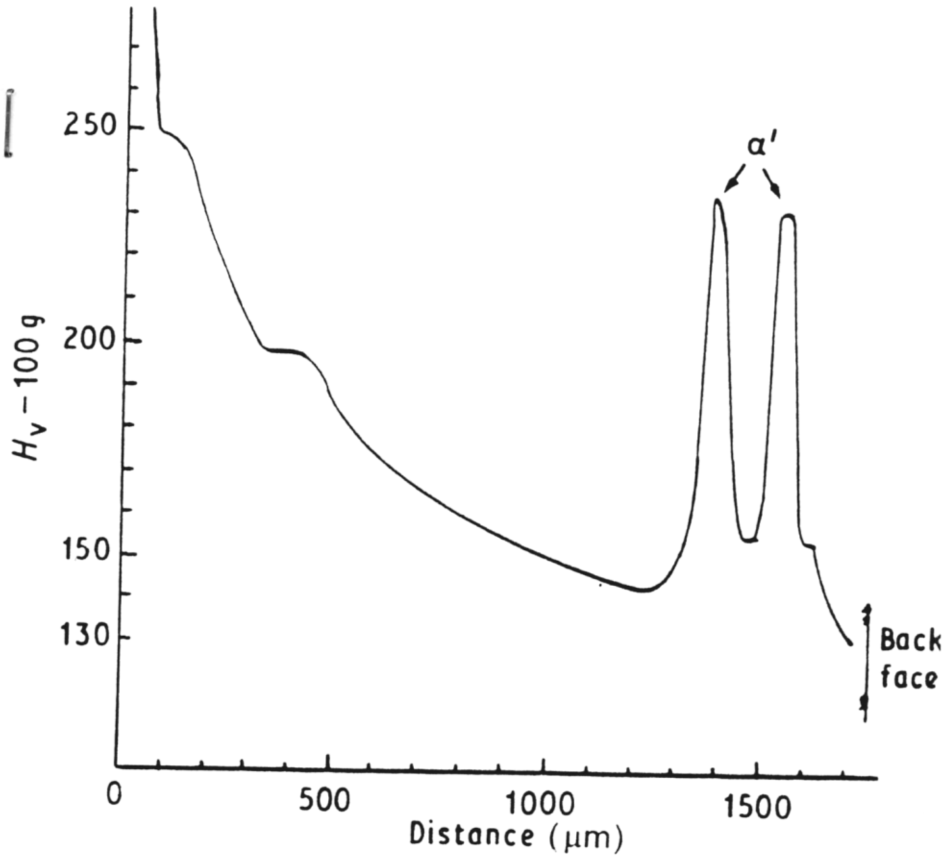


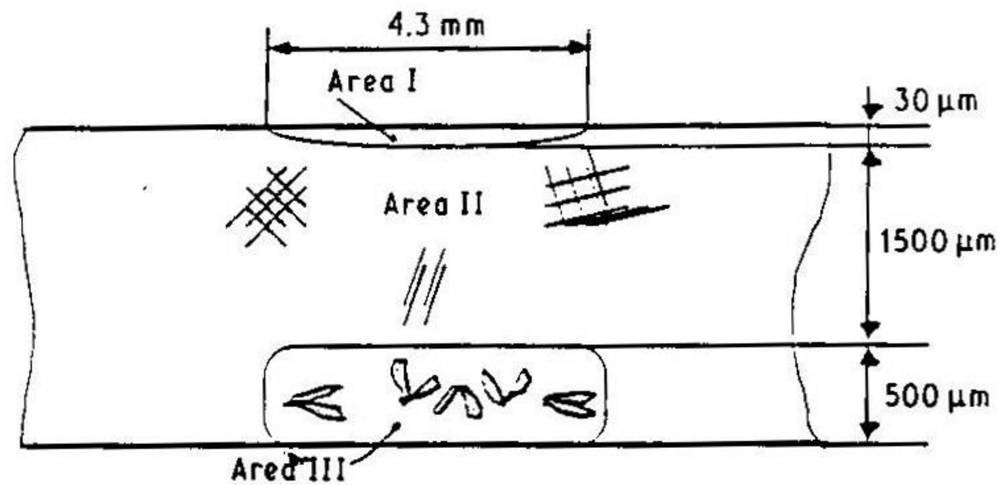
Microstructure modification (1)

<u>Example 1 :</u> martensite formation on a austenitic stainless steel 304L under monotonic tensile test



Microstructure modification (2)





<u>Example 2 :</u> Phase change due to laser shock of an austenitic steel

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property	RS influence
Acoustic	RS level ➔ V change of ultrasonic wave propagation
Magnetic	RS ➔ modification of coercitif field of Barkhausen effect
Geometric	RS redistribution or/and relaxation ➔ geometric change
Hardness	(+ RS) ➔ Hv decrease, (- RS) ➔ Hv increase
Elastic limit	(+ RS) ➔ σe decrease, (- RS) ➔ σe increase
Erosion and contact	(+ RS) ➔ mass loss increase, (- RS) ➔ mass loss decrease
Stress corrosion cracking	(+ RS) ➔ cracking speed up or resistance decrease, (- RS) ➔ cracking delayed or resistance increase
Fatigue	(+ RS) ➔ loading cycle decrease or resistance decrease, (- RS) ➔ loading cycle increase or loading amplitude increase
Cracking	(+ RS) ➔ crack propagation speed increase, (- RS) ➔ crack propagation speed decrease,
Microstructure	RS level ➔ phase change

Residual stress and properties

Residual stresses analysis: determination and relaxation (3)

Classification of methods (1)

Residual stress Determination → Strain measurement

Mechanical Methods

Measurement of strains associated to stress relaxation (by material remove)

- Hole-drilling Method, Ring core method
- Layer remove method - Sachs
- Layer remove method - deflexion method
- Sectioning method

Physical Method

Direct measurement of strains comparng to a reference or to a standard specimen

- X-ray diffraction
- Neutron diffraction
- Ultrasonic method
- Magnetic method – Barkhausen noise method
- Raman effect method

Classification of methods (2)

Mechanical Methods

Physical Methods

Relaxation → Strain

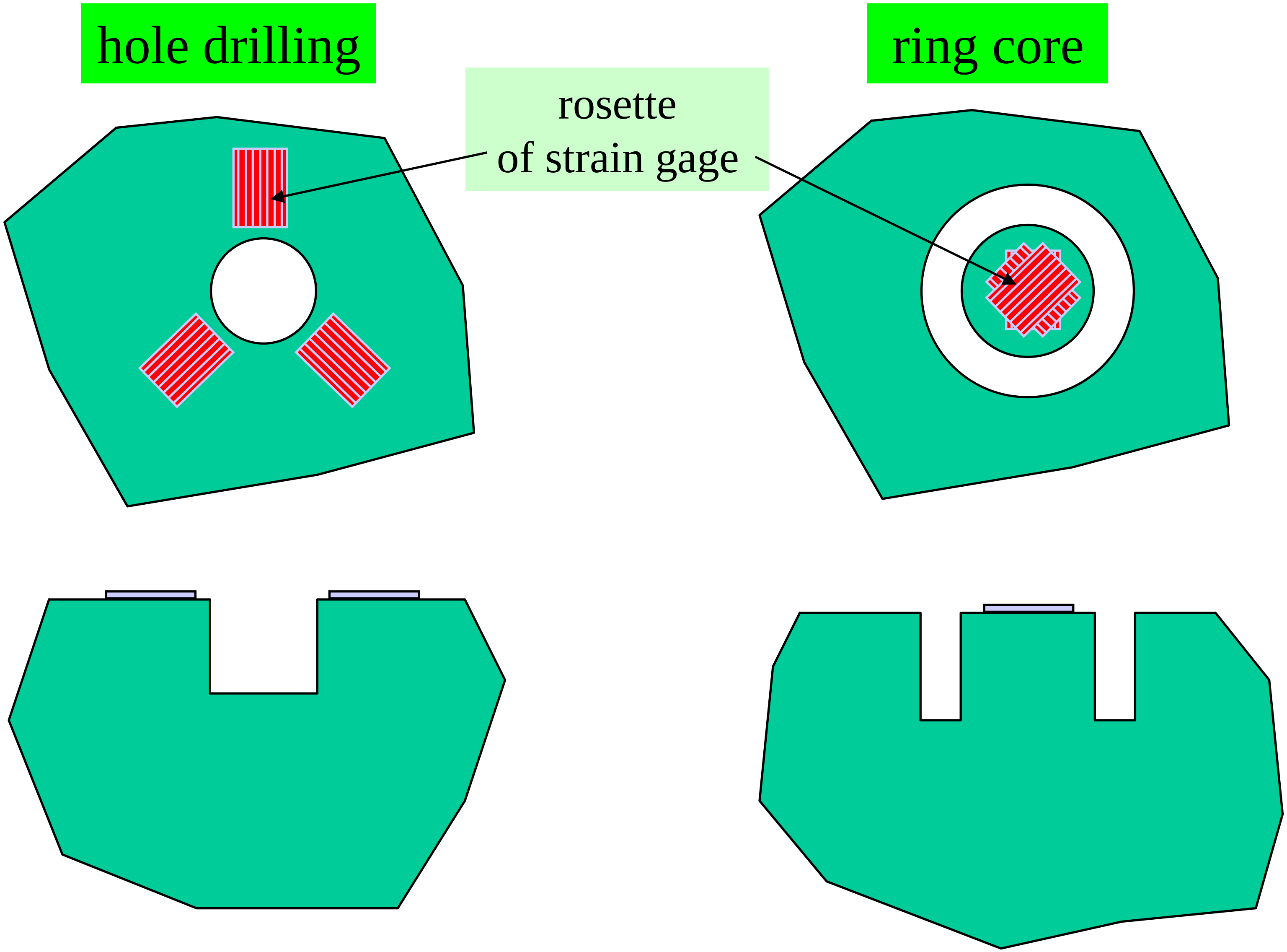
gages

Strain variation → Elastic mechanical Models

Strain → Stress

Elastic mechanical Models → Stress

Hole-drilling and Ring core (1)



Hole-drilling and Ring core (2)

Advantages / Disadvantages

Hole-drilling method

- diam : 1 to 4 mm
- depth ≈ diam.
- sensibility to errors on diameter and on excentricity

Ring core method

- diam : 15 to 150 mm
- depth ≈ 25 à 150% diam.
- insensibility to errors on diameter and on excentricity
- step by step working

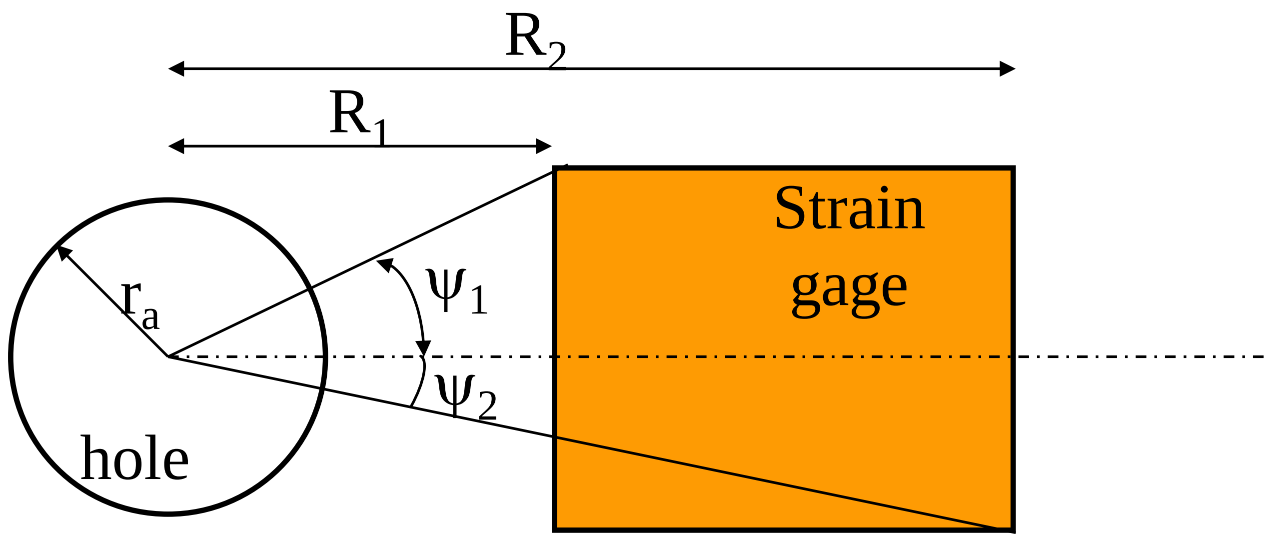
- semi-destructif method
- sensitive to heating
  - stress relaxaion
  - gage damage
- plate bottom of hole
- straight edge of hole

Hole-drilling and Ring core (3)

Simplified theoritical consideration

$$\varepsilon = (\sigma_{max} + \sigma_{min})\bar{A} + (\sigma_{max} - \sigma_{min})\bar{B}\,\mathrm{Cos}(2\beta)$$

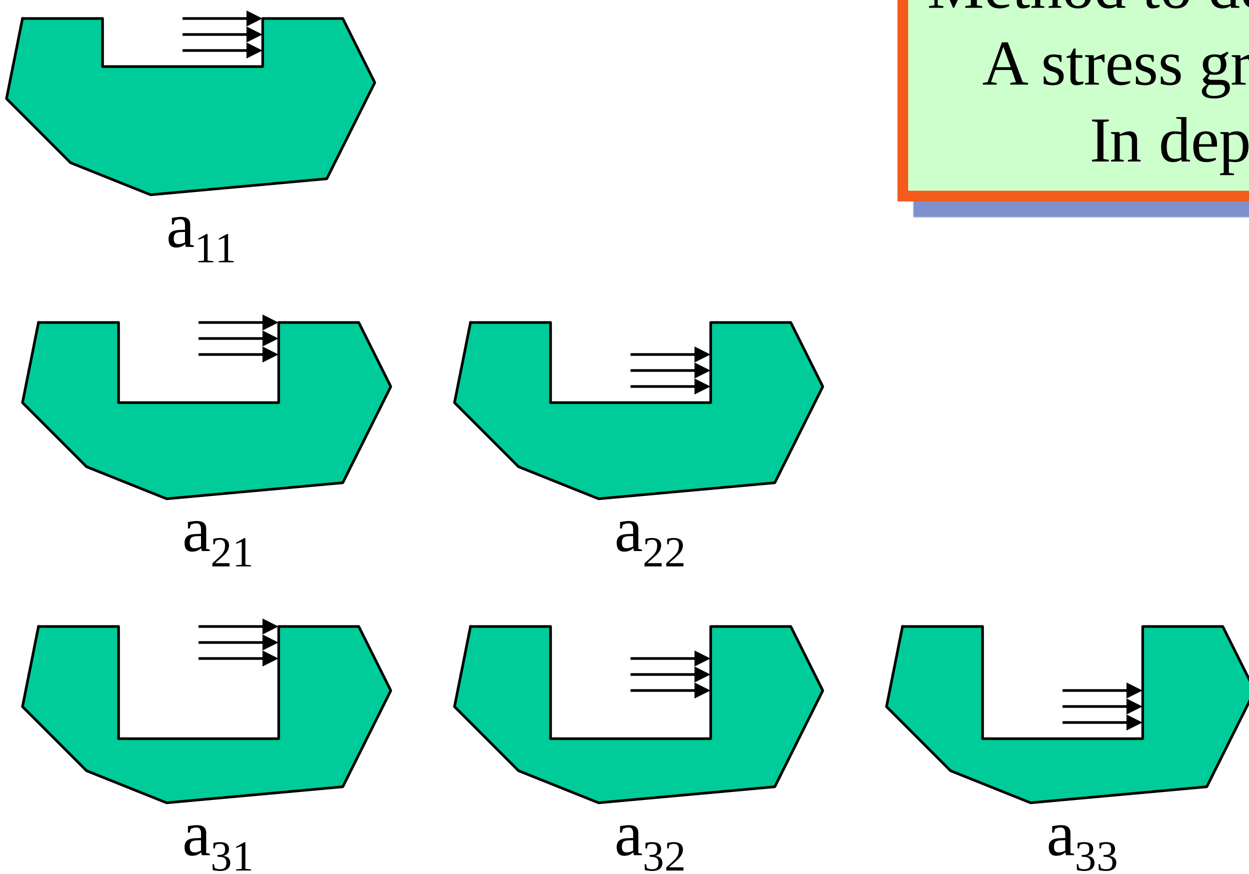
A and B : calibration constant obtained by experimentation or by theoritical calculation, A and B = fonction (rosette, E, υ, r_a, ψ_1, ψ_2...)
β: the angle from the axis to σ_{max}



Hole-drilling and Ring core (4)

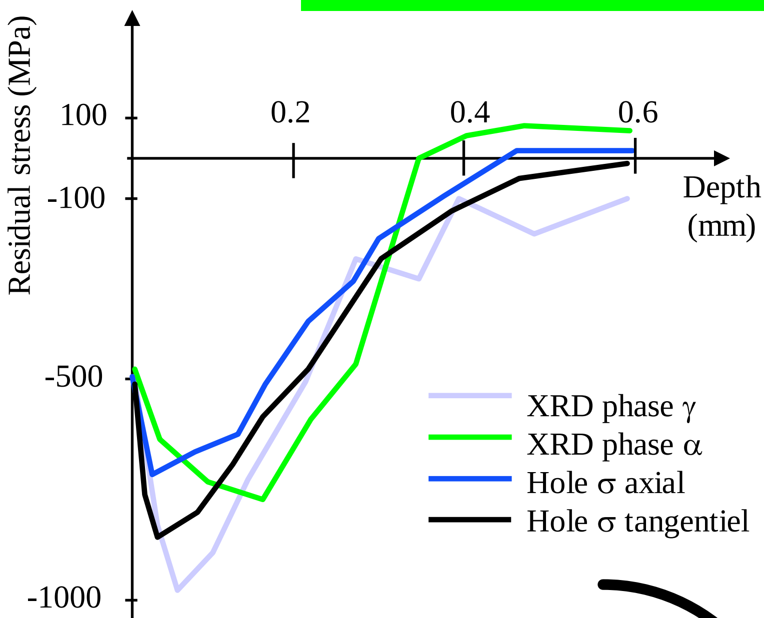
Incremental method

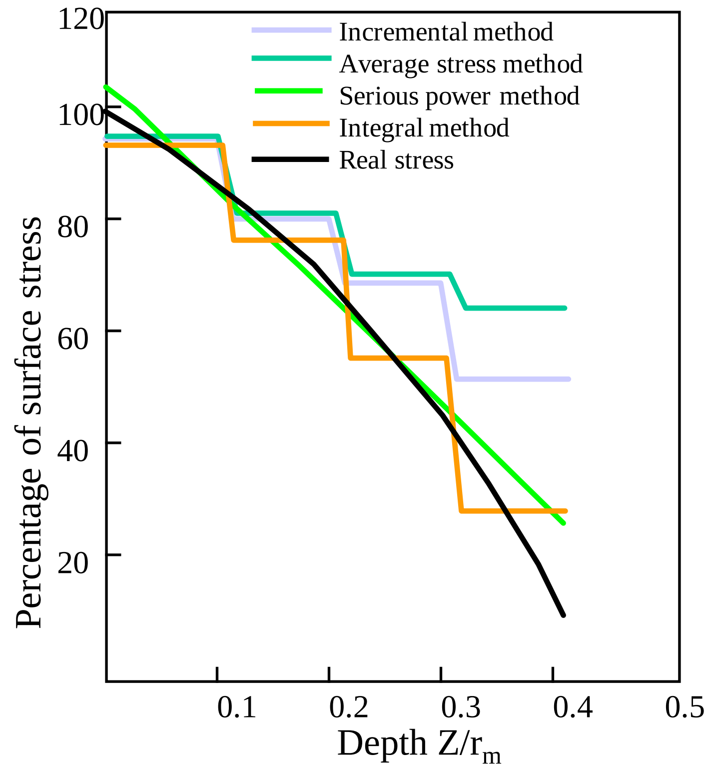
Method to determine
A stress gradient
In depth



Hole-drilling and Ring core (5)

Incremental method

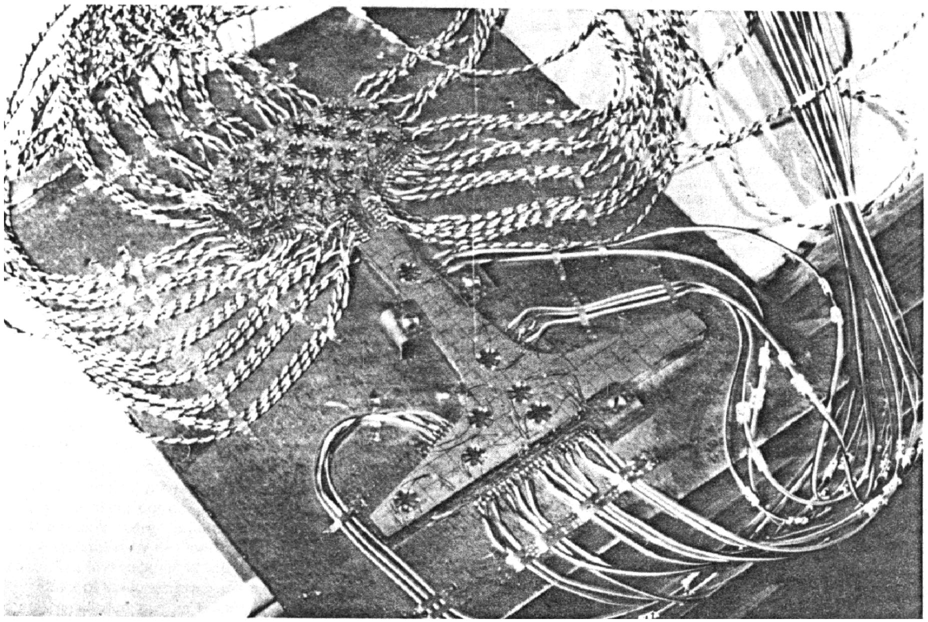




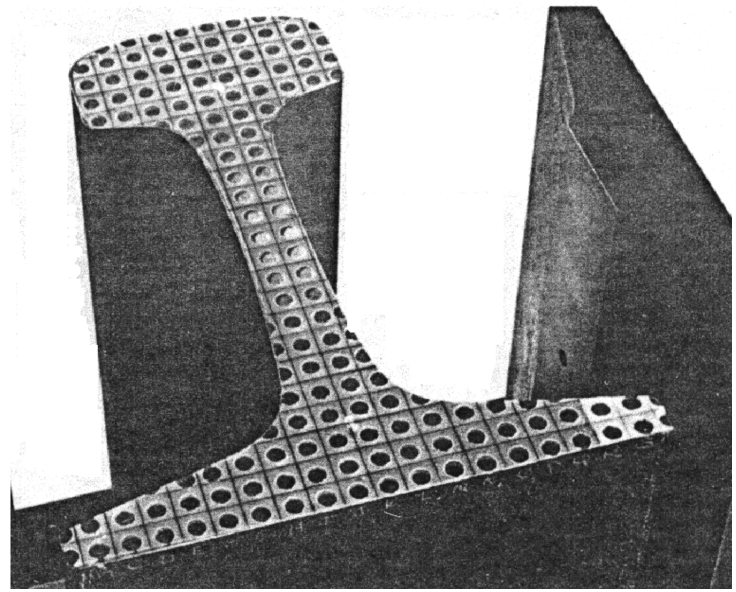
X-ray diffraction method î 1 day
Automated incremental hole drilling î 2 hours

Hole-drilling and Ring core (6)

Case of rail for railway



Instrumentation

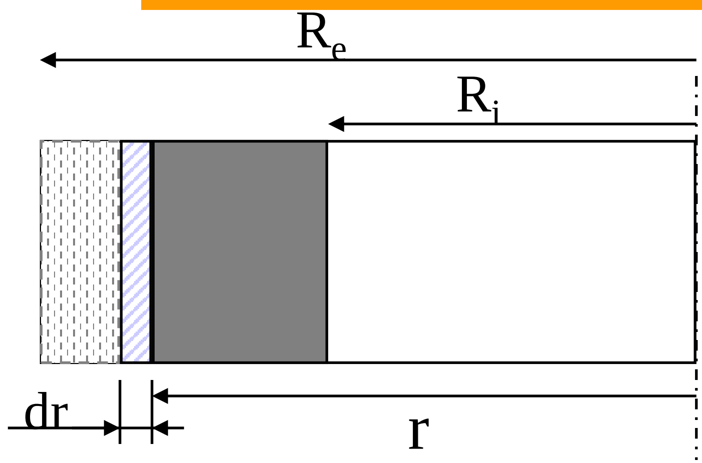


After drilling

Layer remove method – Sachs (1)

Principal and applications of the method

- Hypothesis
  - cylindric component
  - symmetric distribution of residual stress
  - destructive method



This method is spacially used for residual stress determination with thermal or surface mechanical treatment such as shot-peening

Layer remove method – Sachs (2)

Theoritical aspects of the method

$$\Delta = \lambda + \mu\theta$$

$$\Lambda = \theta + \mu\lambda$$

λ : longitudinal strain
θ : circumferential strain
μ : Poisson's coefficient

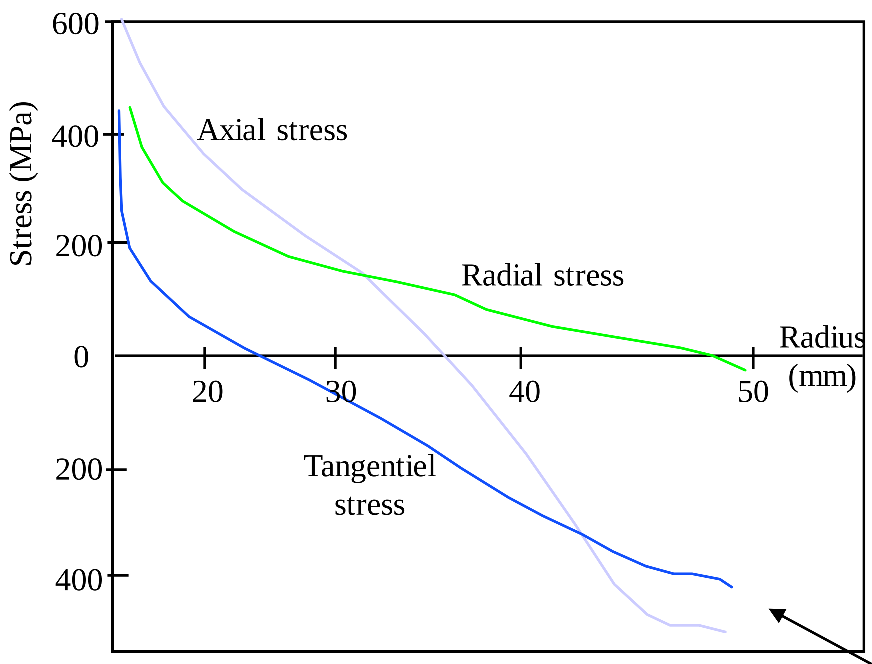
$$\sigma_L = \frac{E}{1-\mu^2}\left[(S_e - S)\frac{d\Delta}{dS} - \Delta\right]$$

$$\sigma_t = \frac{E}{1-\mu^2}\left[(S_e - S)\frac{d\Lambda}{dS} - \frac{S+S_e}{2S}\Delta\right]$$

$$\sigma_R = -\frac{E}{1-\mu^2}\Lambda\frac{S_e - S}{2S}$$

Layer remove method – Sachs (3)

Centre in tension



Bar in Titanium alloy R=50 mm
After quench treatment

Surface in compression

î Advantages

- deep depth
- rapid method

î Disadvantages

- limited geometry
- destructif

Layer remove method – deflexion (1)

- Frequently used to determine the stresses within coatings and layers.

- Deposition of a layer can induce stresses which cause substrate to curve

- Curvatures can be measured using **contact methods** (profilometry, strain gauges) or **without direct contact** methods (video, **laser scanning**,

grids, double crystal diffraction topology)

- Curvature is related to the **residual stress** using **Stoney's equation**

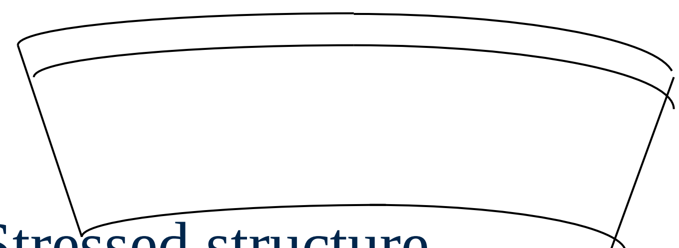
Layer remove method – deflexion (2)

Stoney's Equation

$$\sigma = (E_s / (1-\nu_s)) * (t_s^2 / t_l) * [1/R_2 - 1/R_1)$$

Where, $E_s/(1 - \nu_s)$ is the substrate biaxial modulus, t_s and t_l are substrate and film thickness, R_1 and R_2 are radia of curvature of substrate before and after deposition respectively. It is assumed that $t_l << t_s$

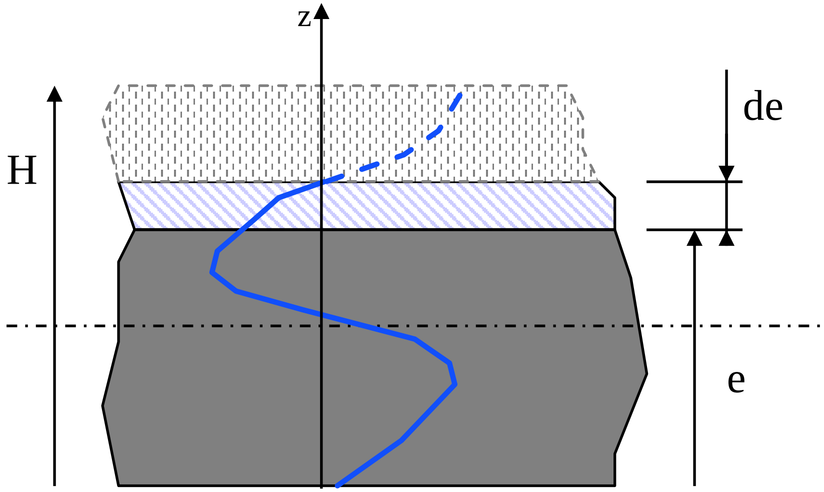
Free and unstressed film and substrate

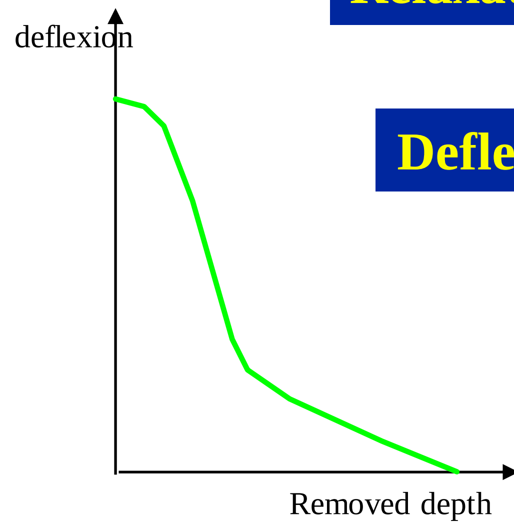


Stressed structure

Layer remove method – deflexion (3)

Massive component → **Cutting** → **Relaxation** → **Deflexion measurement** → **Stress Calculation**



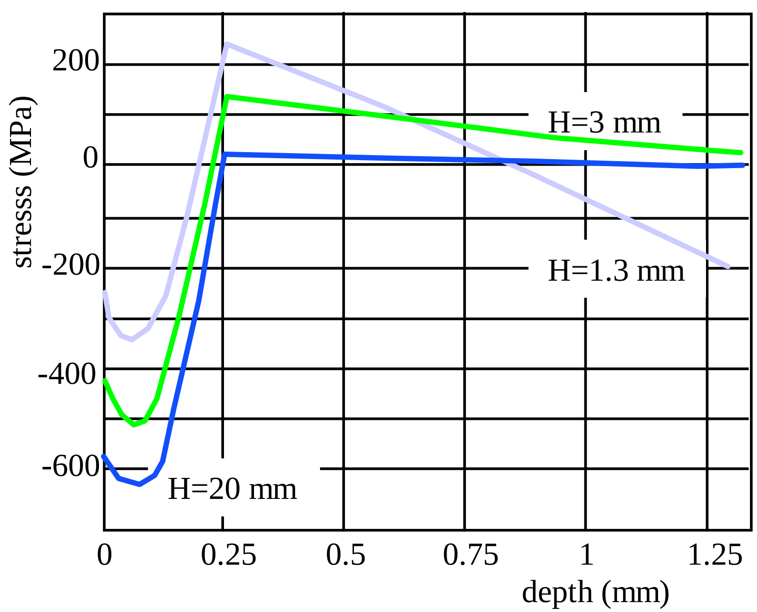


Hypothesis

- samples with great length comparing to it's width
- σ_{33} : negligible
- σ_{11} : principal axis
- material removing should not introduce additional stress

Layer remove method – deflexion (4)

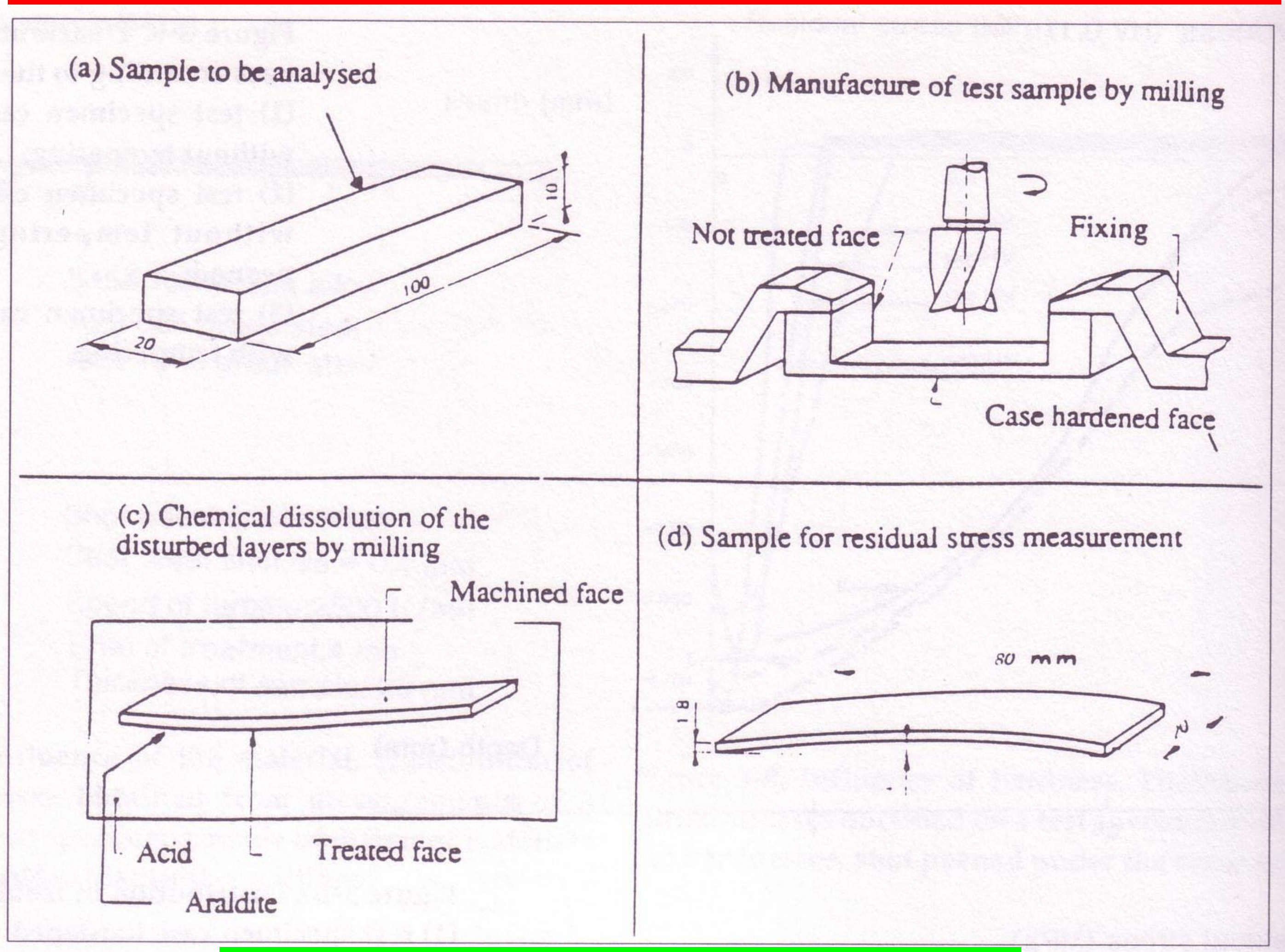
$$\sigma_e = -4\frac{E_e^2}{3l^2}\frac{df_e}{de} + \frac{8E_e}{l^2}(f_H - f_e) + \frac{8E}{3l^2}\int_H^e edf$$



î same conditions than surface shot-peening

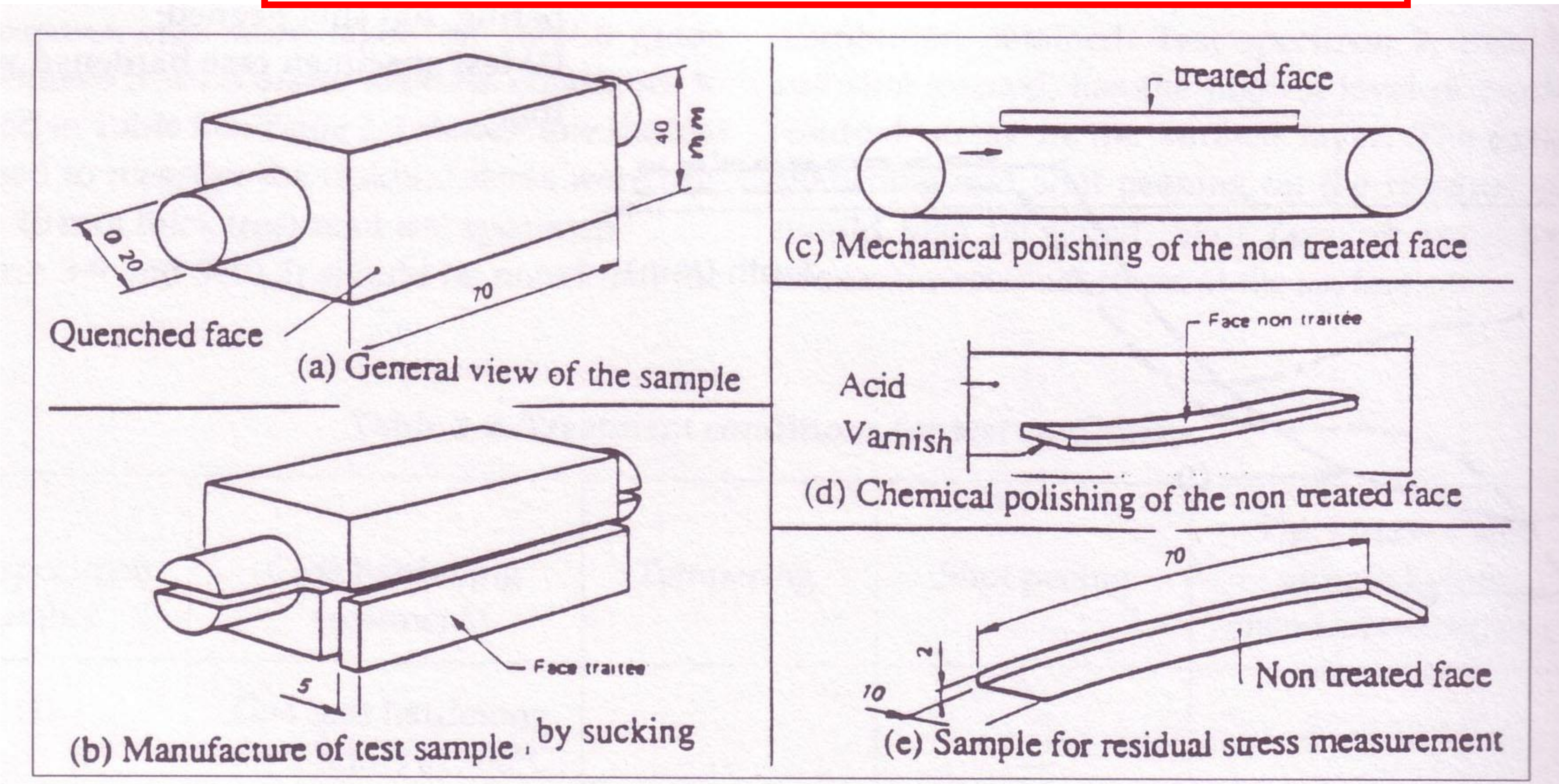
 3 samples with differents thickness

Layer remove method – deflexion (5)



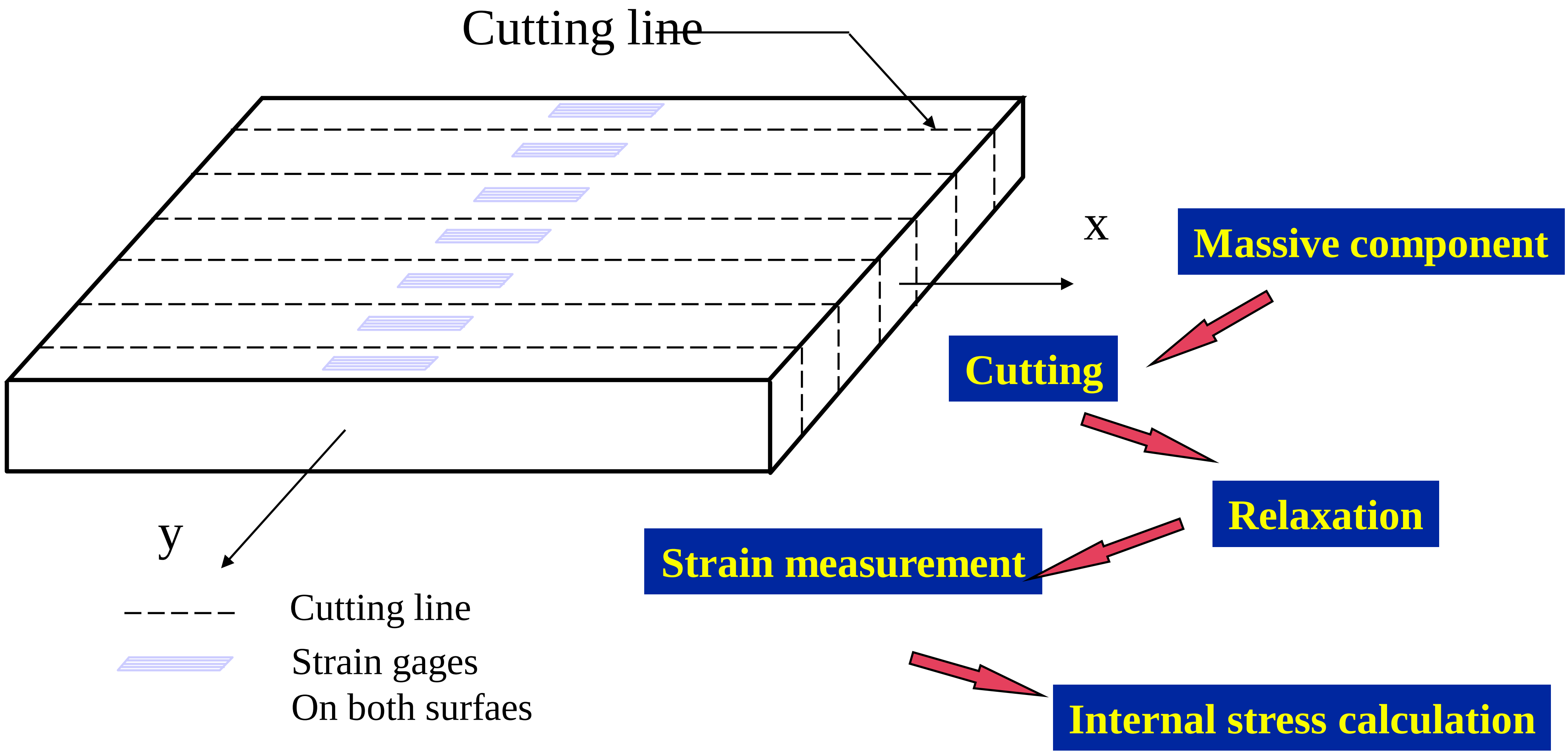
Preparation for tested specimens

Layer remove method – deflexion (6)

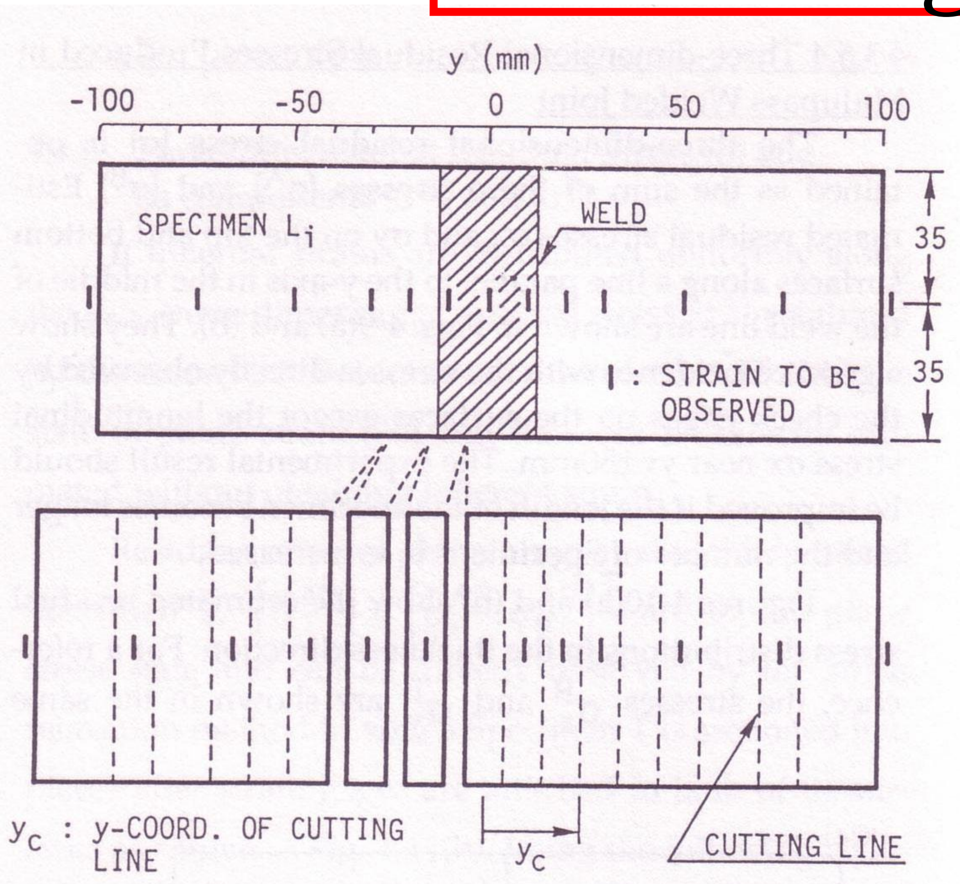


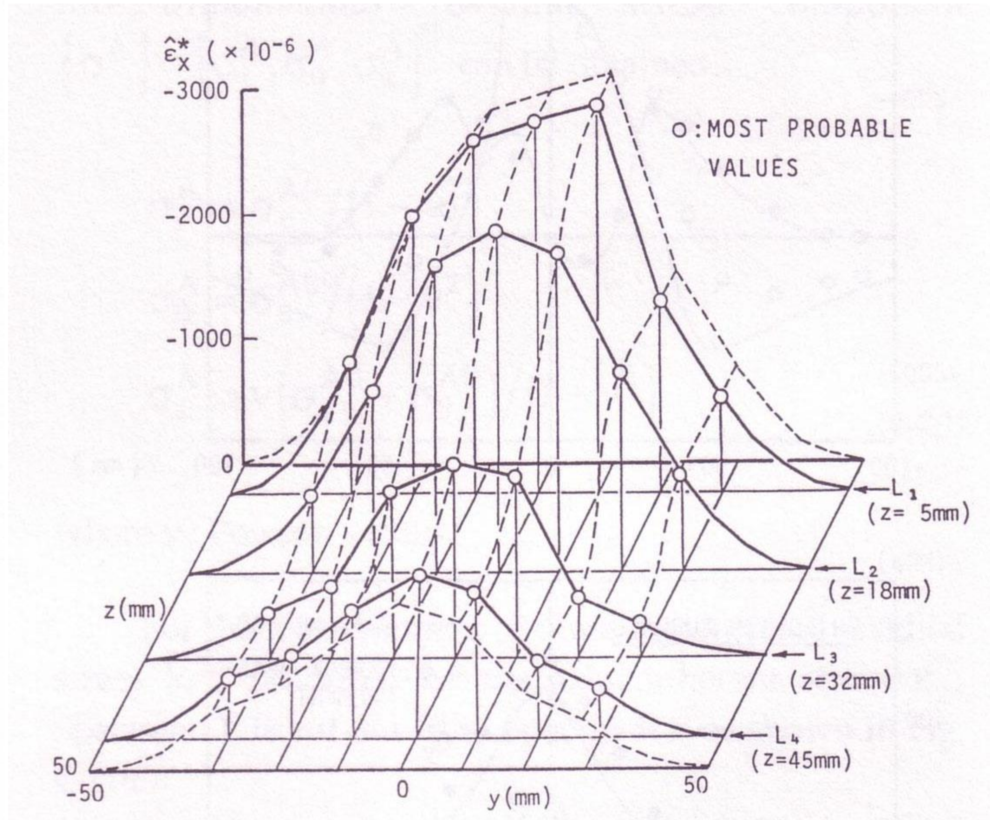
Used method for speciment preparation from induction treated component

Sectioning method (1)



Sectioning method (2)





Location of observing points and procedure of cutting

Most probable values of longitudinal inherent strains

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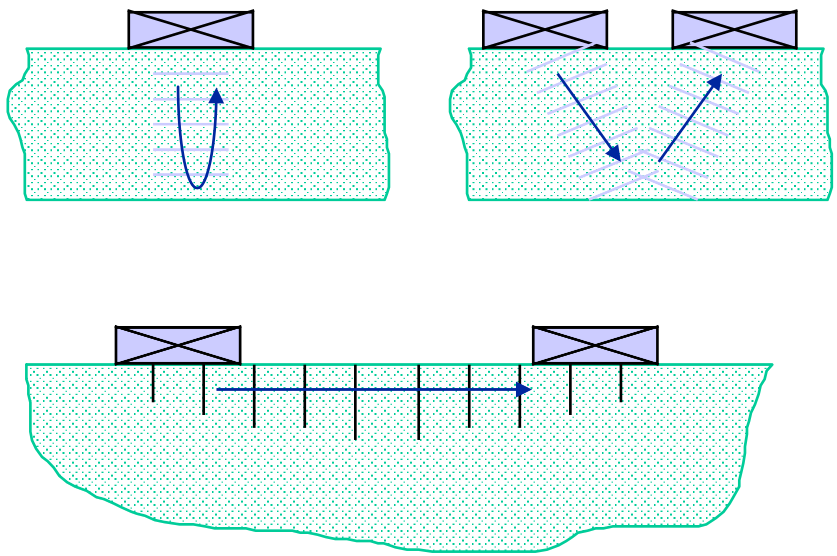
Comparaison of methods

Methods for RS determination by stress and strain field modification

	Modification of stress field due to material removing			
Method	**Hole-drilling**	**Ring core**	**Deflexion**	**Sachs**
Hypothesis on material	Plate stress	Plate stress	Plate stress length >> width >> e	Cylindric piece Homegeneous field on surface
Analysisvolume	2 mm² x 2 mm	100mm² x 200mm	10 cm² x 0.1 mm	1 cm² x 0.2 mm
Mini. depth	20 µm	20 µm	20 µm	1 mm
Multiphase materials	Global information	Global information	Global information	Global information
Anisotropy sensibility	No	No	No	No
Instrument	Portable	Portable	No	No
Exprimentation duration	5 minutes	30 minutes	1 hour	1 hour
Equipement cost	7 K€ to 40 K€	7 K€ to 40 K€	8 K€	8 K€ to 50 K€

Ultrasonic method (1)

Variation of speed of wave propagation



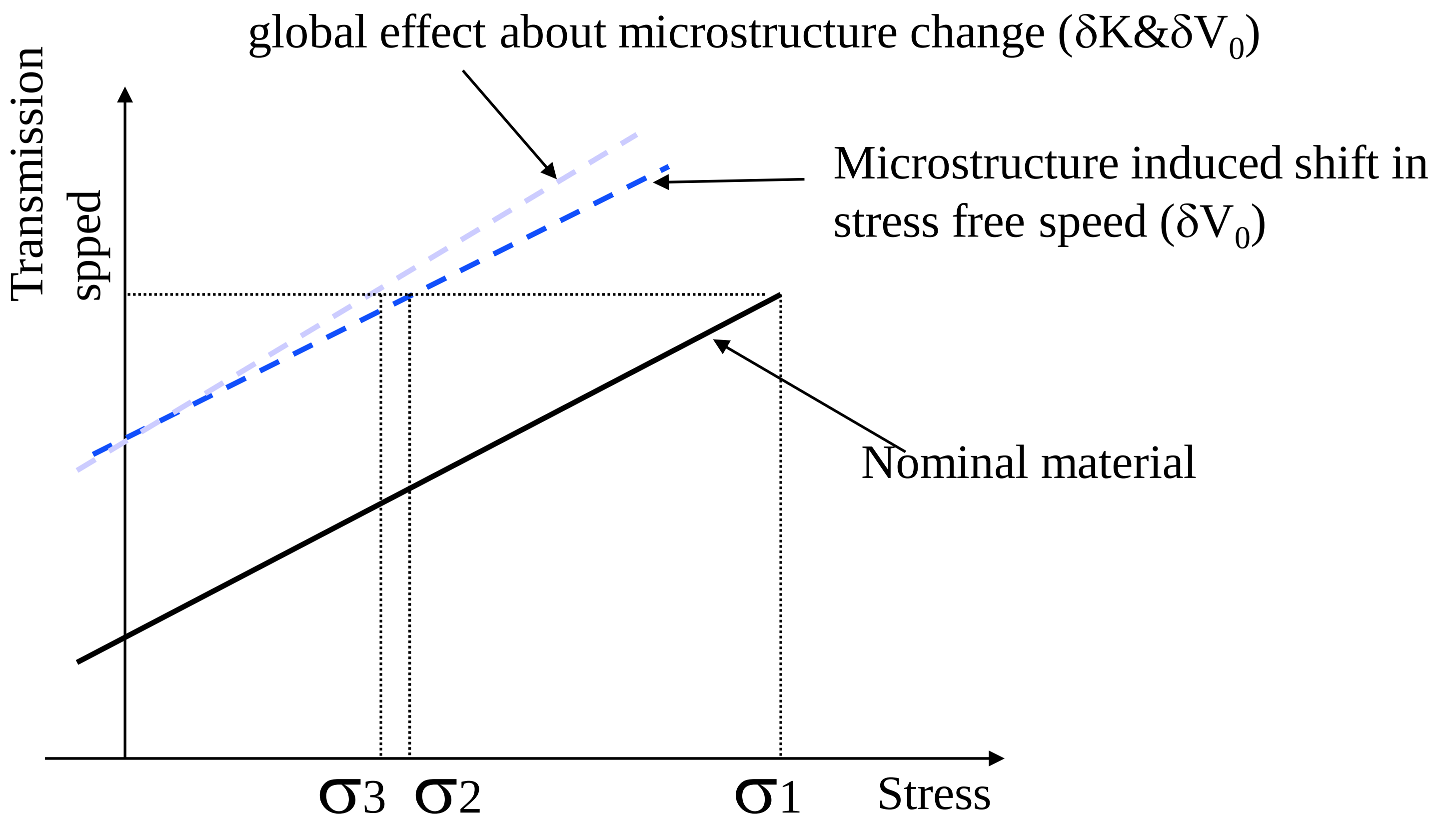
$$V = V_0 + K\sigma$$

speed of wave propagation in material without stress

Acoustoelastic constant In function with material

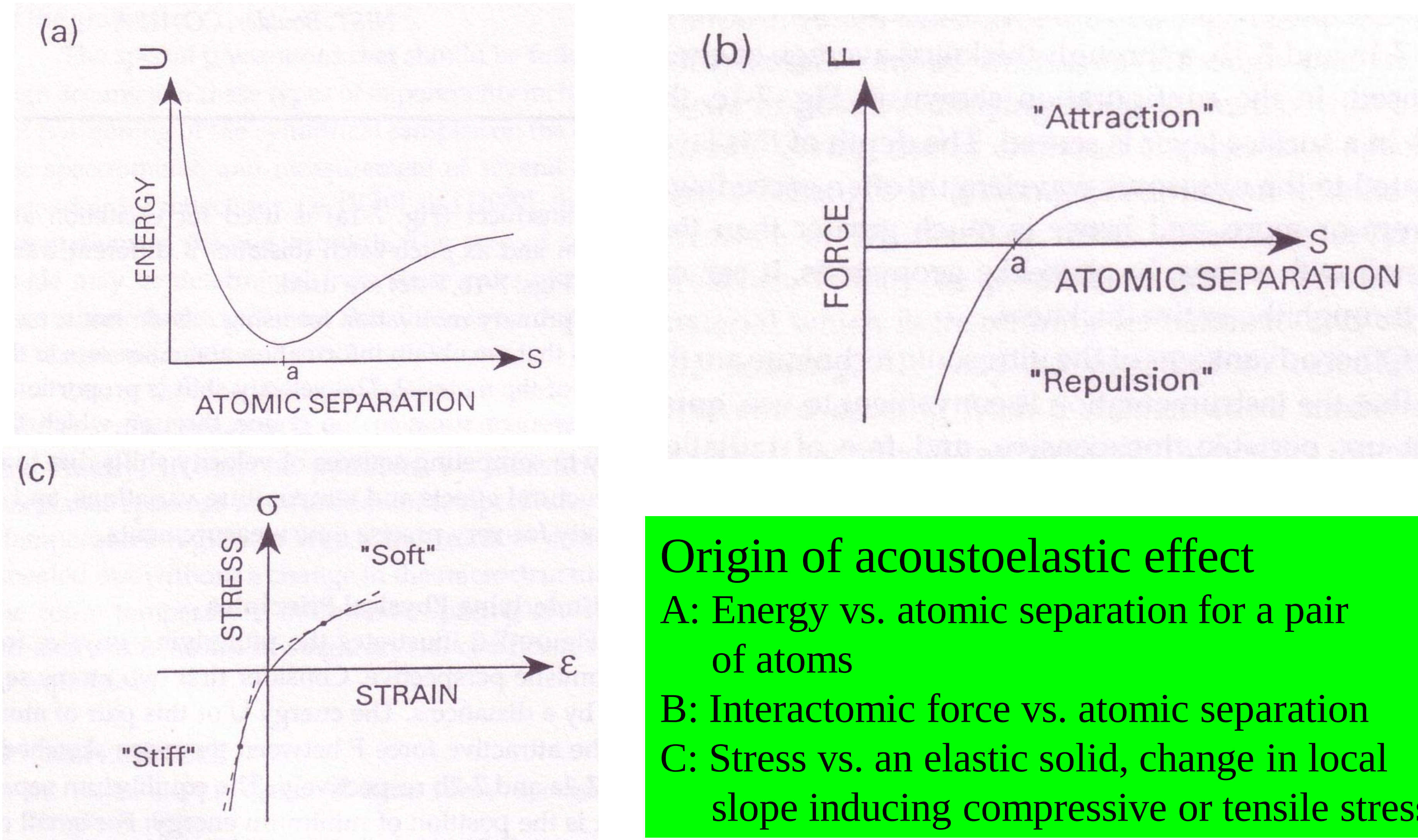
- information about the average information of internal stress
- information only in analysed zone

Ultrasonic method (2)



- î susceptibility on thermal and microstructural variations
- î weak spatial resolution
- î great precision about the measurement vs. time

Ultrasonic method (3)



Origin of acoustoelastic effect

A: Energy vs. atomic separation for a pair of atoms

B: Interactomic force vs. atomic separation

C: Stress vs. an elastic solid, change in local slope inducing compressive or tensile stress

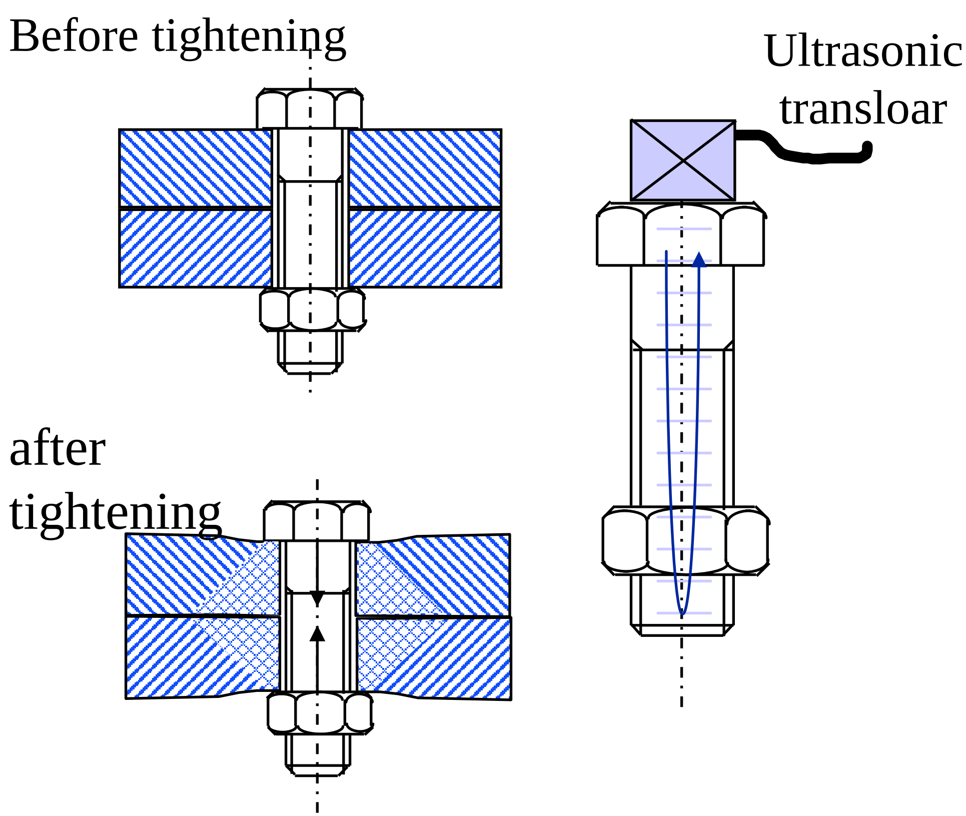
Ultrasonic method (4)

	$\hat{K}_1$	$\hat{K}_2$	$\hat{K}_3$	$\hat{K}_4$	$\hat{K}_5$
Polystyrene[a]	-93.7	-4.49	-4.59	-40.80	-1 1.46
Magnesium (Tooling Plate)[b]	-19.36	-11.76	-1.02	-4.03	0.58
Al Alloy (2S)[b]	-7.73	1.12	-2.15	-3.96	0.79
Rail Steel #1[c]	-1.21	0.18	-0.12	-0.75	0.02
Rail Steel #4[c]	-1.21	0.11	-0.11	-0.71	0.01
Tungsten (Sintered)[b]	-0.91	-0.09	0.15	-0.54	-0.10
Pyrex[a, e]	8.26	-0.99	5.85	4.04	-4.72
ZrO_2[d] (partially stabilized)	-1.59	0.13	-0.31	-0.93	0.26
Al_2O_3[d]	-0.52	-	-	-0.38	-0.014
WC-Co ceramic[d]	-0.28	0.003	-	-0.21	0.003

Acoustoelastic constants of selected materials (%GPa)

Ultrasonic method (5)

Example



- λ = 6 mm/µs
- bolt length = 15 mm
- extention = 5 µs
- 10% variation of σ leads to

  0.1% of speed
- precision on length: 7.5 µm
- time resolution: 2,5 ns

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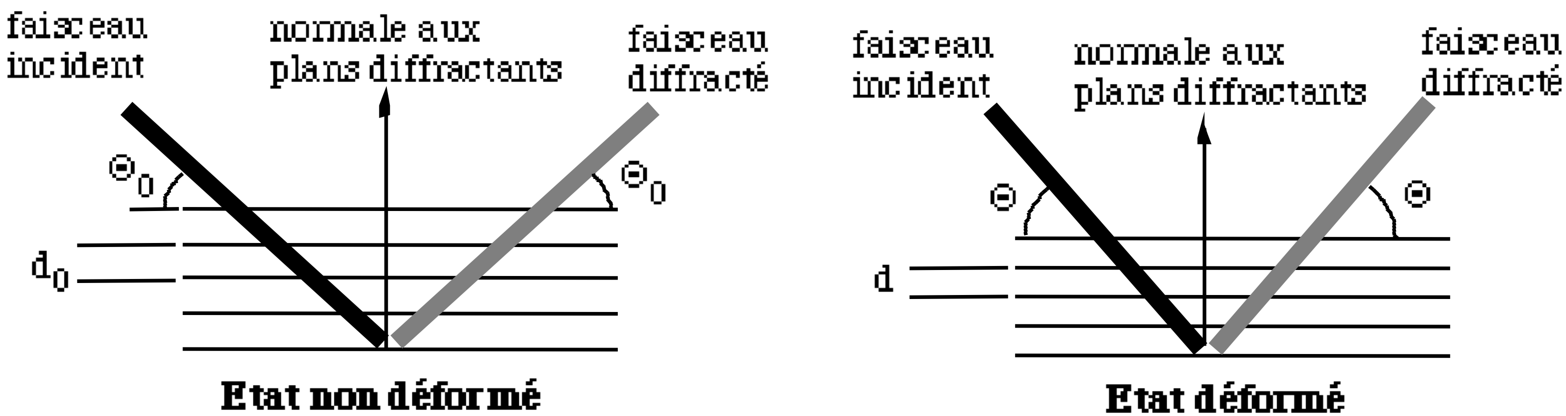
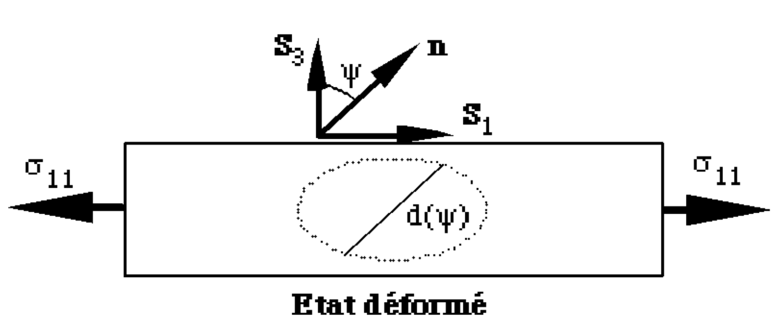
Principal: R.S. and XRD (1)

Parameters	**Explanatory Factors**
Peak Position	* Geometrical aberrations from apparatuses * Average chemical composition * Macroscopical stresses
Peak Intensity	* Phases distribution * Orientation distribution
Peak Forme	* Instrumental broadening * Chemical composition distribution * Elastic strain distribution * Coherent domain size/crystallite size * Strain inside coherent domain/crystallite

Principal: R.S. and XRD (2)





Principal: strain measurement (1)

Measured strain	Different approaches
conventional strain :	$\varepsilon = \frac{d - d_0}{d_0}$ ➔ $\varepsilon = \frac{\sin\Theta_0}{\sin\Theta} - 1$
rational strain:	$\varepsilon = \ln\left(\frac{d}{d_0}\right) = \ln\left(\frac{\sin\Theta_0}{\sin\Theta}\right)$
development in series:	$\ln(x) - \left(\frac{x-1}{x}\right) + \frac{1}{2}\left(\frac{x-1}{x}\right)^2 + \ldots$ ➔ $\varepsilon = 1 - \frac{\sin\Theta}{\sin\Theta_0}$
Differentiation of Bragg law	$\varepsilon = -\operatorname{cotg}\Theta_0 . \Delta\Theta$

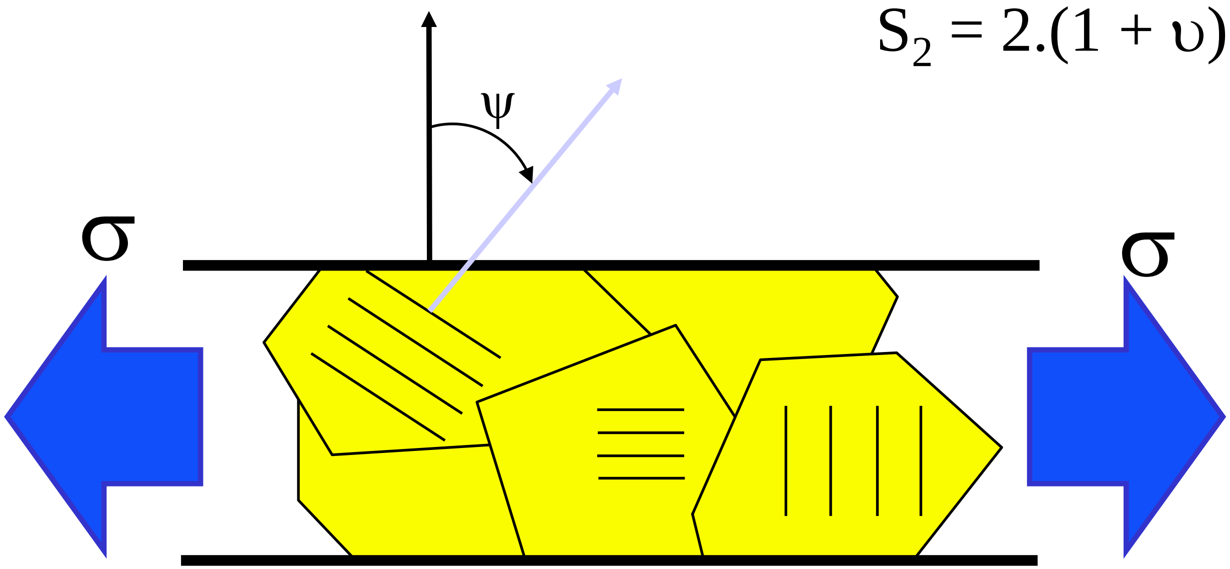
strain ε ➔ diffraction peak shift $\Delta 2\theta$

Principal: strain measurement (2)

$\sin^2\psi$ law:

$$\varepsilon_{\phi\psi} = \frac{1+\nu}{E}\sigma_{\phi}\ \sin^2\psi - \frac{\nu}{E}\mathrm{Tr}(\boldsymbol{\sigma}) = \frac{1}{2}S_2.\sigma_{\phi}.\sin^2\psi + S_1.\mathrm{Tr}(\boldsymbol{\sigma})$$

$S_2 = 2.(1 + \upsilon) / E$ $\quad$ $S_1 = -\upsilon/E$

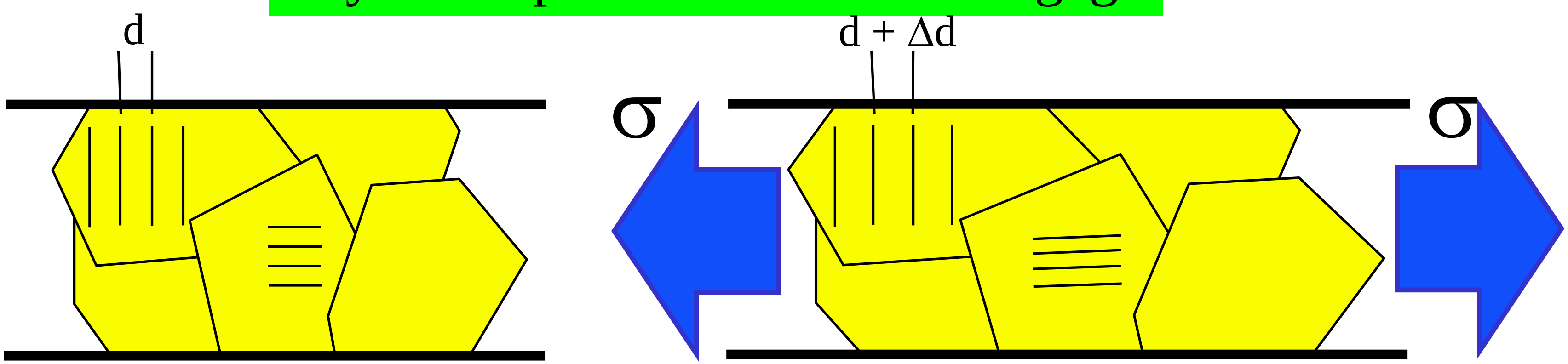


Assumptions

- Homogeneous and isotropical materials
- Elastic strain
- Surface analysis

Principal: stress calculation (1)

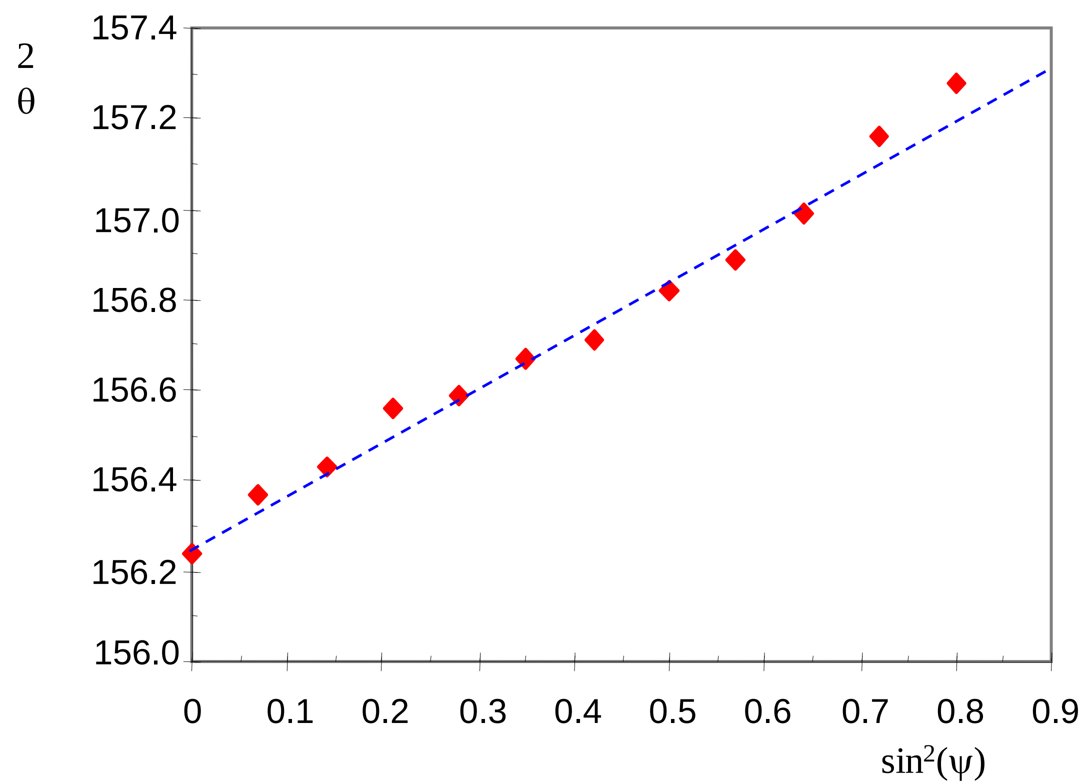
Crystallin plans = Deformation gage



Homogeneous elastic deformations of crystals in material

Variations of inter-reticular distances = macroscopic deformations

Principal: stress calculation (2)



{211} planes of α-Fe with $\lambda_{CrK\alpha}$ $2\theta = 156{,}3°$

σ = -350 MPa ± 30

Principal: analysis standard

- **European stadard**

FA121454 ISSN 0335-3931

norme européenne **NF EN 15305**

Avril 2009

norme française

Indice de classement : **A 09-185**

ICS : 19.100

Essais non destructifs

Méthode d'essai pour l'analyse des contraintes résiduelles par diffraction des rayons X

E : Non-destructive Testing — Test Method for Residual Stress analysis by X-ray Diffraction

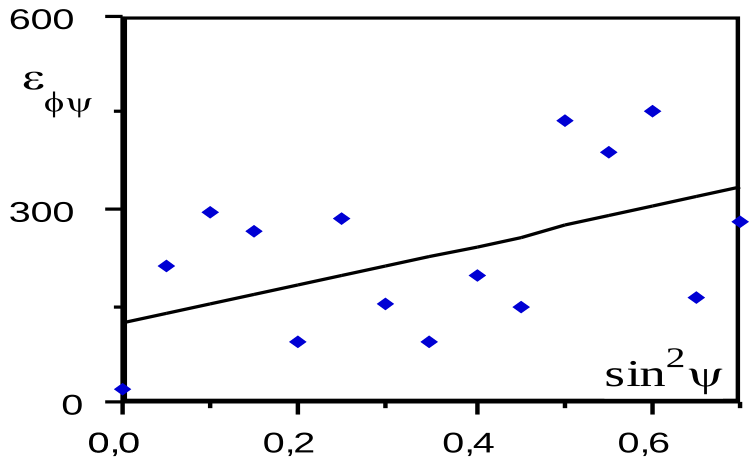
D : Zerstörungsfreie Prüfung — Röntgendiffraktometrisches Prüfverfahren zur Ermittlung der Eigenspannungen

Principal: precautions and limits

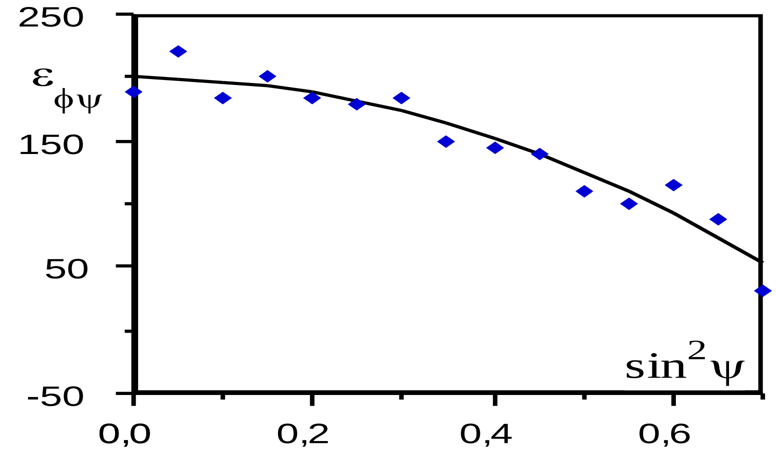
- Analysis volume and depth:
  $\approx$ mm^2 x a few tens μm
- Stress average values:
  in the volume and on the depth
- Elastic Constant and anisotropy:
  microscopical REC
- Micro-macro passage :
  REC evaluation or measurement

- Grains size
- Gradient
- Texture
- anisotropy
- Multiphase
- Specimen geométry
- Thin films
- crystalline symmetry

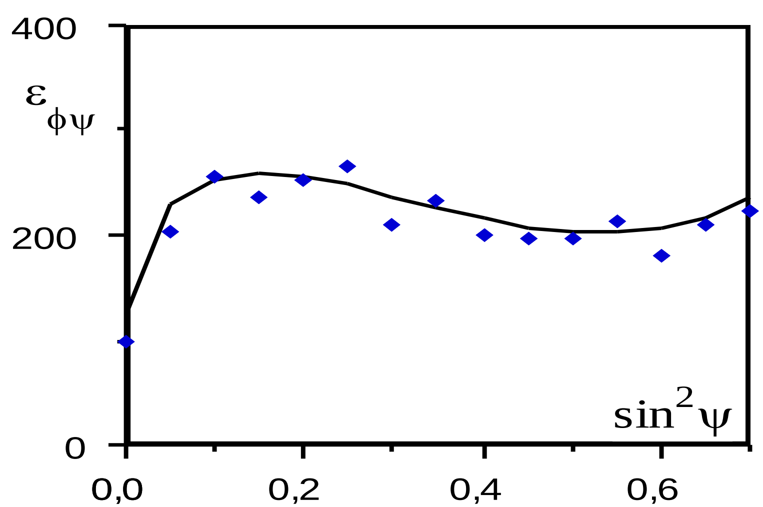
precautions and limites



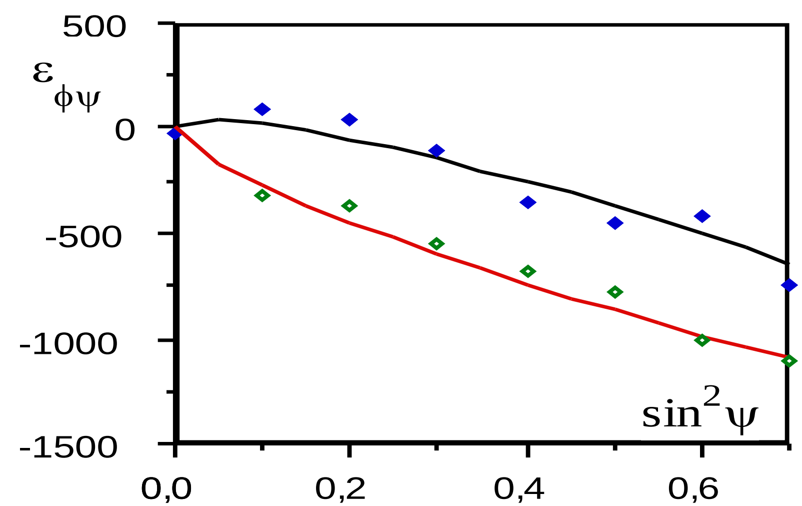
(a) Material with coarse grains



(b) Material with stress gradient

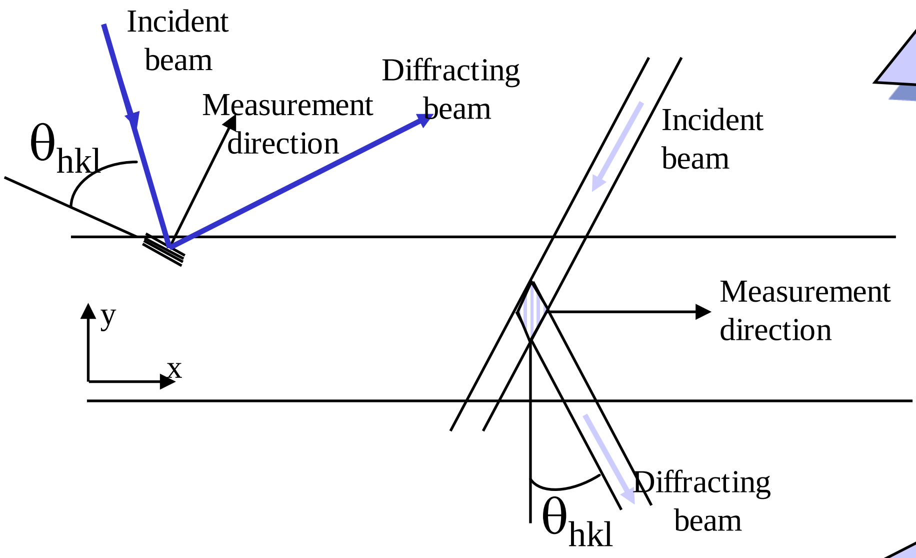


(c) Material with strong texture

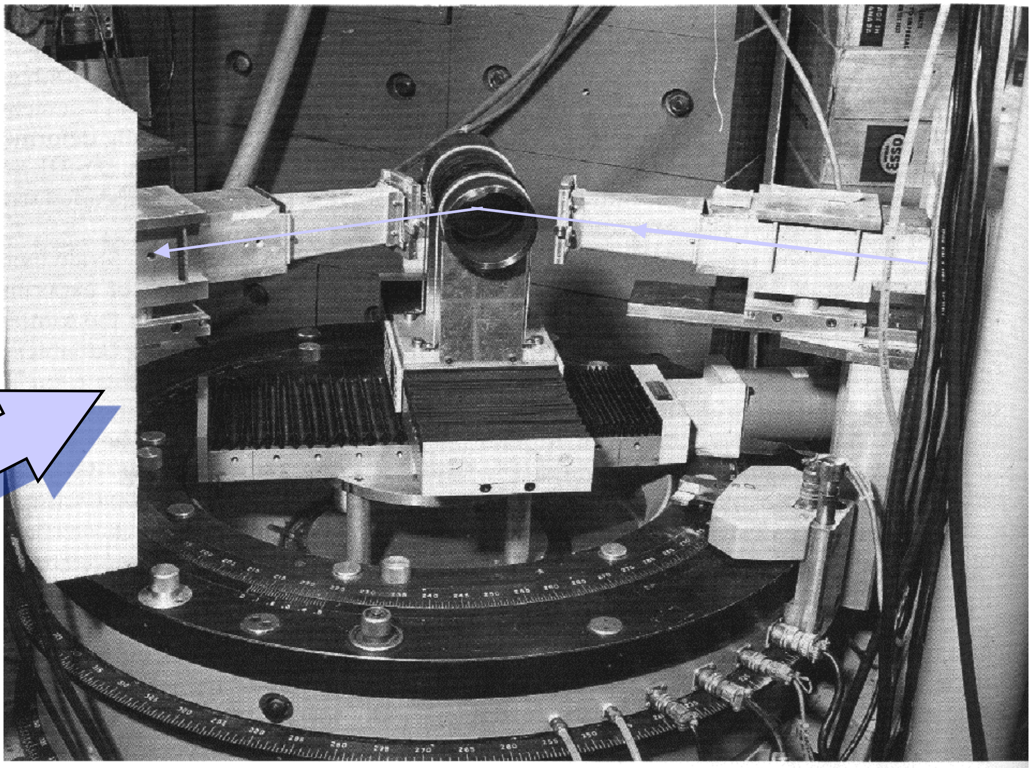


(d) Isotropic materail, with 3-axial stress state

Neutron diffraction (1)

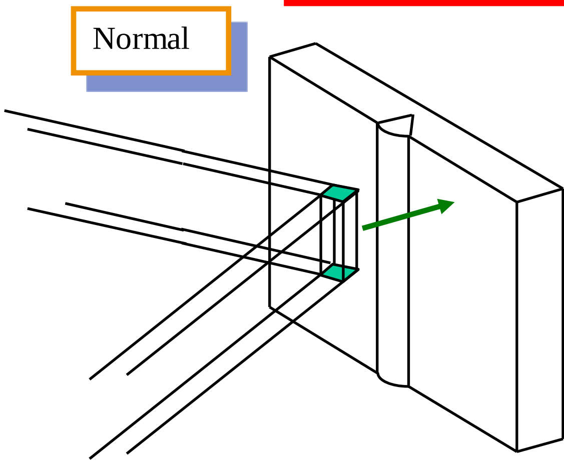


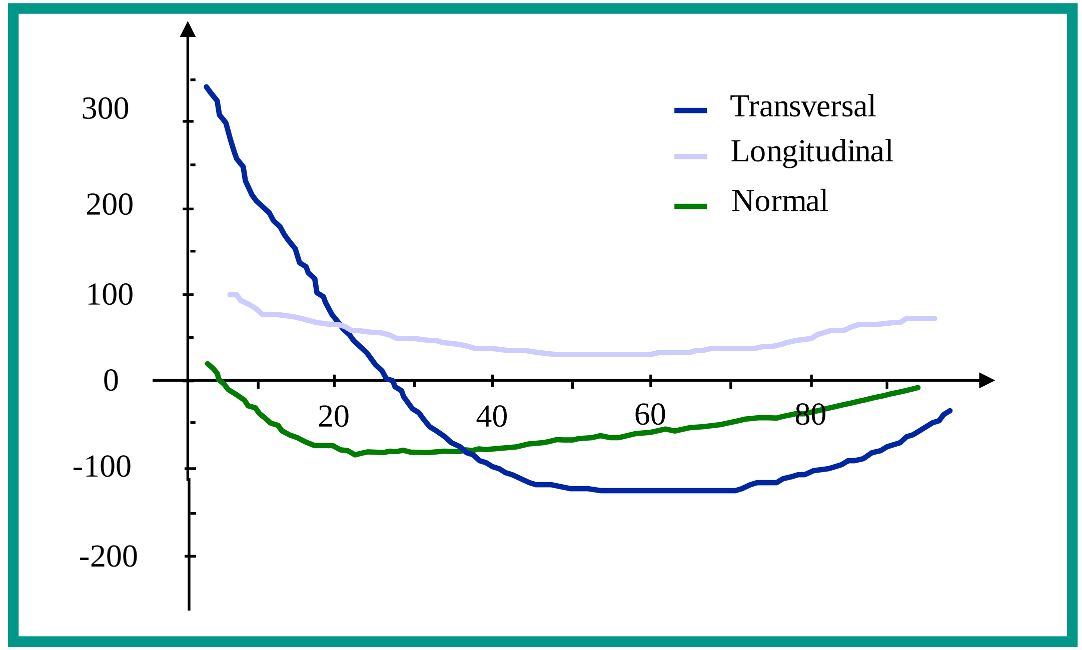
Principal of method

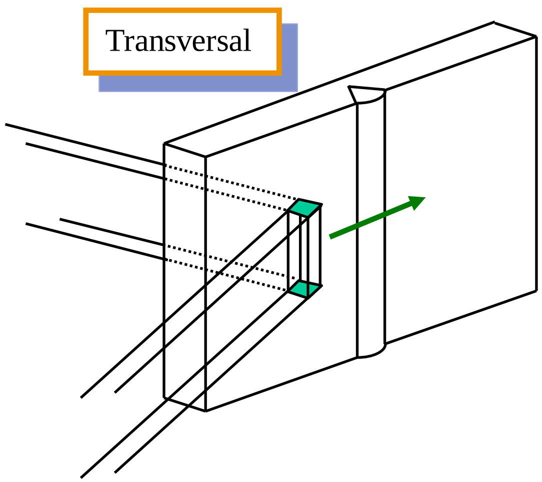


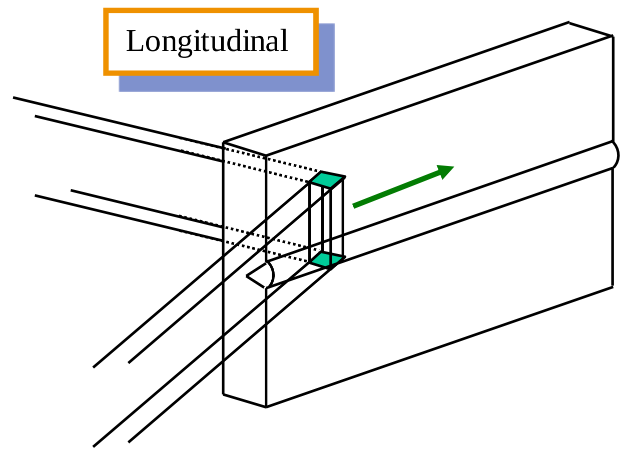
Goniometer for residual
Stress analysis
By neutron diffraction

Neutron diffraction (2)

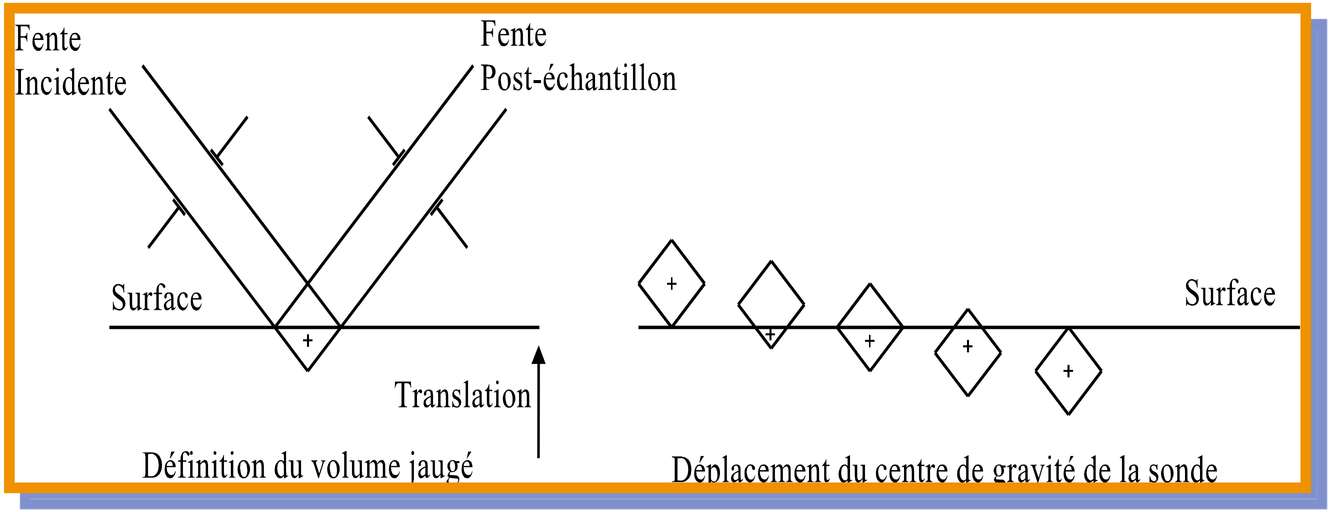


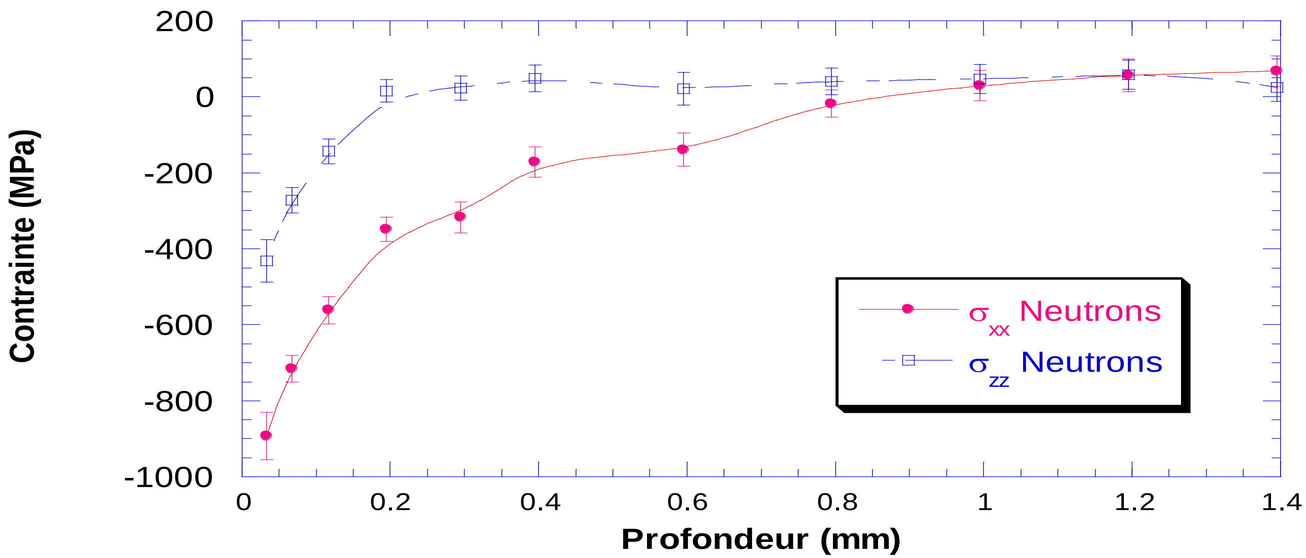






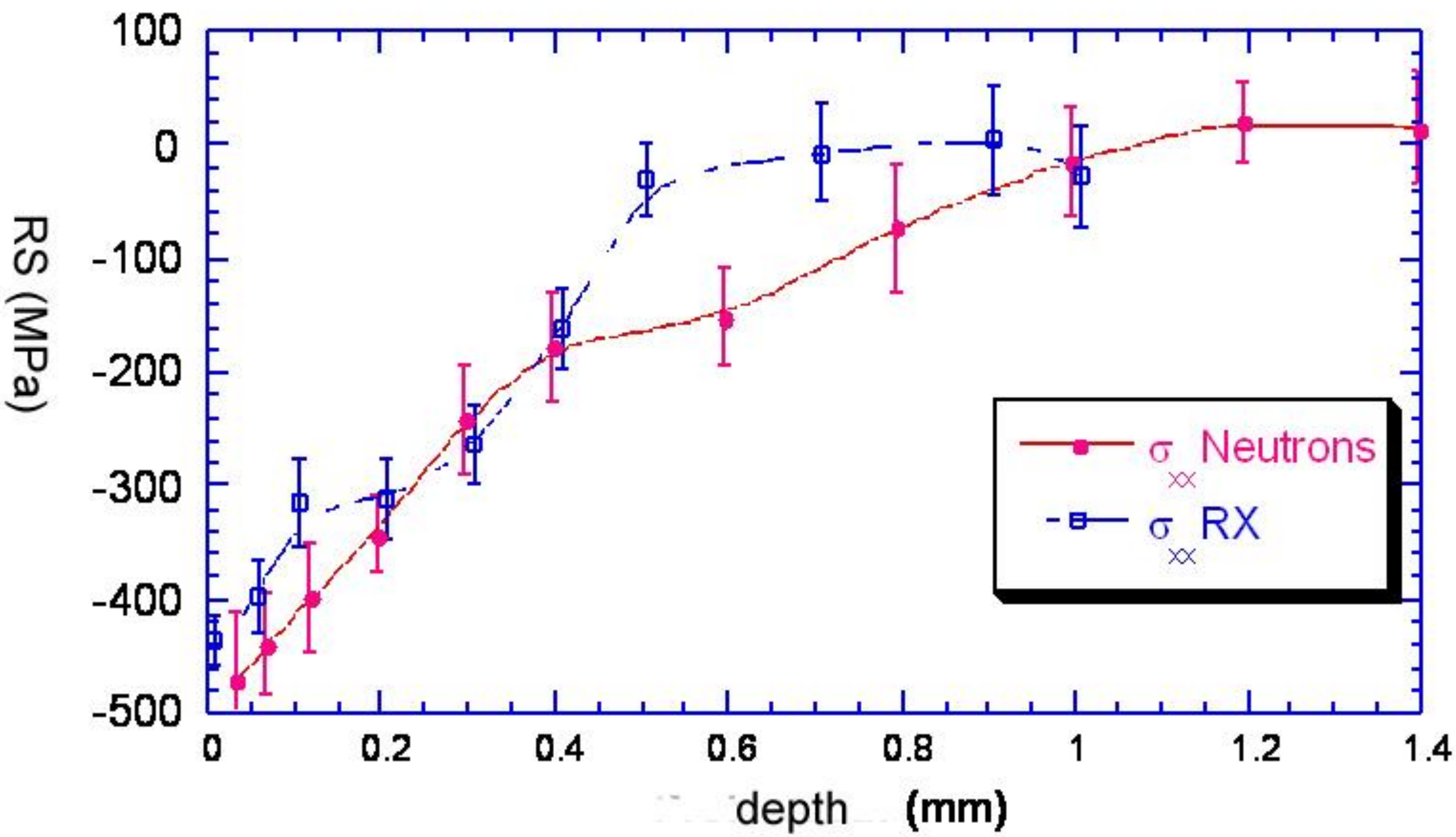
Neutron diffraction (3)



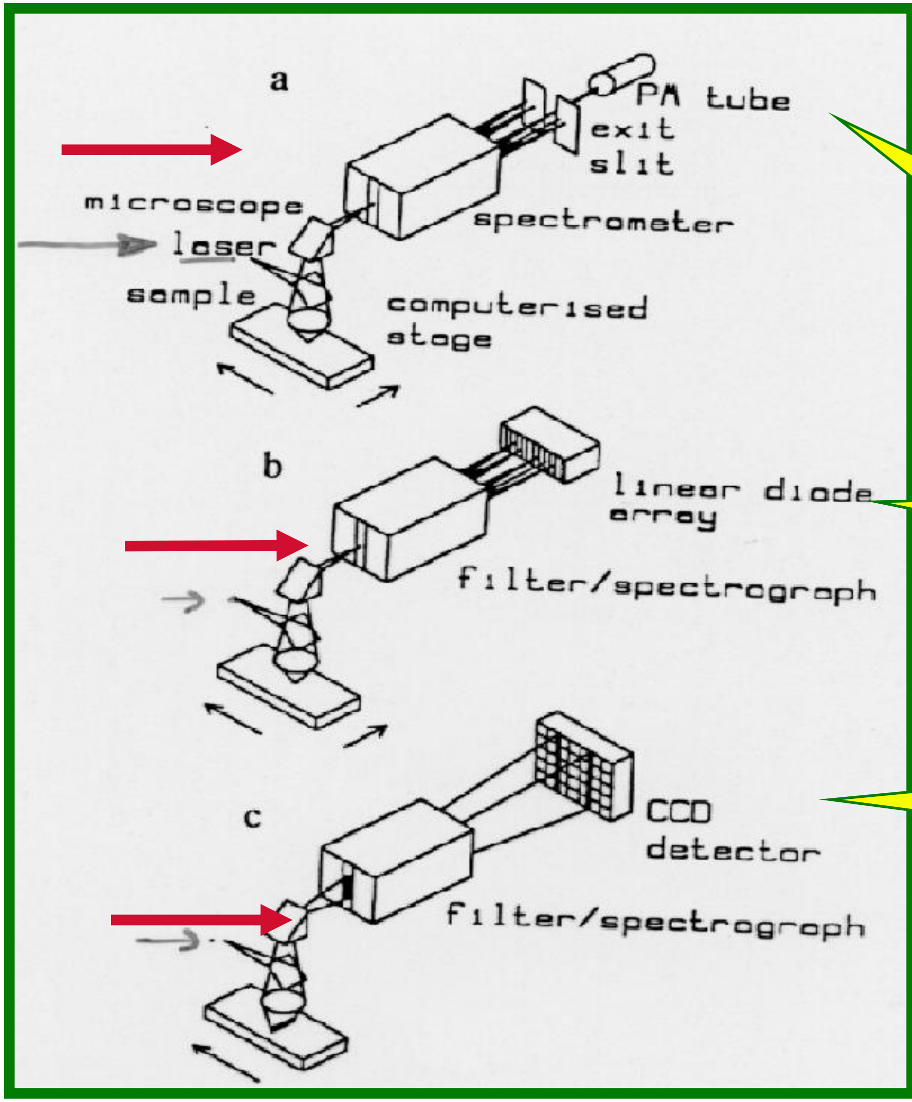


Neutron diffraction (4)

Comparasion between X-ray diffraction and neutron diffraction



Raman effect (1)



Differents configurations of Raman microscope

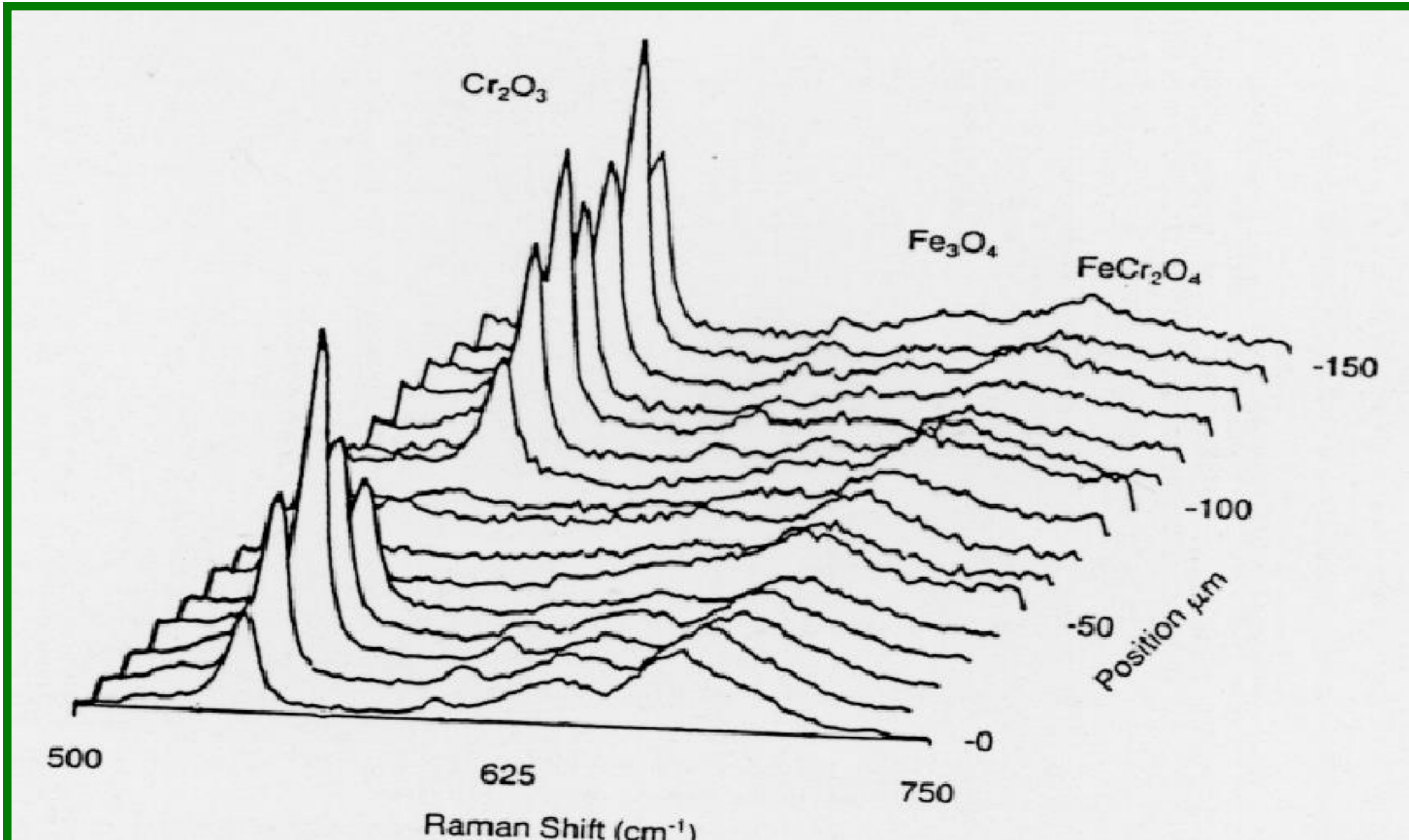
A Photomuliplificator Detector

B Linear Detector

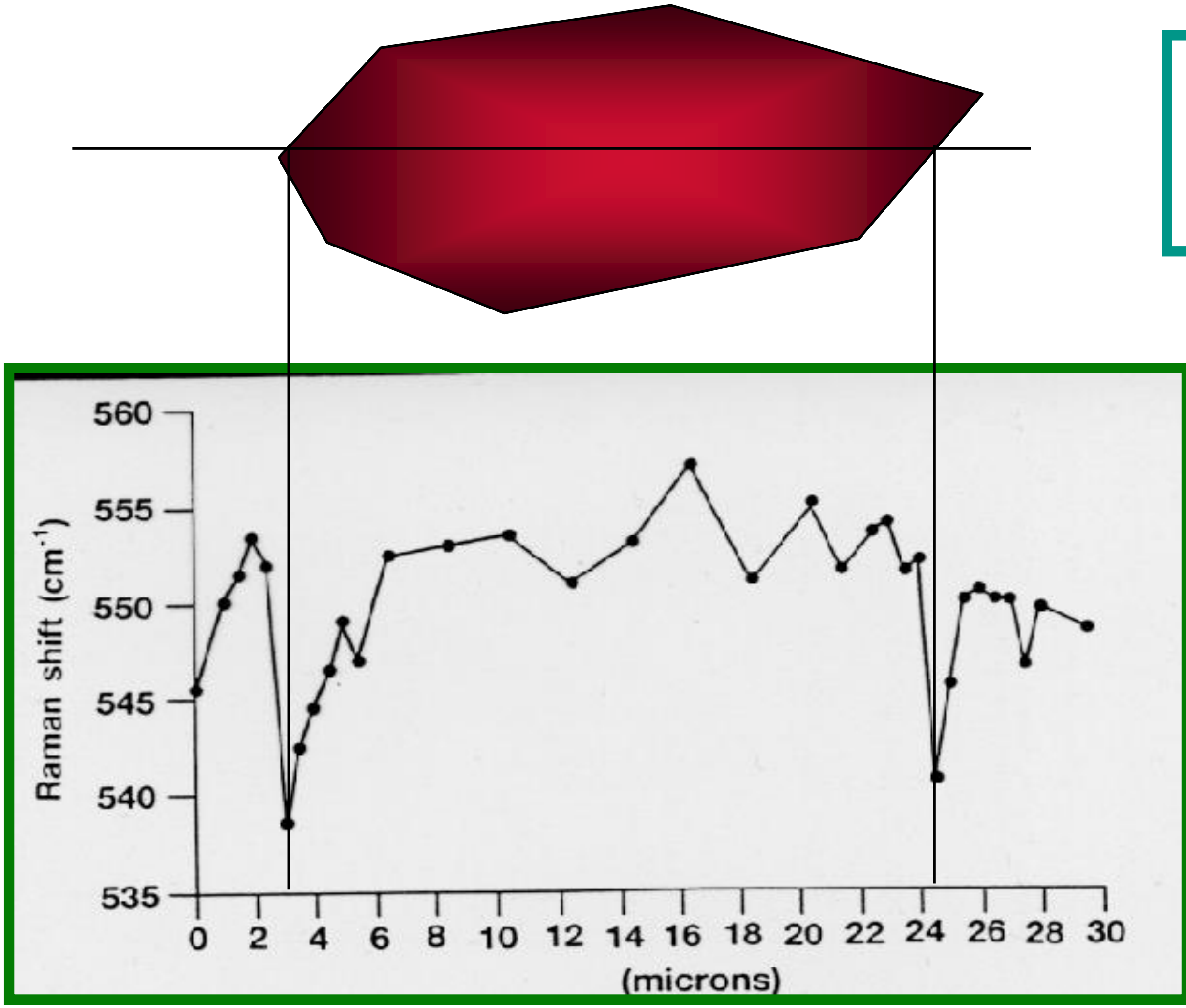
C CCD Detector

Spot dimension > 5 µm

Raman effect (2)



Raman effect (3)

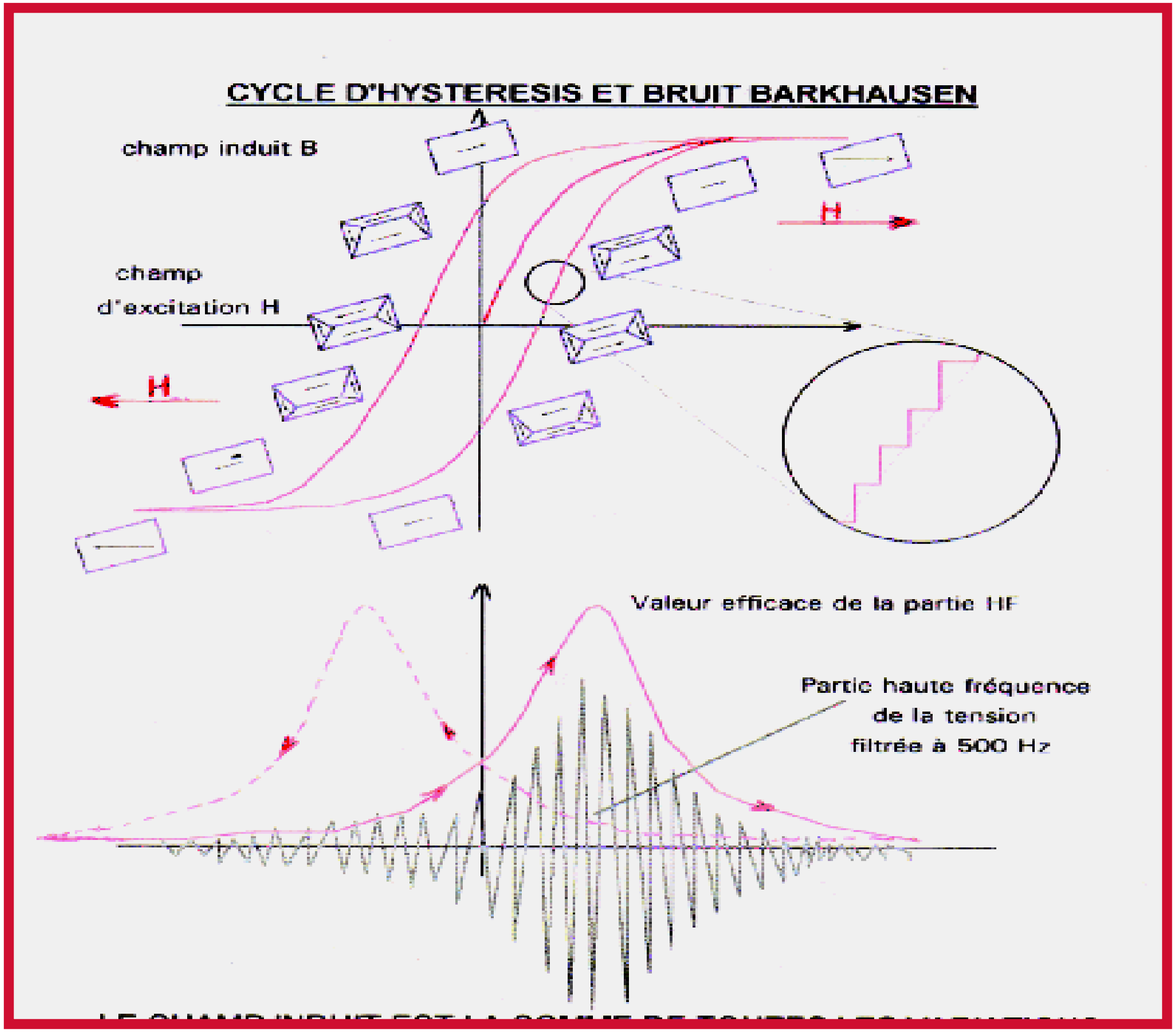


decrease of Cr_2O_3 at grain boundary leads to apparition of intra-granular stress

Compression

Tension

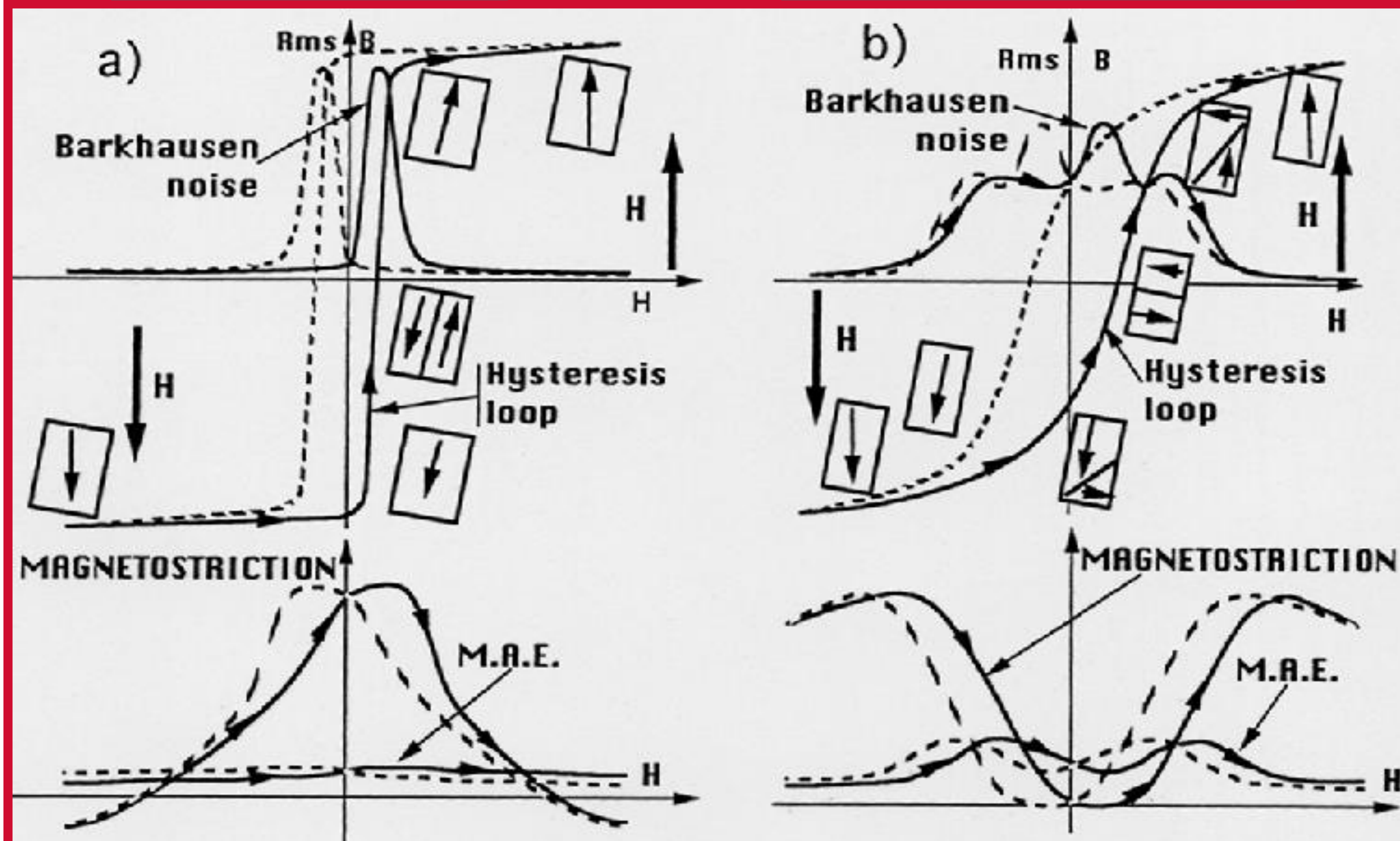
Barkhausen noise (1)



Barkhausen noise (2)

Applied tension

Applied compression



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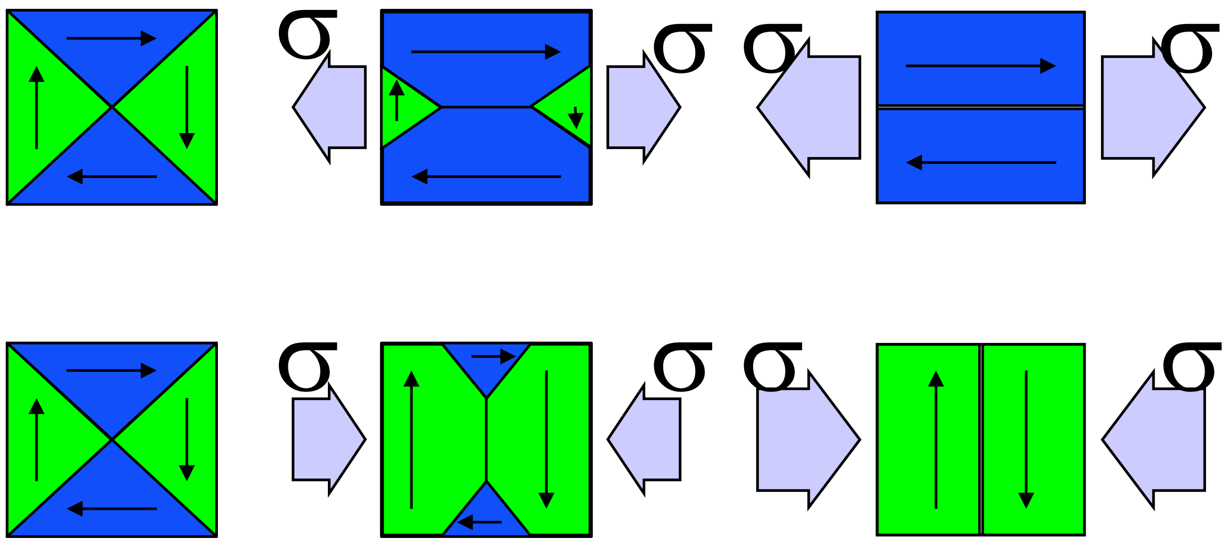
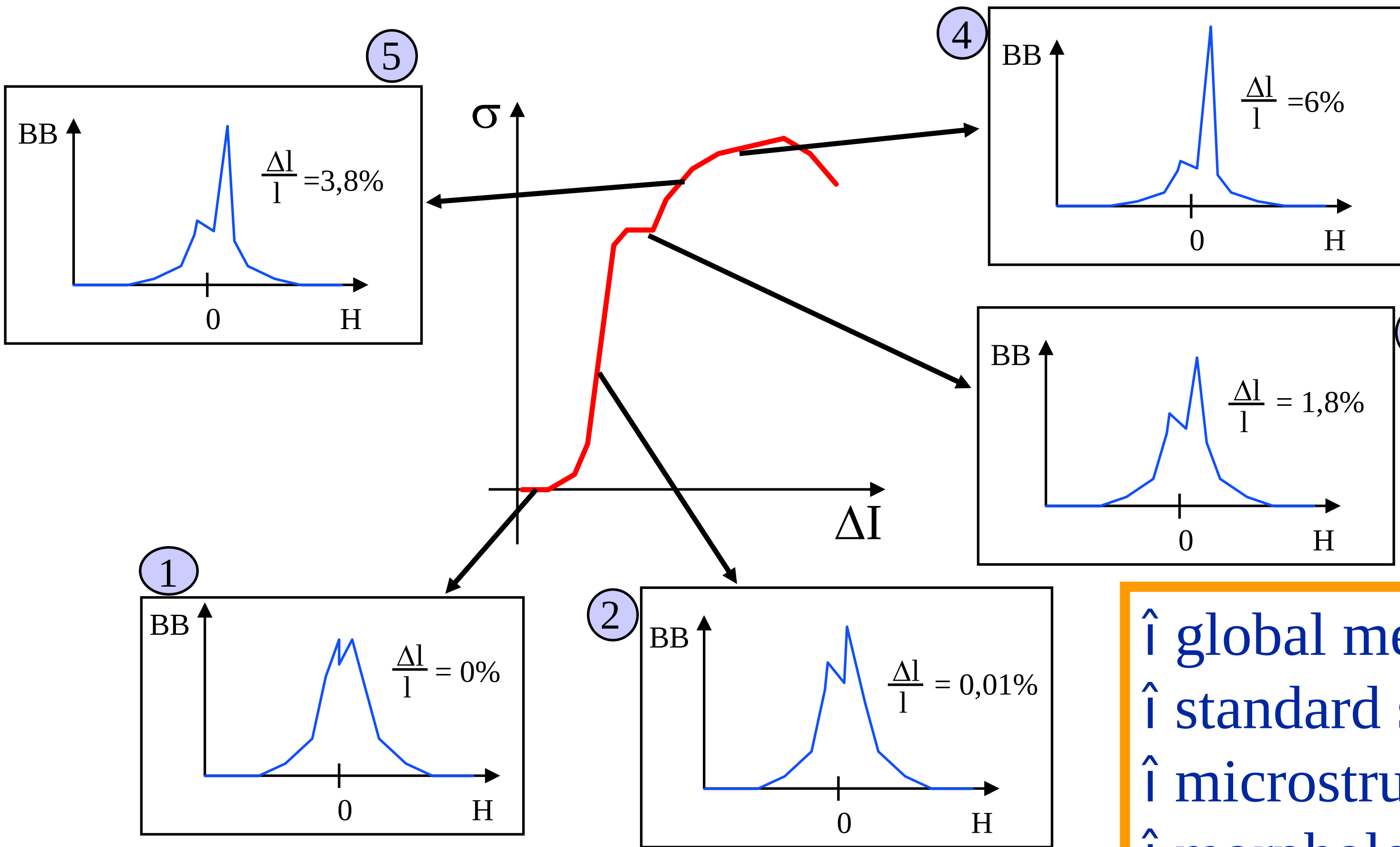
Barkhausen noise (3)

Stress field modification leads to a modification of arrangement of Weiss magnetic domains



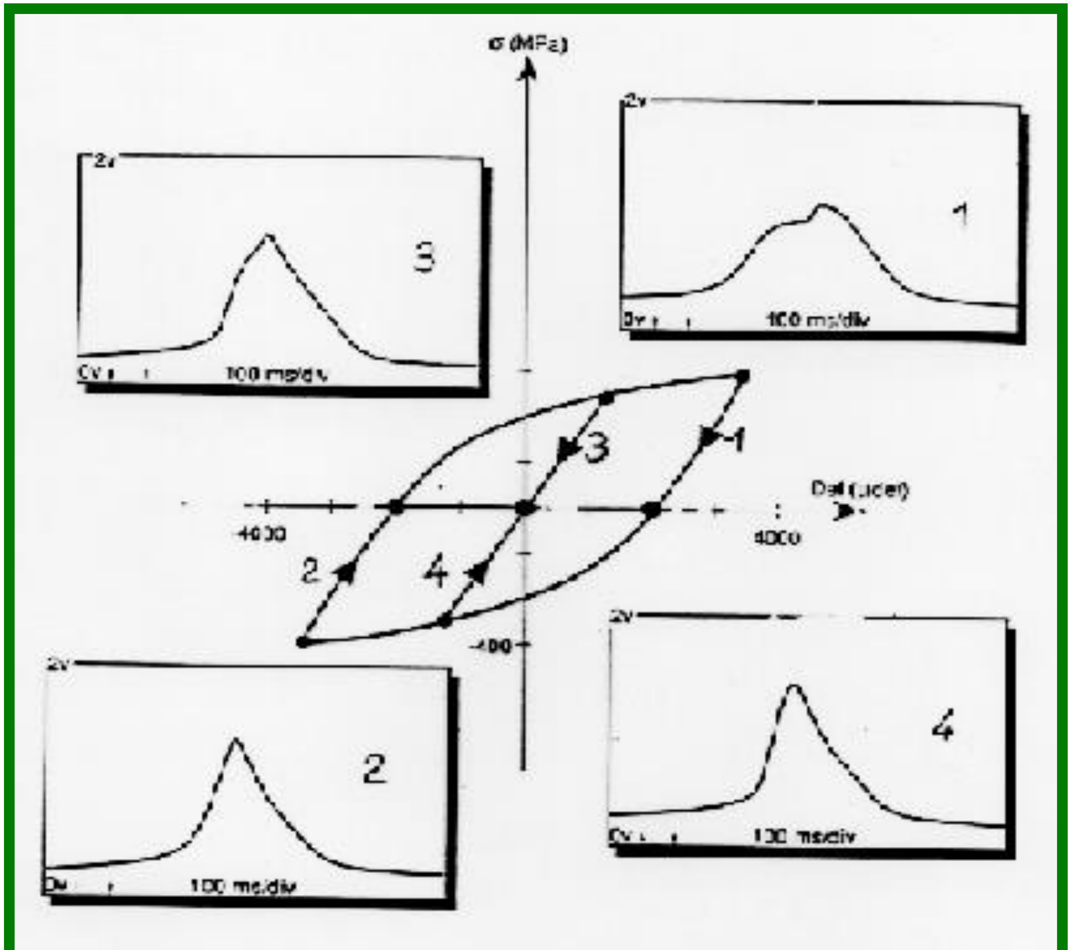
î non destructive method î ferromagnetic material

Barkhausen noise (4)



î global method
î standard specimen
î microstructure
î morphology
î macroscopic method

Barkhausen noise (5)



INFLUENCE DU MODE DE DECHARGEMENT
SUR LE BRUIT FERROMAGNETIQUE

Unloading effect on ferromagnétic noise

Comparaison of methods

Methods for RS determination by physical order measurement

	d_{hkl} : interreticular distance		US propagation speed	magnetism
Method	**DRX**	**Neutron**	**Ultrason**	**Barkhausen**
Hypothesis on material	Polycristalline with small grains (< 50 μm) homogeneious, isotrope	polycristalline, homogeneious, isotrope	Homogeneious, isotrope σ homogeneous in analysis zone	ferromagnetic
Analysis volume	1 mm^2 x 15 μm	10 mm^3	30 mm^2 x thickness	1 mm^2 x 1 mm
Depth	5 to 100 μm	50 mm	some 100 cm	1 mm
Info. Multiphase materials	Information in each phase	Information in each phase	Global information	Global information
Sensibility to l'anisotropy	Yes	No	Yes	Yes
Instrument	portable	No	Portable	portable
Experimentation duration	5 to 30 minutes	2 hours	2 minutes	several s
Equipement cost	70 K€ to 200 K€	Price of a reactor ?	30 K€ to 150 K€	7 K€ to 50 K€

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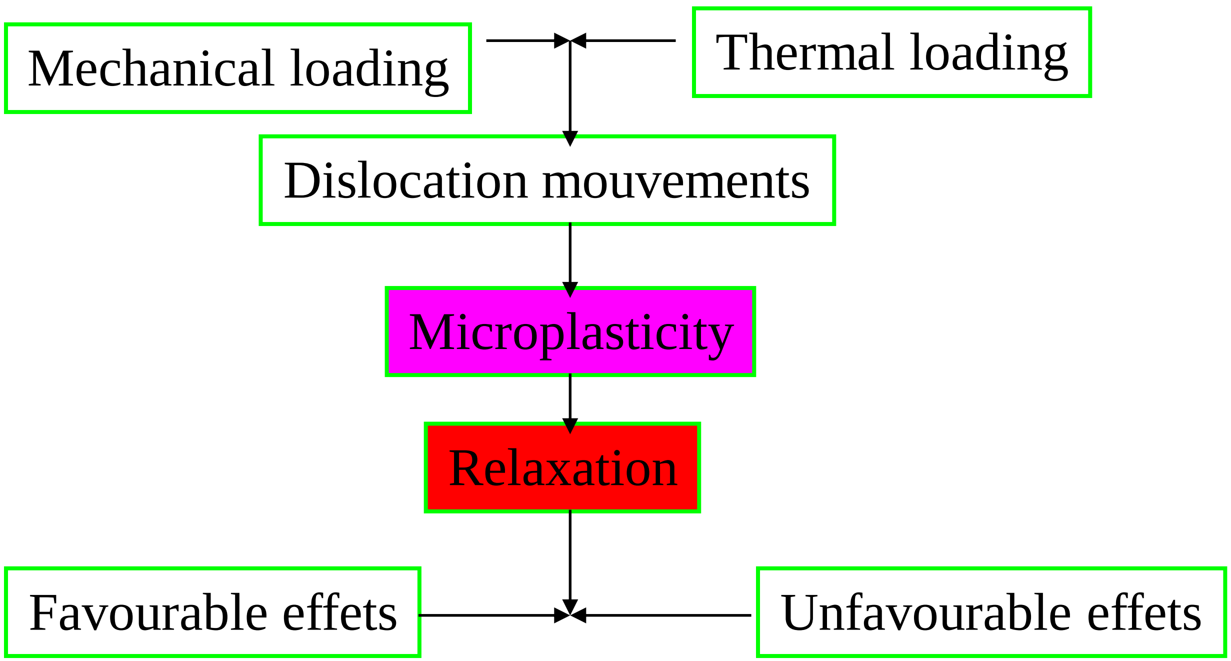
RS relaxation (1)

- Fatigue
- Vibration
- Plastic deformation

- Isotherme heat
- Thermal cycling



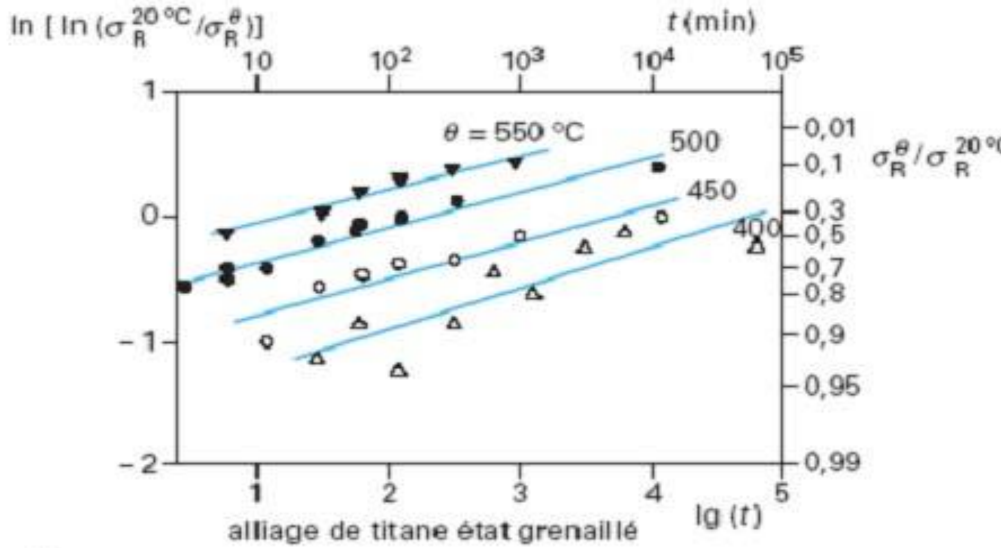
- Reduction of tensile RS
- Dimensional stability during forming

- Reduction of compressive RS
- Dimension and forme modification of components

Schematic presentation of origin and consequenc of RS relaxation

RS relaxation (2)

Thermal relaxation



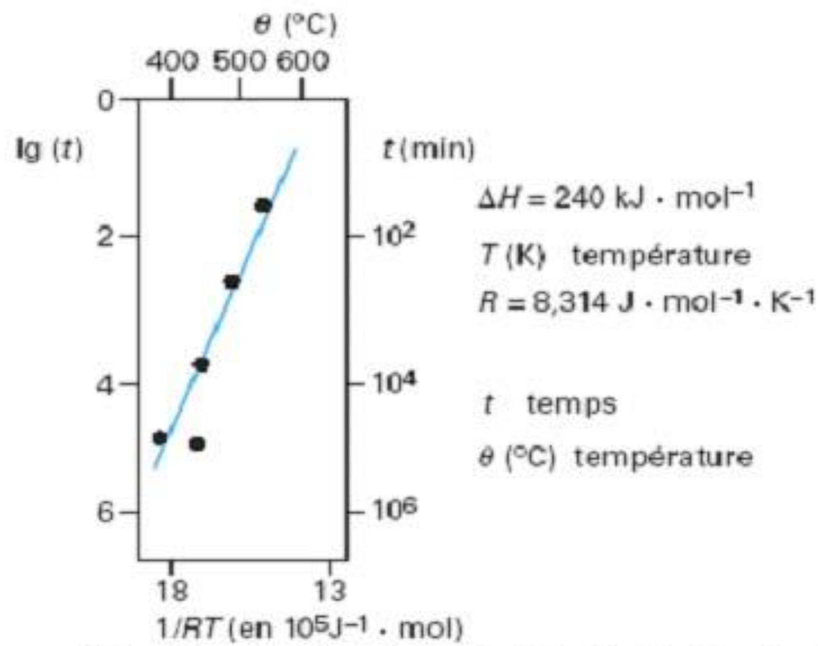
ⓐ **évolution des contraintes résiduelles en fonction du temps pour différentes températures**

$$\frac{\sigma_T(t)}{\sigma_0} = \exp\left\{-\left[A\ t\ \exp\left(-\frac{\Delta H}{RT}\right)\right]^m\right\}$$

$$\ln\left(\ln\frac{\sigma_0}{\sigma_T(t)}\right) = m\left(\ln A + \ln t - \frac{\Delta H}{RT}\right)$$

avec R constante des gaz parfaits,

ΔH enthalpie d'activation de relaxation.

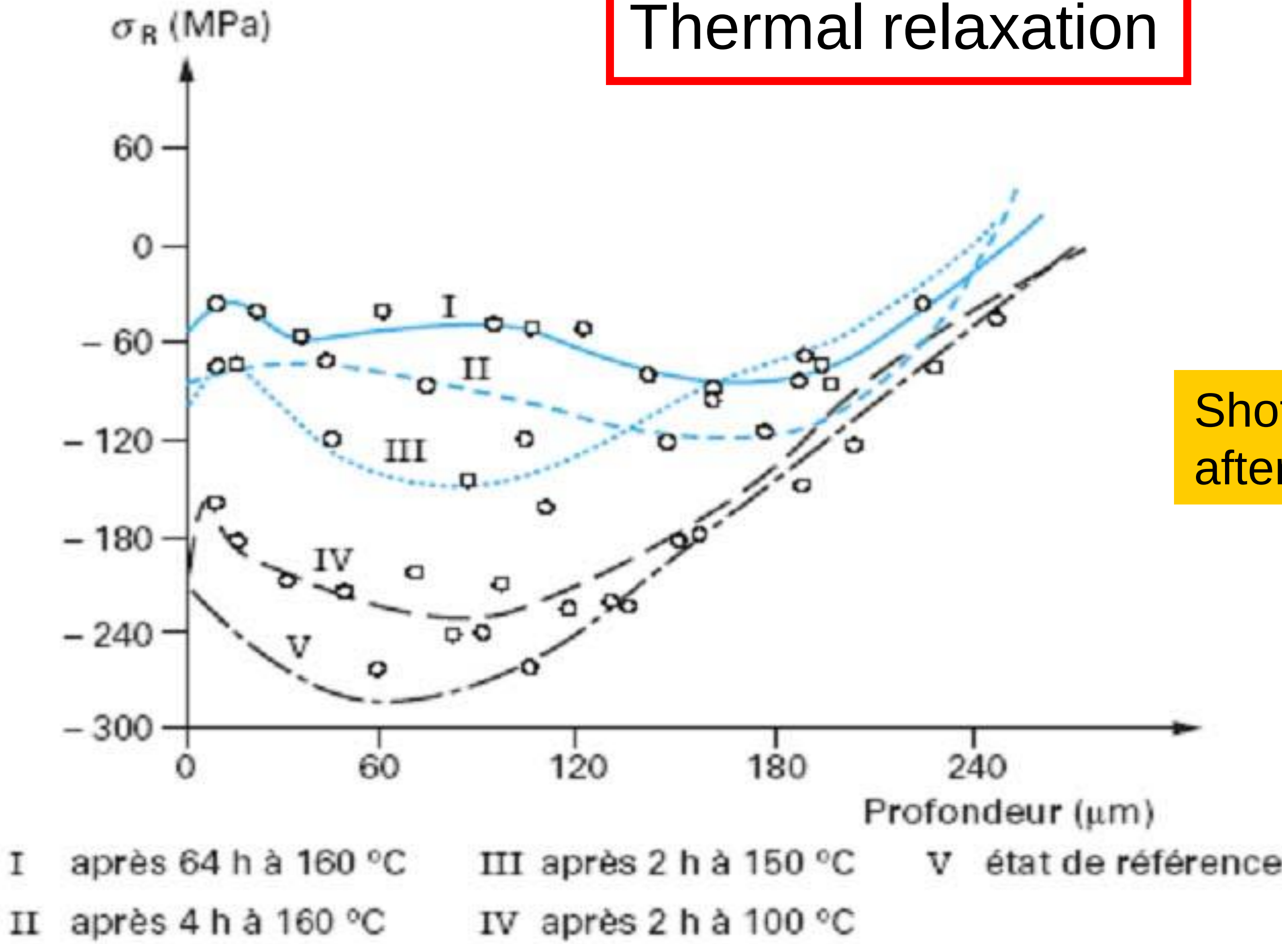


ⓑ **détermination de l'enthalpie d'activation de relaxation**

Thermal relaxation of RS due to surface shot-peening of X22CrMoV12 steel

RS relaxation (3)

Thermal relaxation

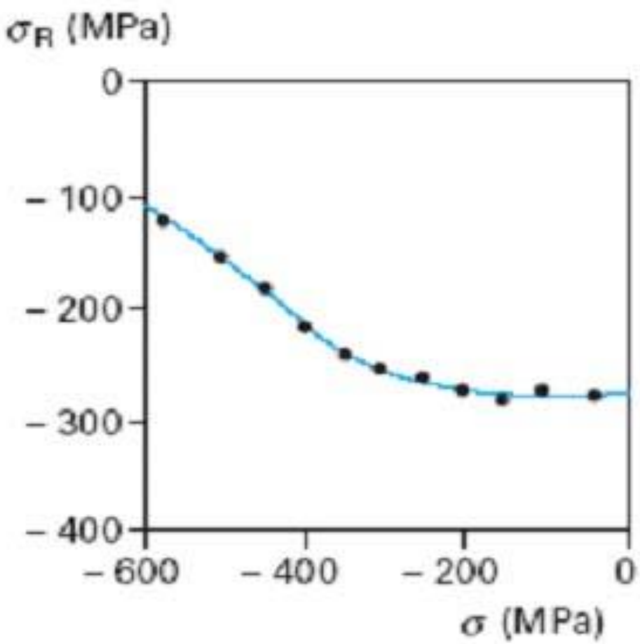


acier 45SiCrMo6

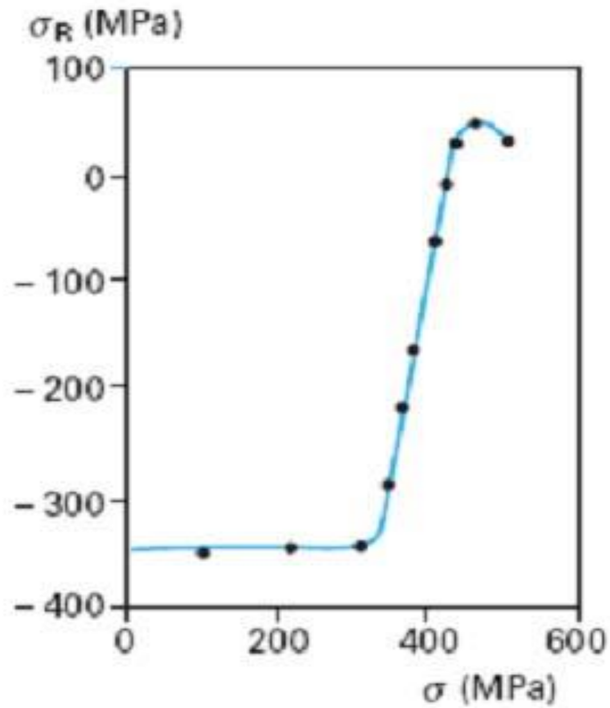
Shot-peening stress after thermal relaxation

RS relaxation (4)

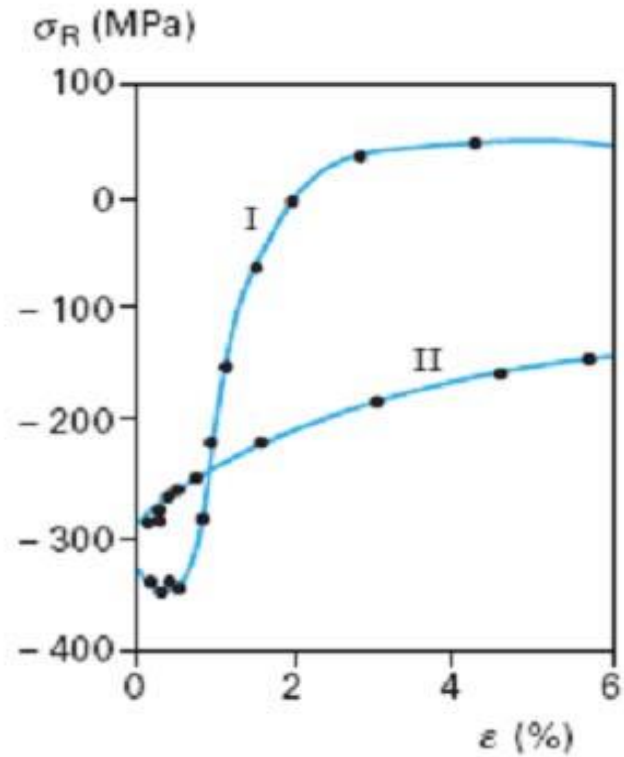
Mechanical relaxation



Shot-peened Al 2014
under compression



Shot-peened Al 2014
Under tensile test

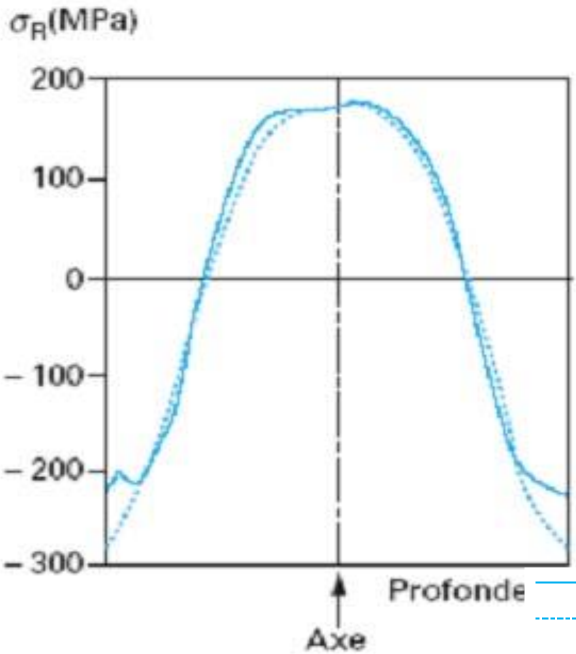


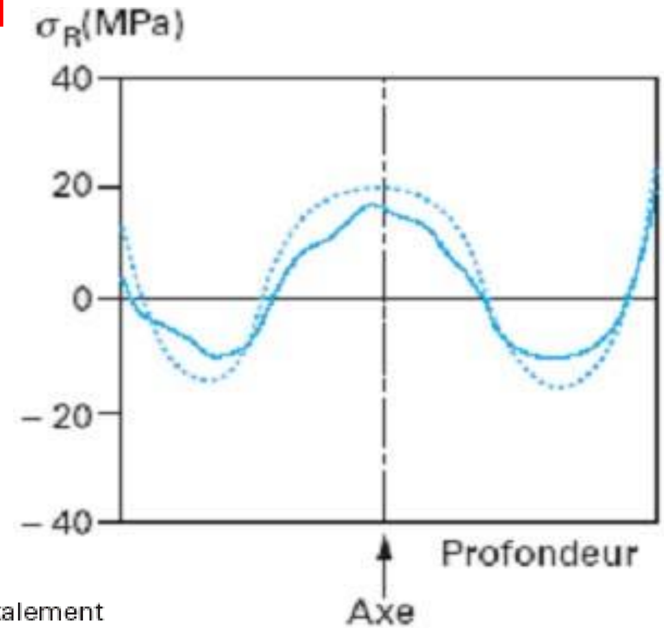
I: tensile relaxation
II: compression relaxation

Mechanical relaxation by uniaxial plastic deformation of shot-peened residual stress

RS relaxation (5)

Mechanical relaxation





profil de contraintes obtenues expérimentalement
profil de contraintes calculées

RS befroe plastic deformation

RS after uniaxial plastic deformation (tensile test with 2,2% in longitudinal direction of piece)

Mechanical relaxation by uniaxial plastic deformation of RS from quenching
Al 7075 quenched in water at 20 °C, sheet with 70 mm of thickness

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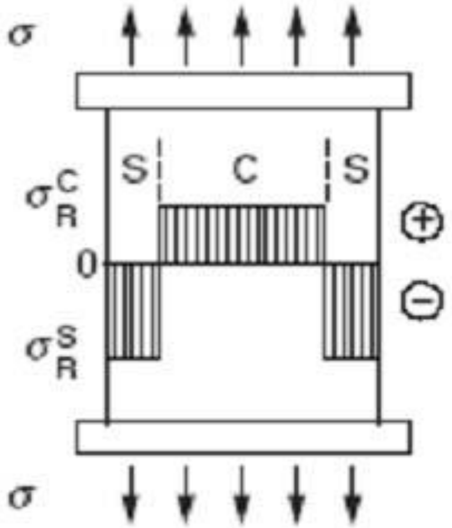
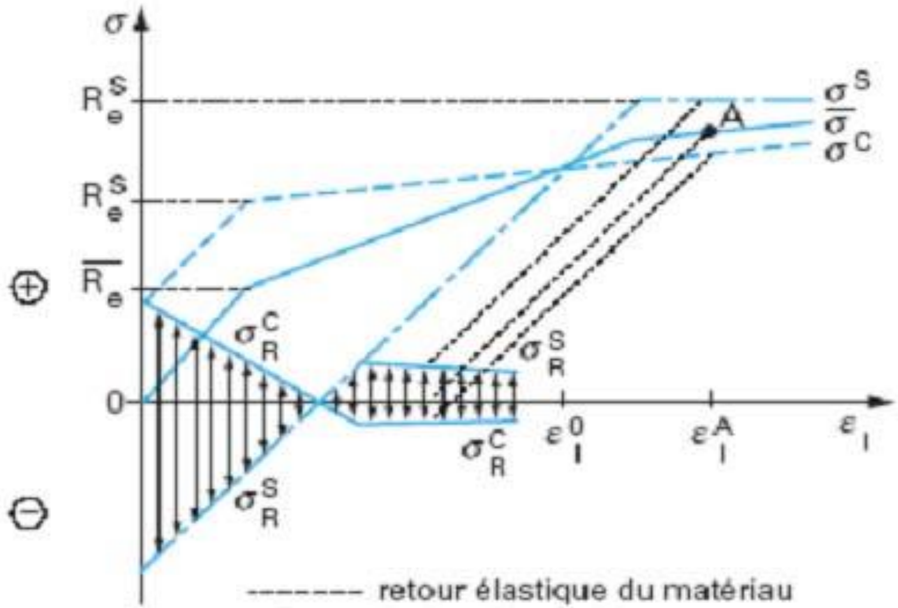
RS relaxation (6)

Mechanical relaxation



C cœur S surface

RS in piece before relaxation



Stress vs plastic deformation

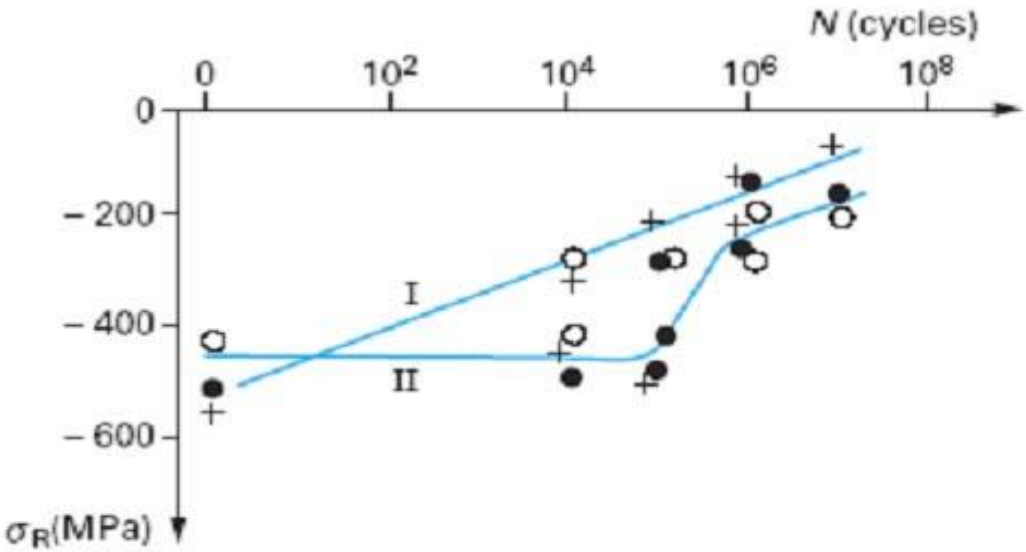
-------	retour élastique du matériau
R_e	limite d'élasticité
ε_l	déformation longitudinale
ε_l^0	déformation longitudinale standard (éprouvette sans contraintes résiduelles
ε_l^A	déformation longitudinale quand $\overline{\sigma}$ atteint le point A
σ	contrainte appliquée
σ_R	contrainte résiduelle

Les valeurs surlignées sont des valeurs moyennes

macroscopic relaxation schema of RS by plastic deformation

RS relaxation (7)

Mechanical relaxation - fatigue



intensité Almen de grenaillage

+ 6-8 N

● 12-14 A

○ 8-10 C

acier 35 CrMo4 trempé et revenu

N nombre de cycles

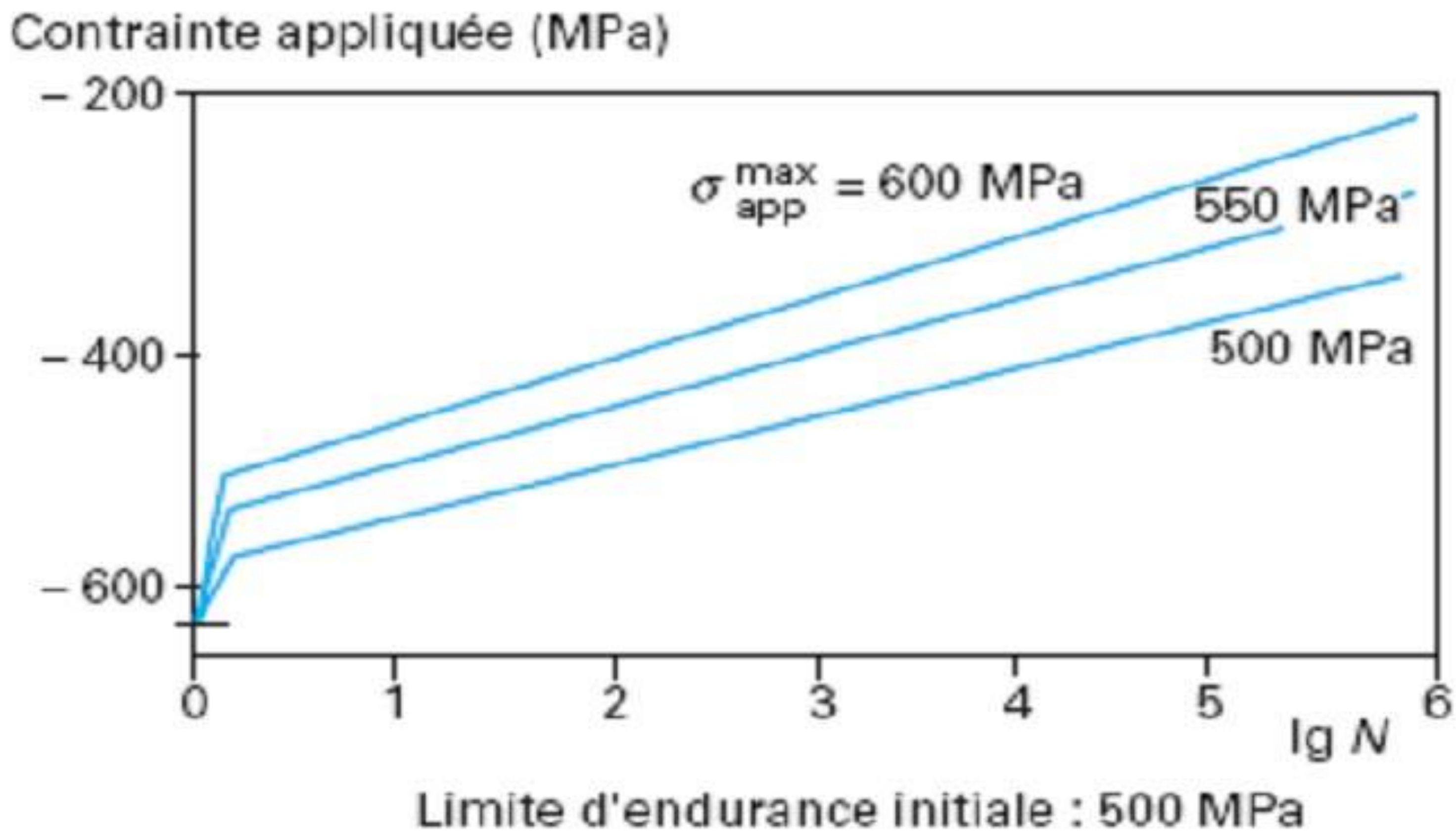
I contrainte appliquée ± 330 MPa

II contrainte appliquée ± 230 MPa

mechanical relaxtion of RS of shot-peening by fatigue

RS relaxation (8)

Mechanical relaxation - fatigue



Evolution of shot-peening RS under repeated tensile loading for 35CD4 steel

RS relaxation (9)

General consideration

RS relaxation is related to resistance to microplasticity R_i of material. Relaxation under an applied stress *s and* with the presence of σ_R begins when: $\sigma + \sigma_R > R_i$ resistance to microplasticity Ri takes different values according cases. It's related to T°C, time, frequence and microstructural state of material

Sollicitation	Contrainte appliquée σ	R_i
Thermique	$\sigma = 0$	R_p (t) résistance au fluage
Déformation uniaxiale	$\sigma \nearrow$	R_e limite d'élasticité
Fatigue	$\sigma \sim$	σ_D limite d'élasticité cyclique
t temps.		

Value of resistance to microplasticity R_i for different loadings

Traitements « mécaniques »

Les enjeux techniques concernent :
— l'amélioration de la résistance à la fatigue sous certains type de sollicitations ;
— l'amélioration de la résistance à la corrosion simple ou à la corrosion sous contrainte ;
— l'amélioration de la résistance à l'usure.

À l'échelle micro-, les «défauts» situés en surface sont soumis à l'attaque du milieu environnant. Le mouvement des dislocations est libre et les domaines cristallins qui « débouchent » en surface se déforment plus aisément.
À l'échelle macro-, les zones de concentration de contrainte (raccordements, entailles, stries d'usinage, trous, ...) sont souvent associées aux surfaces libres des pièces. En outre, la plupart des modes de sollicitation génèrent des maxima de contraintes situés en surface.

Traitements « mécaniques »

➔modification d'une couche superficielle de la pièce originale sur une épaisseur suffisante par traitement superficiel mécanique ou thermique

➔ **traitements de mise en précontrainte superficielle** sont des processus contrôlant parfaitement la source primaire de génération des contraintes résiduelles. Ils peuvent être classés en deux grandes catégories selon la nature de la source primaire active

— les traitements mécaniques d'écrouissage superficiel ;

— les traitements thermiques ou thermochimiques superficiels.

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Traitements « mécaniques »

Type de traitement	Origines principales des contraintes	Noms des traitements
Mécanique	Déformation plastique locale	Sablage, grenaillage, martelage, galetage, polissage, etc.
Thermique	Dilatation différentielle et transformations de phase	Trempe et trempe superficielle
Thermochimique	Diffusion, dilatation différentielle et transformations de phase	Cémentation, carbonitruration, nitruration, etc.

Traitements de précontraintes

Traitements « mécaniques »

Dénomination	Mise en œuvre	Profondeur de traitement	Avantages et inconvénients
Tribofinition	Frottement	de 0,01 à 0,03 mm	Long et coûteux à réaliser
Grenaillage	Projection contrôlée de billes de différents diamètres, de différentes mesures et de différentes vitesses	de 0,1 à 0,6 mm suivant le matériau et les conditions	Quelques problèmes d'incrustation, de microdéfauts et parfois de rugosité S'adapte à toutes les géométries
Martelage	Impact d'aiguilles à extrémité sphérique	de 1 à 2 mm	Problème d'état de surface, ne s'applique qu'aux géométries simples
Galetage	Roulement d'un galet avec une forte force d'appui	de 2 à 3 mm	Variations dimensionnelles, nécessite une géométrie particulière
Ondes de choc	Explosion Laser impulsionnel de très forte puissance	jusqu'à 4 mm	S'adapte à toutes les géométries (pour le laser) Pas de modification de l'état de surface Traitement en cours de développement
Préconformage Autofrettage	Flexion, expansion ou torsion avec passage en plasticité	quelques mm	Traitement directionnel

Différents traitements mécaniques de surface, modifier

— caractéristiques géométriques de la surface;

— microstructure dans une couche sur la densité des défauts

grenaillage

Le grenaillage (Shot peening) change

➔

- la distribution des contraintes résiduelles
- la morphologie superficielle
- la dureté de la couche superficielle
- la microstructure de la couche traitée

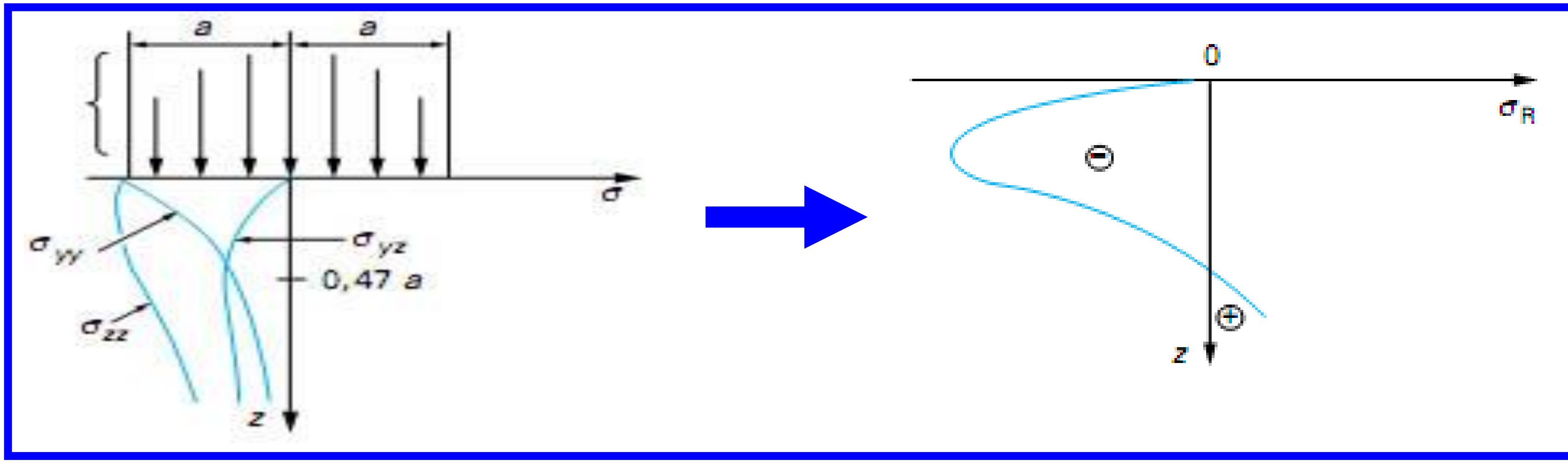
grenaillage

Les objectifs du grenaillage:
- augmentation de la limite en fatigue
- diminution des risques de corrosion sous-contrainte (stress corrosion and stress corrosion fatigue)
- diminution des risques de fatigue-abrasion (fretting and fretting corrosion)
- augmentation de la resistance anti-usure (abrasion and cavitation)

Shot-peening & RS

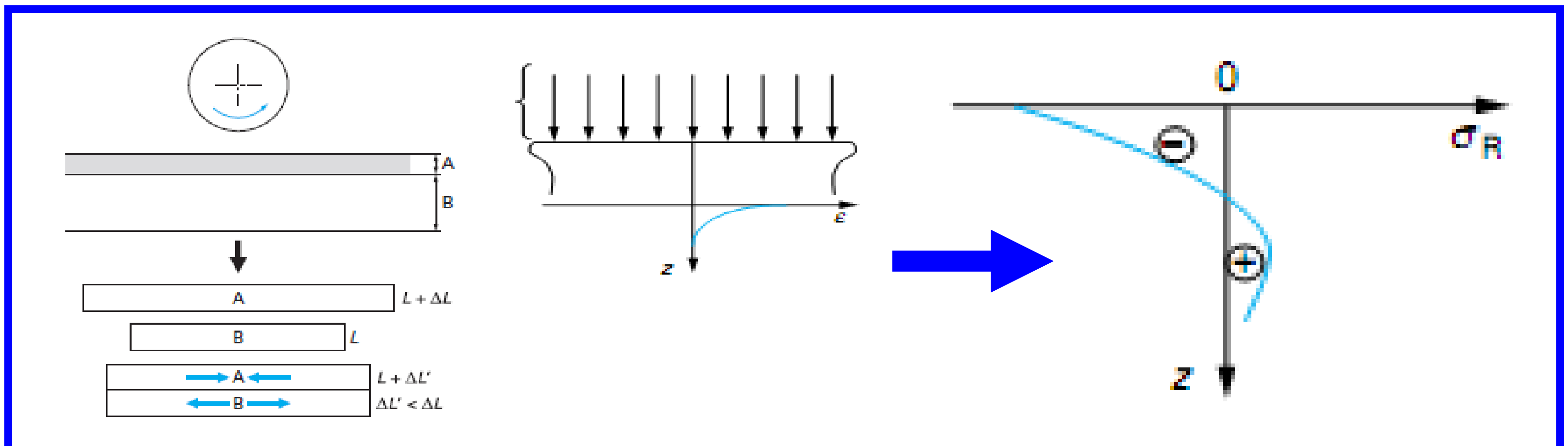
During shot-peening: After shot-peening:

Hertz Pressure

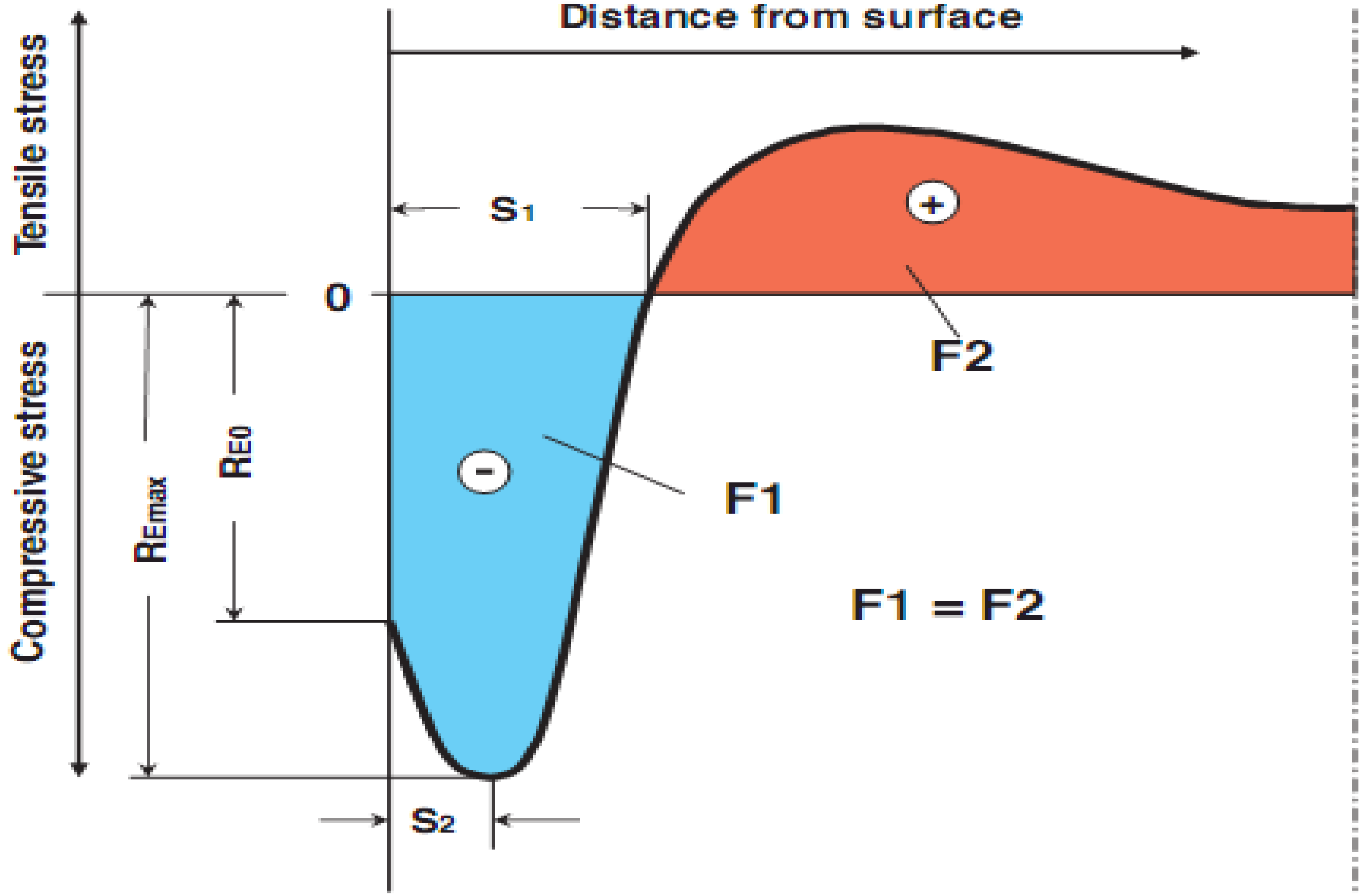


+

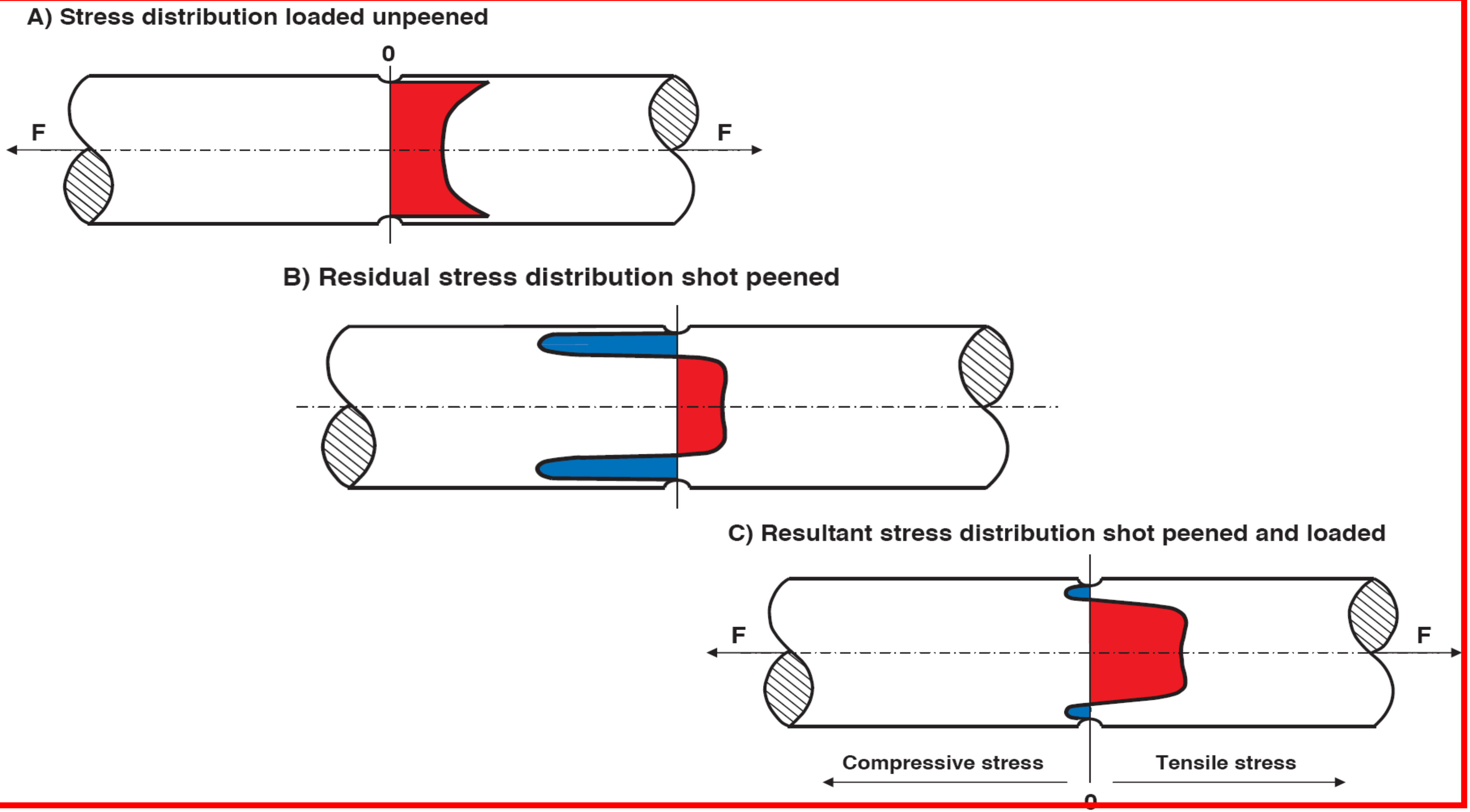
Side Plastic Deformation



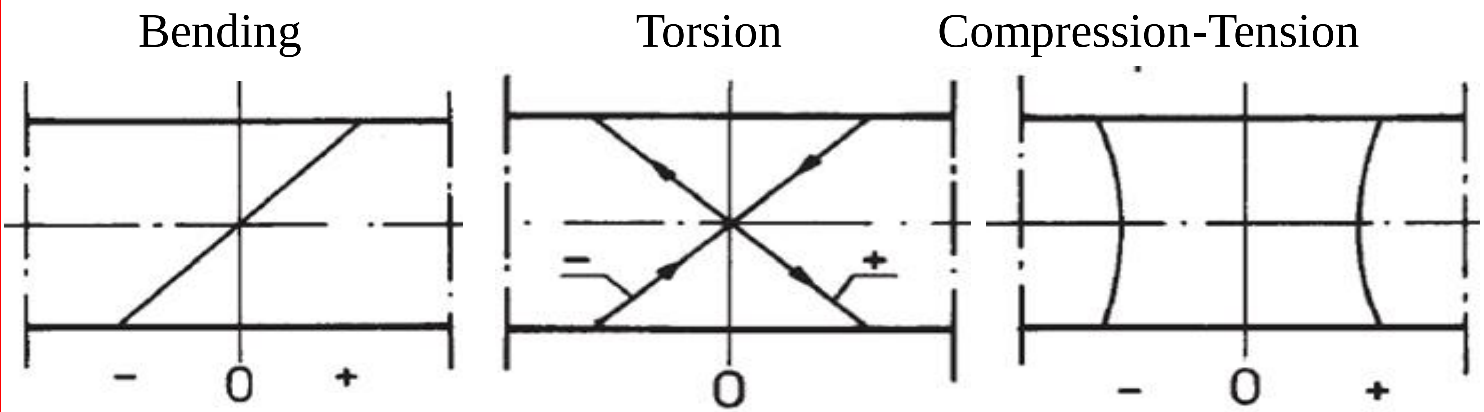
Shot-peening & RS



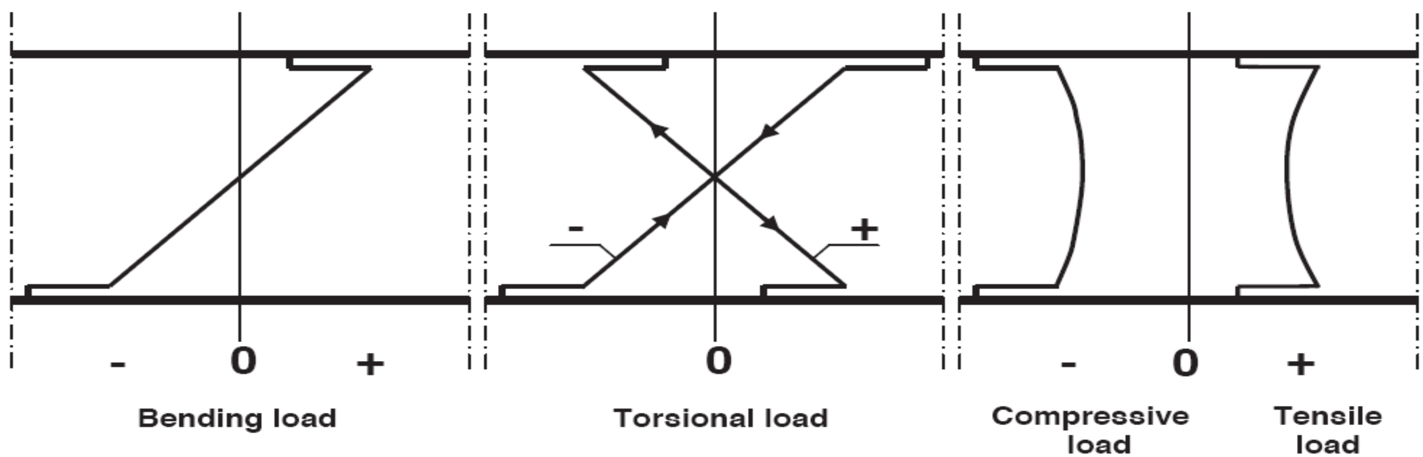
Shot-peening & RS



Shot-peening & RS

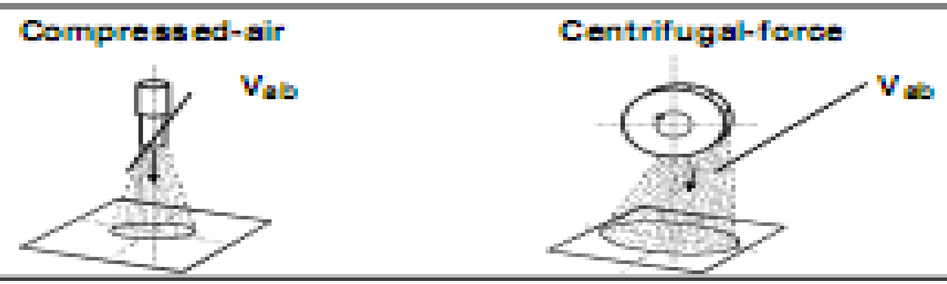
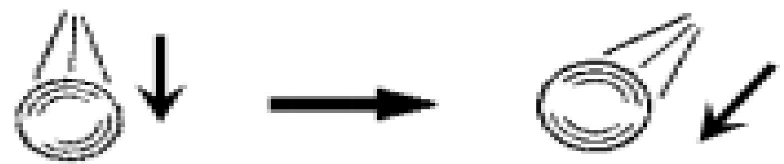
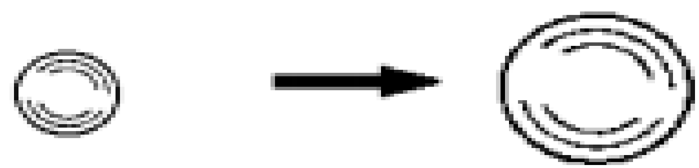
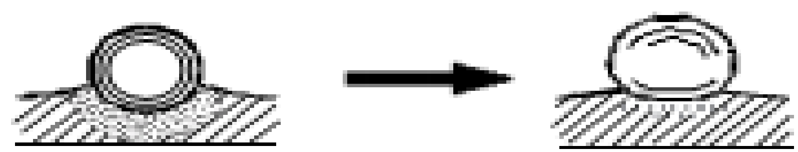


distribution des contraintes avant grenaillage et chargement



distribution des contraintes après grenaillage et chargement

Shot-peening & process

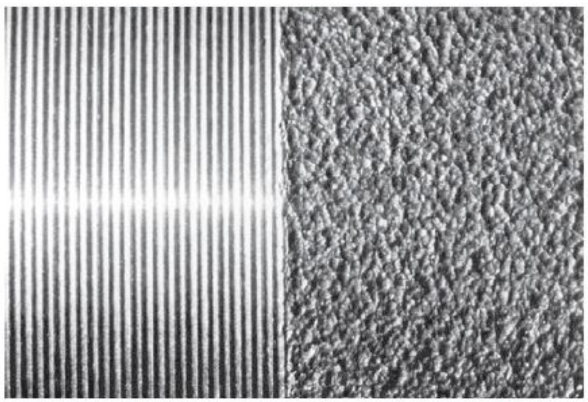
Shot peening system: comressed-air or centrifugal-force	
Velocity of impact Angle of impact	
Diameter of shot peening media Density of shot peening media	
Hardness of shot peening media	
Amount of impacts Peening time	Coverage

Shot-peening & process

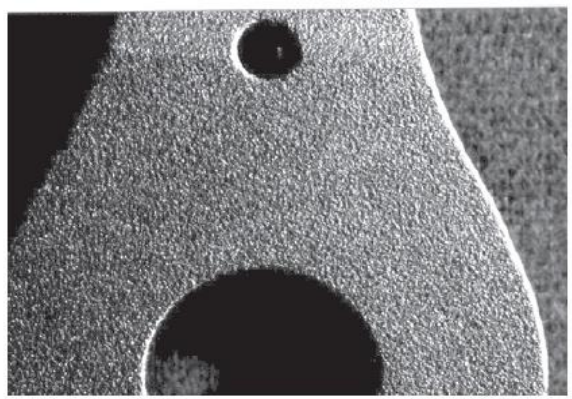
Coverage ratio

Coverage: the percentage of the surface impacted by the shot-peening process. A coverage of 100% is only a theoretical limit and is neither realizable nor measurable. In the shot-peening process a minimum coverage of 98% is mandatory. A coverage of 98 % is the highest measurable limit.

Intensity and coverage are the most important parameters in the shot-peening process.



Not shot peened Coverage 98 %

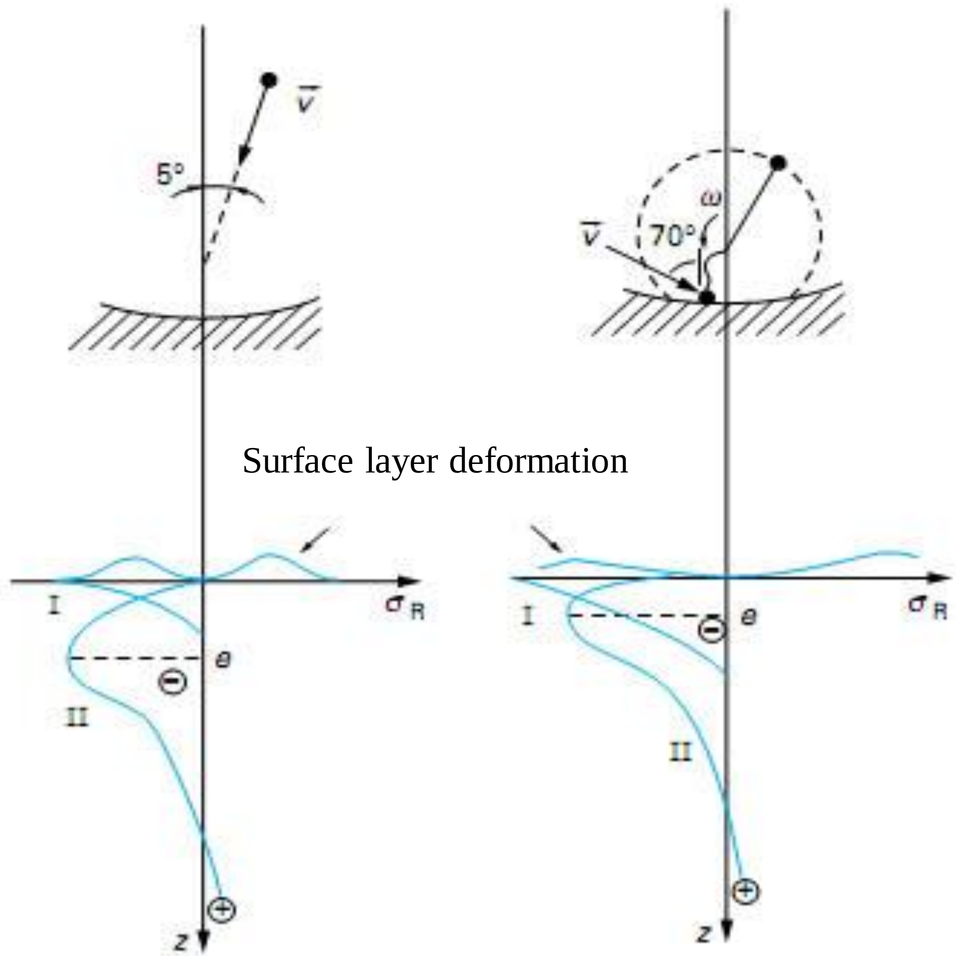


Coverage 98 %

Shot-peening & process

Impact angle

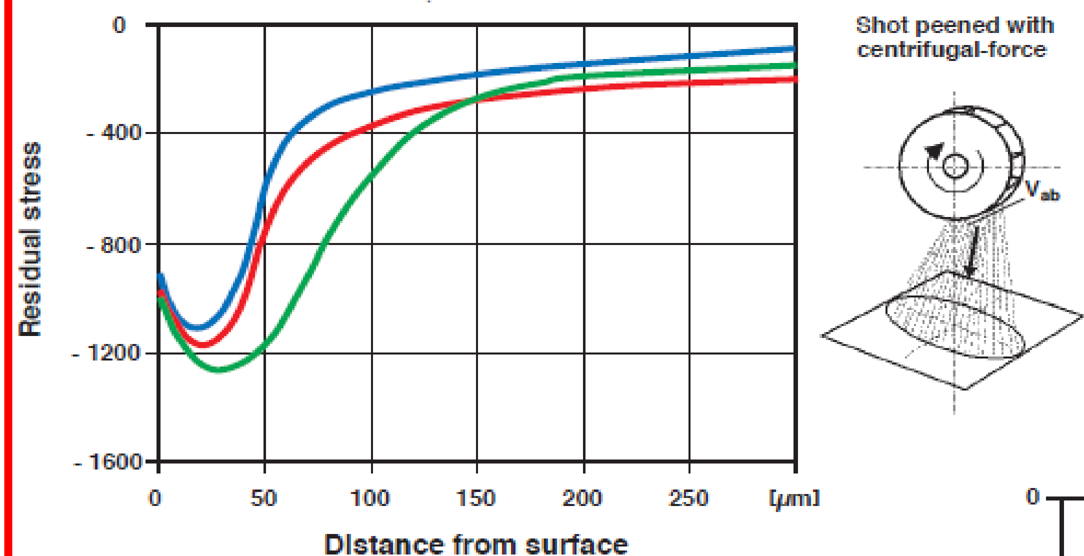
random
ball peening
(external surface
Treatment):
➔↑Ra
➔↑θ
➔↓σ_{Rmax}



grazing
ball peening
(inner surface
Treatment):
➔↓ Ra
➔↓ θ
➔↑σ_{Rmax}

Shot-peening & process

Shot-peening Systeme



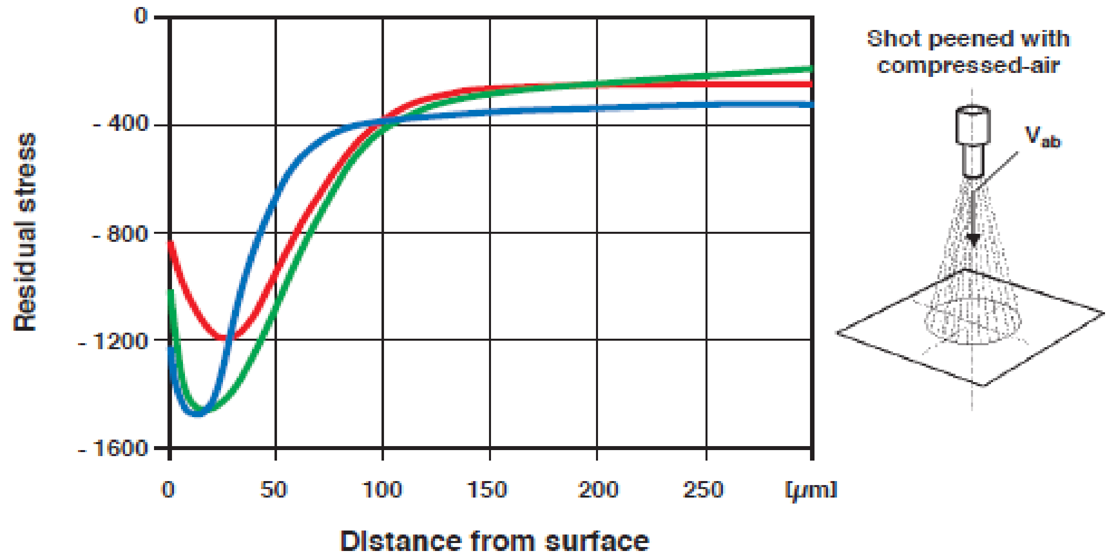
Shot peening parameters

Shot peening media: cut wire, spherical (G3), 0.8 mm Ø, 58 - 60 HRC

Coverage : 2 x t 98 %

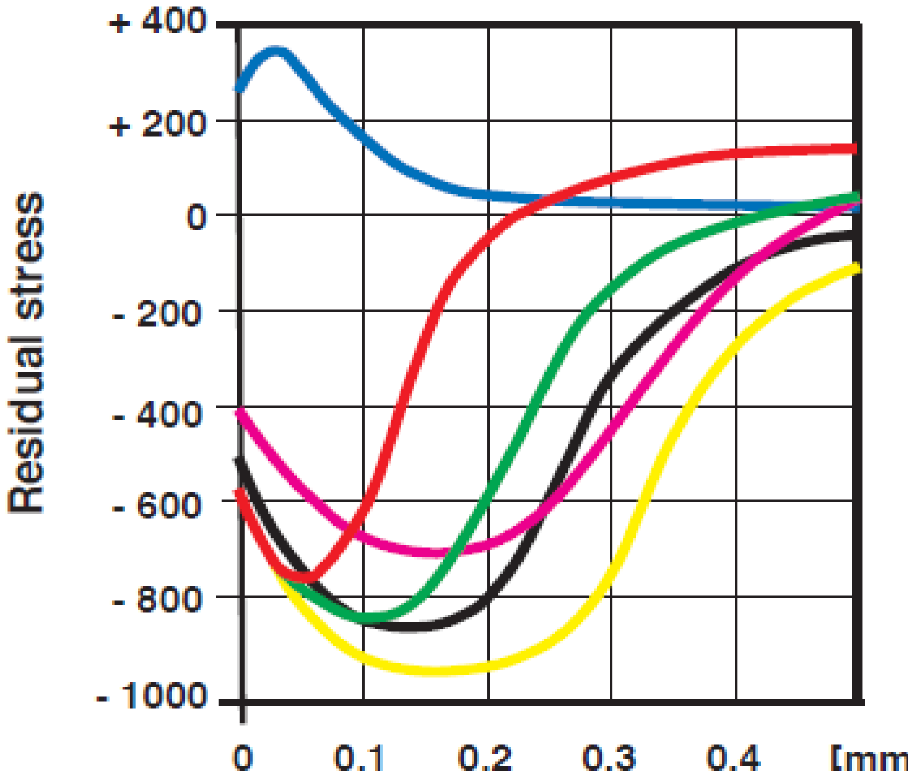
Intensity :

- = 0.20 mm A
- = 0.30 mm A
- = 0.40 mm A



Shot-peening & process

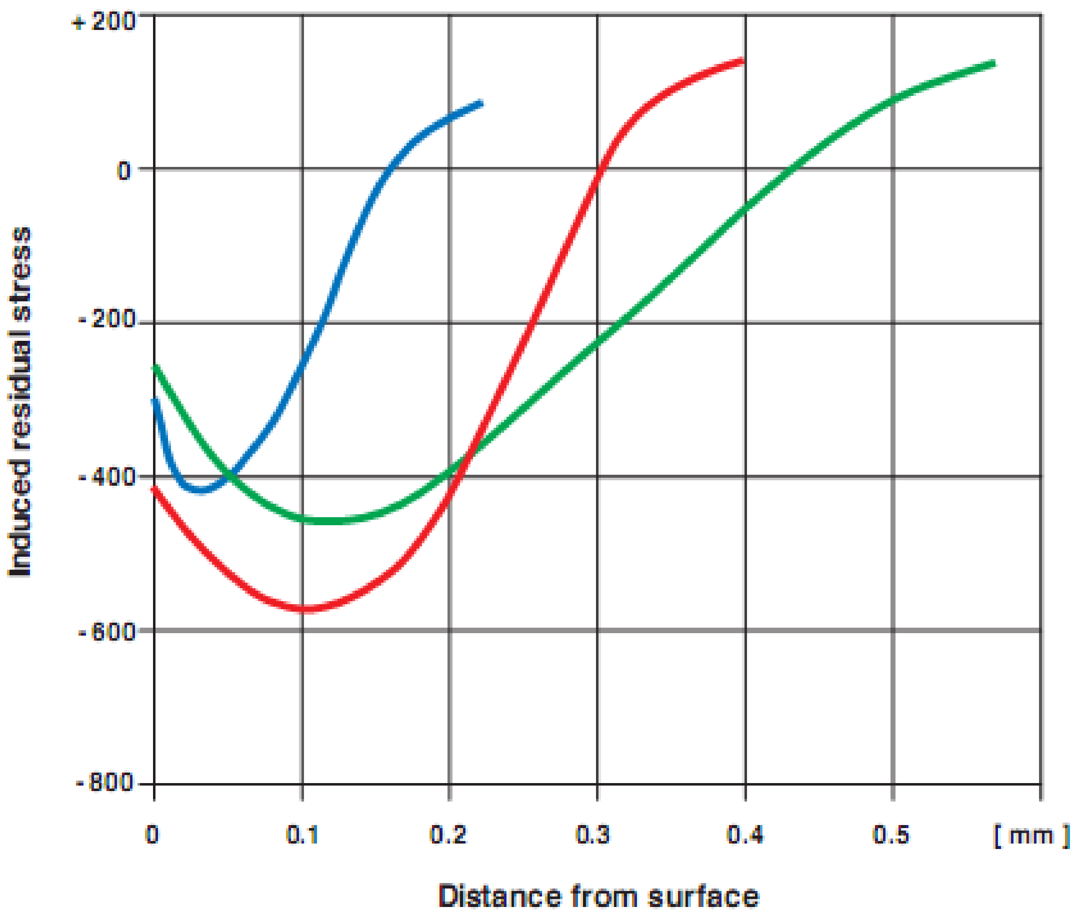
Intensity



Line	Hardness of shot [HCR]	Shot size [mm Ø]	Intensity [mm A]	Coverage
(blue)	Unpeened	——	——	——
(red)	46 - 51	0.6	0.25	98 %
(green)	46 - 51	0.6	0.45	98 %
(black)	46 - 51	0.6	0.55	98 %
(magenta)	46 - 51	0.6	0.65	98 %
(yellow)	46 - 51	0.6	0.55	6 x t 98 %

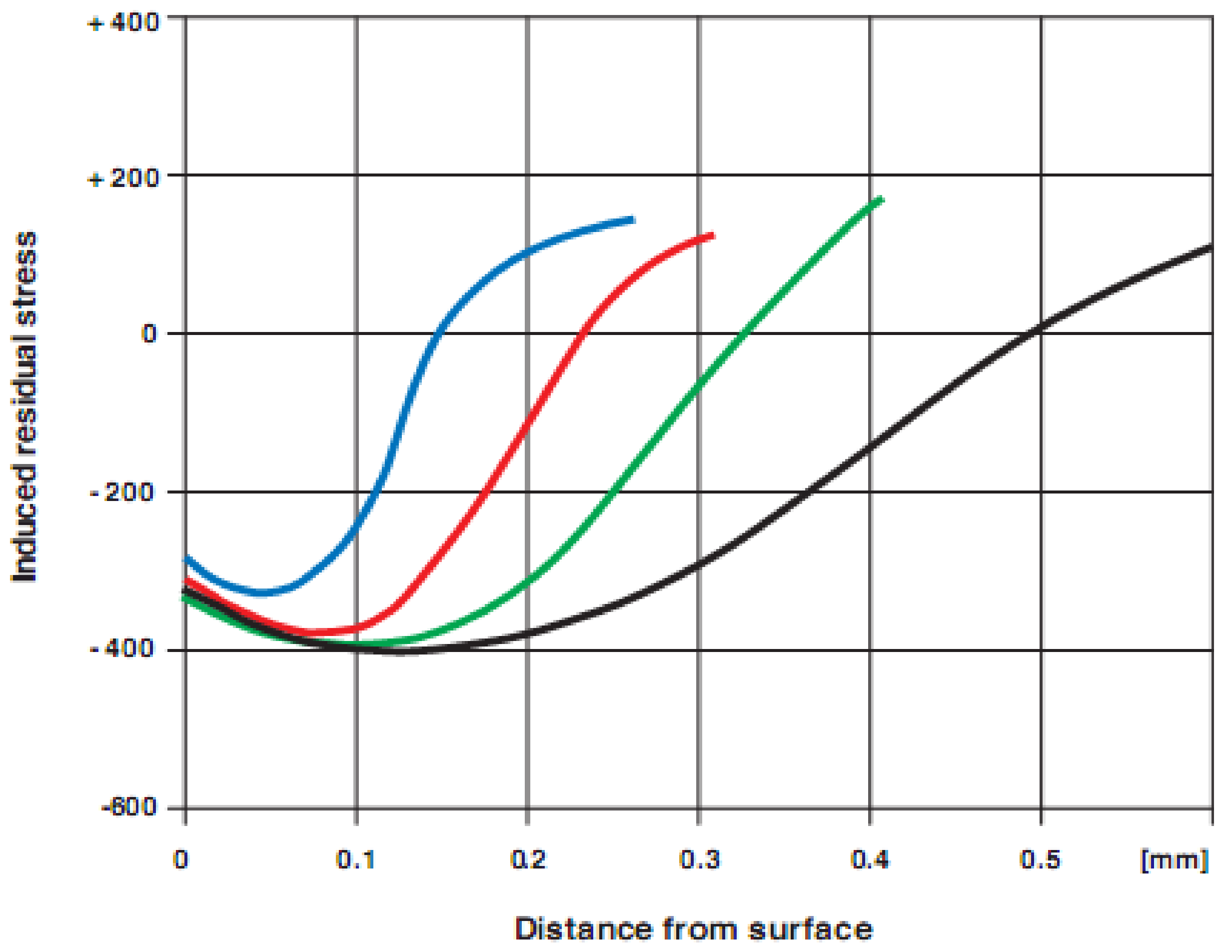
Shot-peening & process

Nature & shot size



Line	Shot media	Shot size [mm Ø]	Intensity [mm A]
blue	Glass beads	0.2	0.15
red	Cut wire shot	0.6	0.30
green	Cut wire shot	1.0	0.40

Shot-peening & process

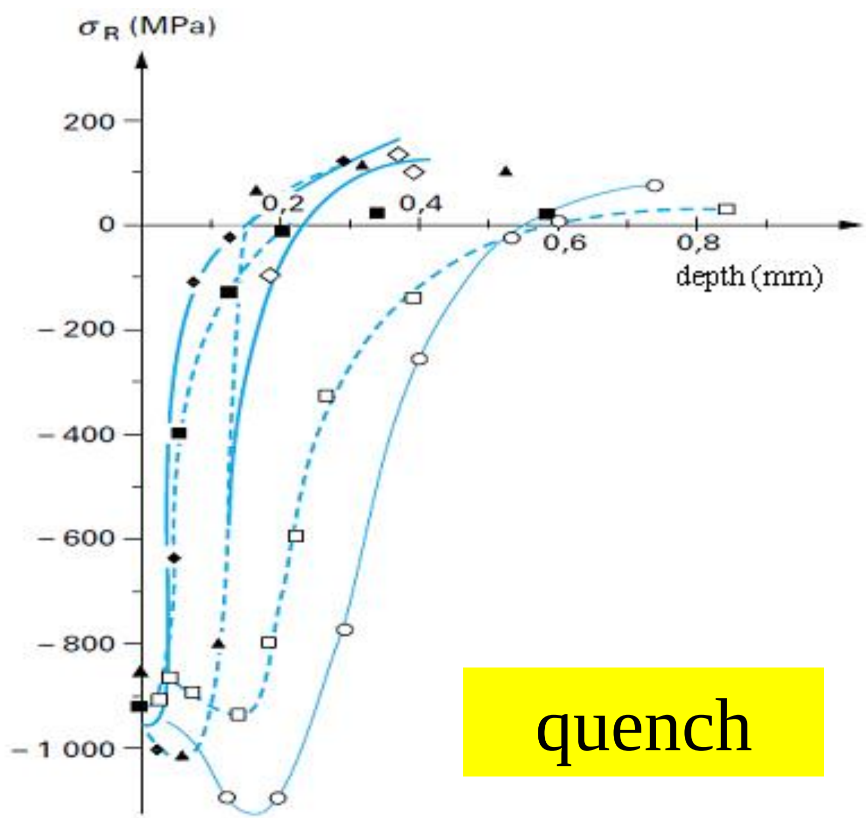


Shot size

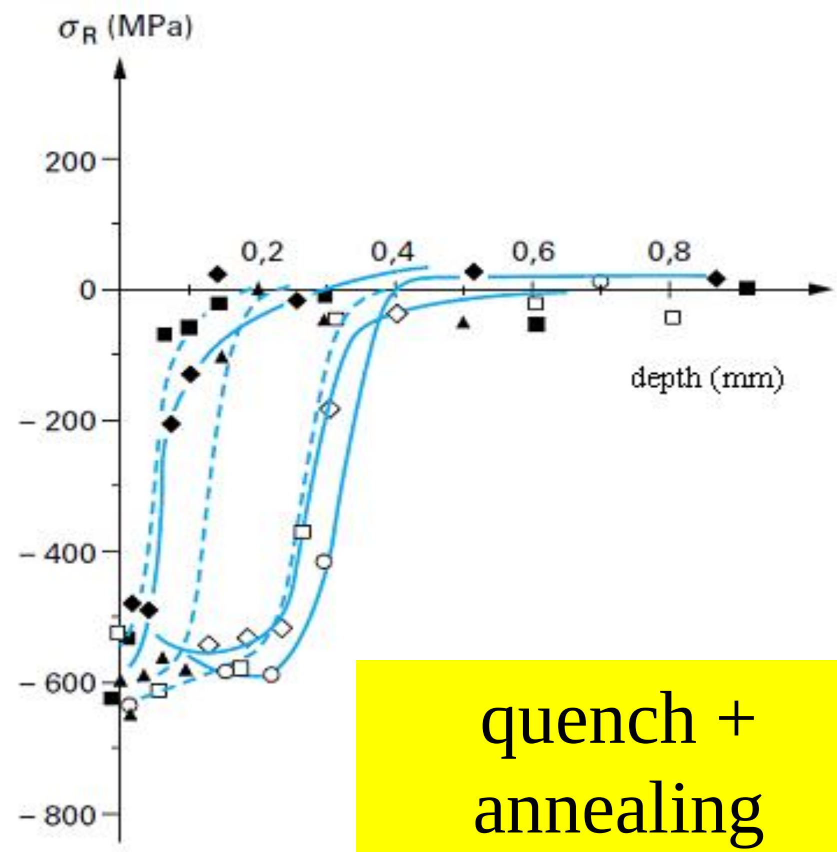
Line	Intensity [mm A]	Shot size [mm Ø]	Coverage
blue	0.18	0.5	98 %
red	0.28	0.5	98 %
green	0.35	0.7	98 %
black	0.90	1.2	98 %

Shot-peening & process

Metallurgical influence



quench



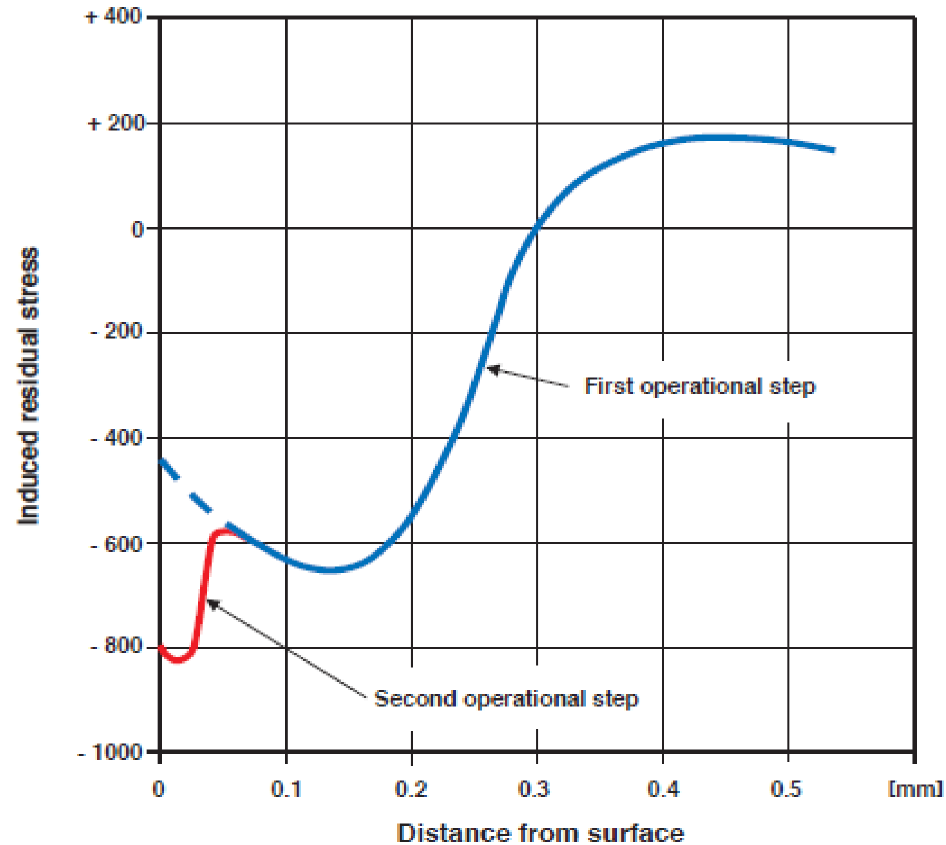
quench + annealing

SP: applications

DUO-Shot peening

-In the 1st operation, a high intensity jet and a shot size of up to 1.2 mm Ø are used with spherical cut wire in a centrifugal-force shot peening machine.

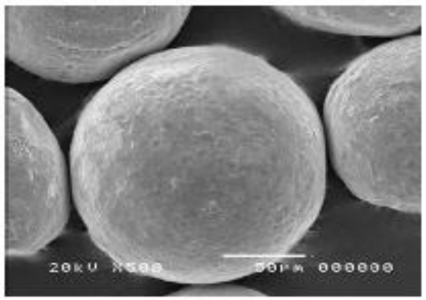
- In the 2nd operation, a low intensity jet and small shot size are applied, with glass beads in a nozzle shot peening machine powered by compressed-air.



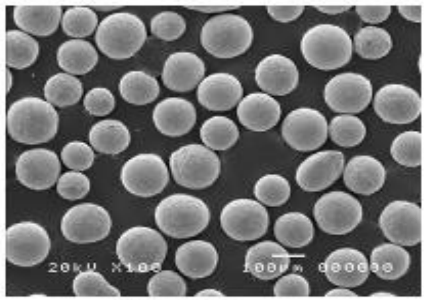
Line	Intensity [mm A]	Shot size [mm Ø]	Coverage	Shot peening media
blue	0.35 - 0.40	0.8	1.25 x t 98 %	Cut wire
red	0.10 - 0.15	0.3	98 %	Glass beads

SP: applications

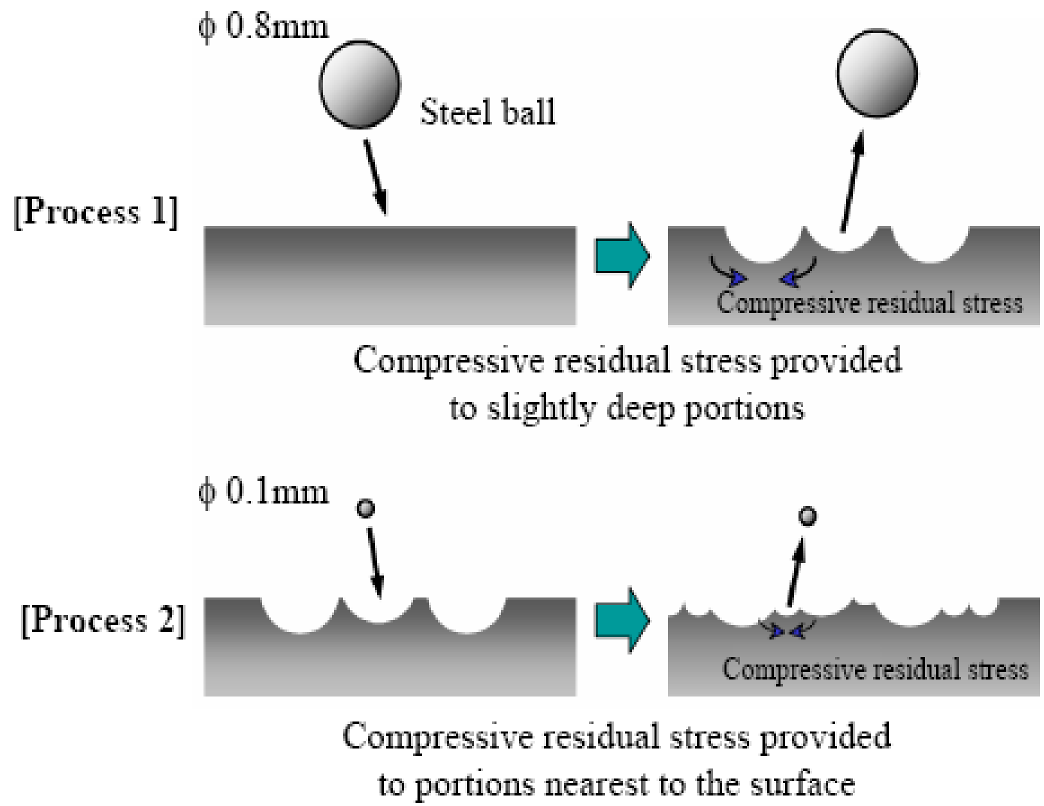
DUO-SP on carbon steel



(a) ϕ 0.8mm

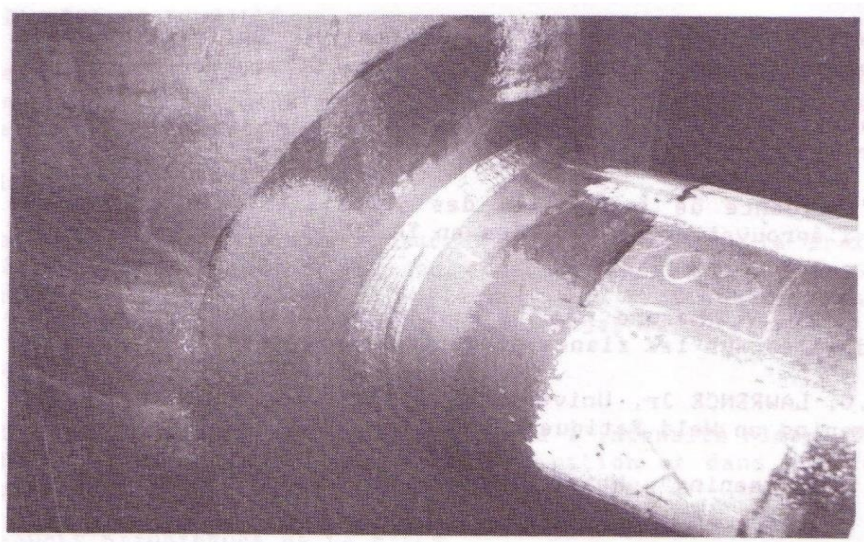


(b) ϕ 0.1mm



SP: applications

Example 1: welded carbon steel component



1st SP: steel shots,
ϕ=0.3 mm, Hv = 45/55 HRC,
F 15/20A
> 125%

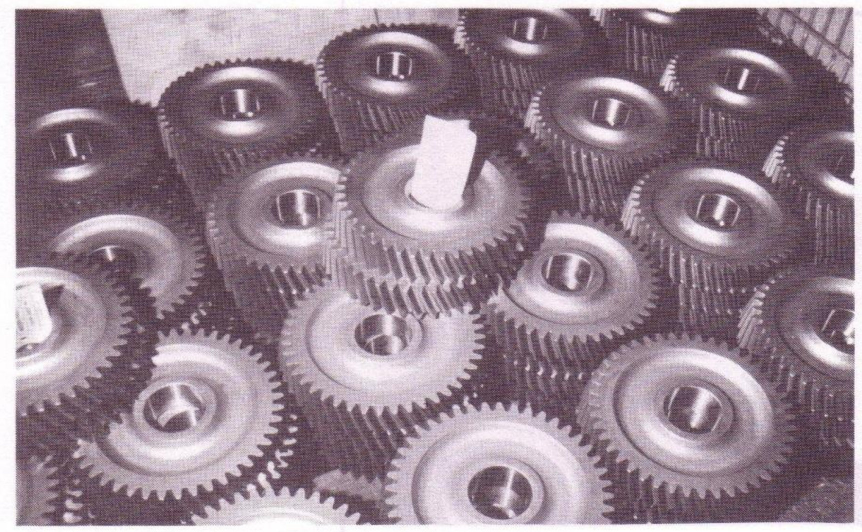
2nd SP: steel shots,
f=1.4 mm, Hv = 45/55 HRC,
F 20/23C
> 125%

Material characteristics:
- -Re = 460 MPa
- -Rm = 585 MPa
- -A = 25%
- -Hv < 25 HRC

Component:
- -Thickness: 30 mm
- -Admissible treatment thickness > 1 mm
- -Mimimum radius : R=0.5 mm
- -Roughness: Ra < 2 µm

SP: applications

Example 2: steel gears after carbonitriding



1st SP: steel shots,
ϕ=0.6 mm, Hv = 55/62 HRC,
F 40/45A
= 150%
2nd SP: glass shots,
ϕ=0.2 mm,
F 15/20 N
> 100%

Material characteristics:
- -Re = 850 MPa
- -Rm = 1300 MPa
- -A = 8%
- -Hv = 62 HRC

Component:
- -Thickness: 3 mm in tooth head
- -Admissible treatment thickness > 0.3 mm
- -Mimimum radius : R=1.5 mm
- -Roughness: Ra < 1.2 µm

SP: applications

Example 3: steel gears teeth after surface induction quench

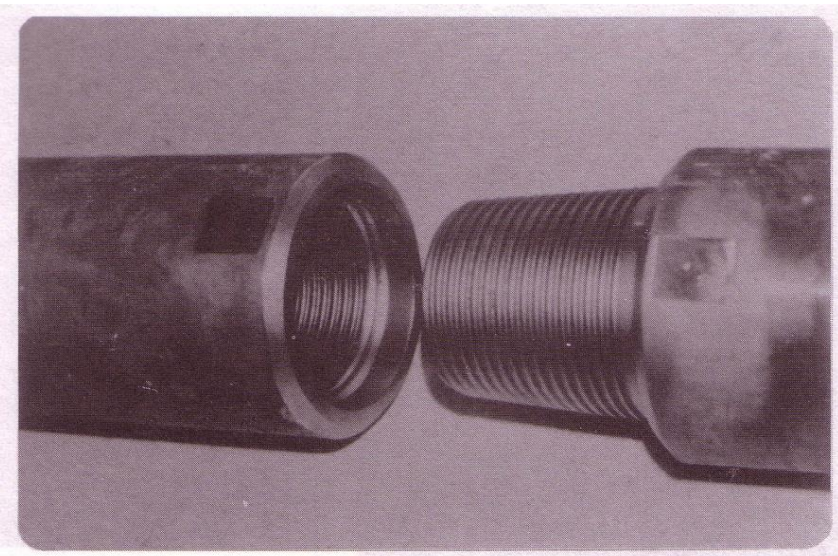
SP: steel shots,
ϕ=0.8 mm, Hv = 45/55 HRC,
F 40/45A
> 150%

Material characteristics:
- -Re = 600 MPa
- -Rm = 920 MPa
- -A = 10%
- -Hv = 58/60 HRC

Component:
- -Thickness: 10 mm
- -Admissible treatment thickness > 1 mm
- -Mimimum radius : R=2.5 mm
- -Roughness: Ra <1.6 µm

SP: applications

Example 4: inside thread in steel with Nickel



SP: ceramic shots,
ϕ=0.215 mm,
F 10/15A
> 125%

Material characteristics:
- -Re = 700 MPa
- -Rm = 800 MPa
- -A = 10%
- -Hv = 20 HRC

Component:
- -Thickness: > 10 mm
- -Admissible treatment thickness > 1 mm
- -Mimimum radius : R=0.6 mm
- -Roughness: Ra = 2 µm

SP: applications

Example 5: Louvre Pyramide strainlees steel structure

1st SP: stainless steel shots,
ϕ=0.8 mm,
F 45/50A
> 100%
2nd SP: glass shots,
ϕ=75/150 mm,
F 10/12 N
> 100%

Material characteristics:
- Re = 750 MPa
- Rm = 950 MPa
- A = 30%
- Hv = 35 HRC

Component:
- Thickness: > 10 mm
- Admissible treatment thickness > 1 mm
- Roughness: Ra = 6.4 µm

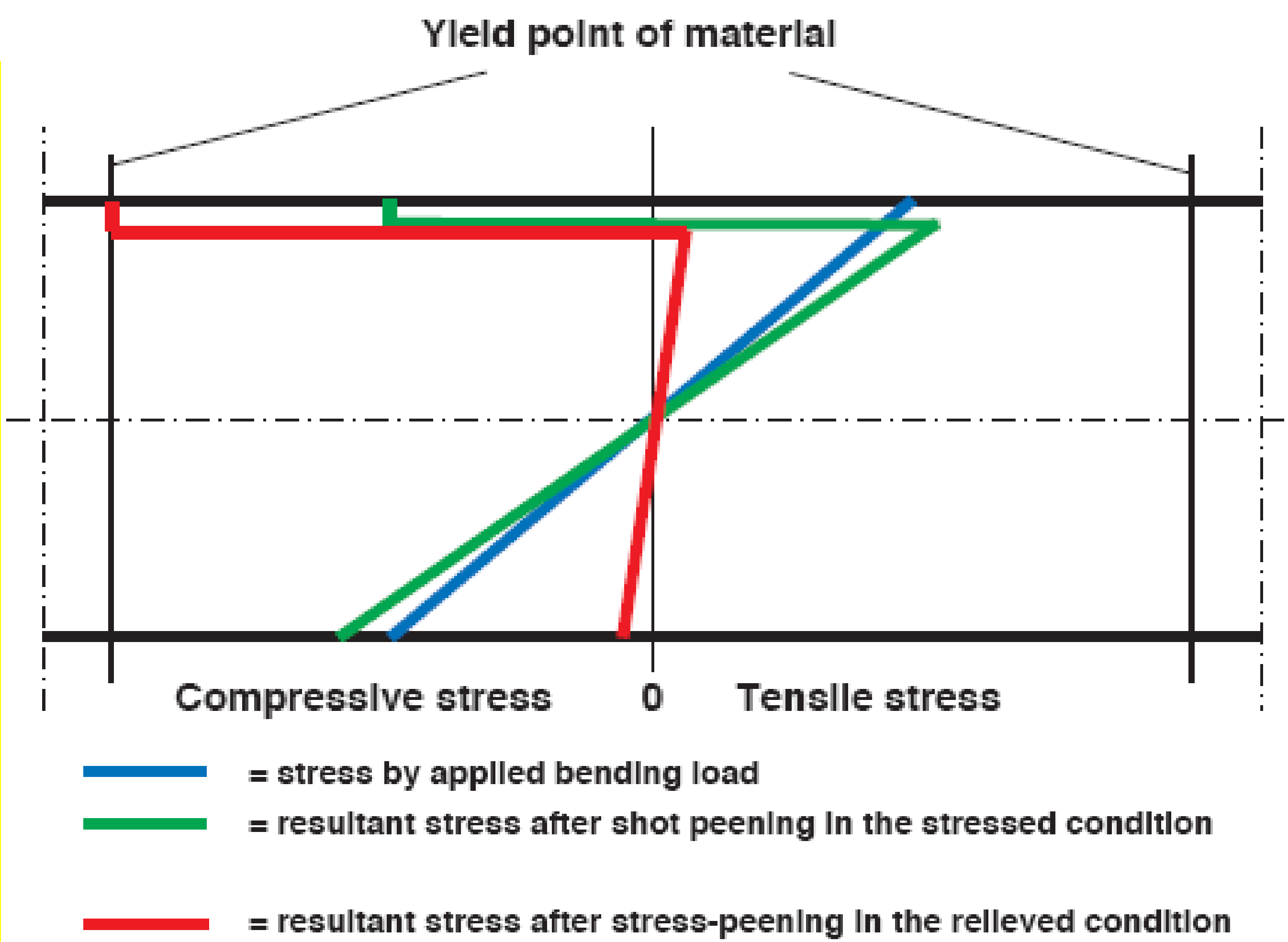
New technologies

- Stress peening
- Peen Forming
- Ultrasonic peening
- Water peening
- Laser peening

New technologies

Stress peening

• A part is shot peened in a externally loaded condition by using a fixture or weight to simulate the operating tensile stress.
* After shot peening, the parts will be relieved of the applied load, leading an even higher compressive residual stress up to the yield stress of the material



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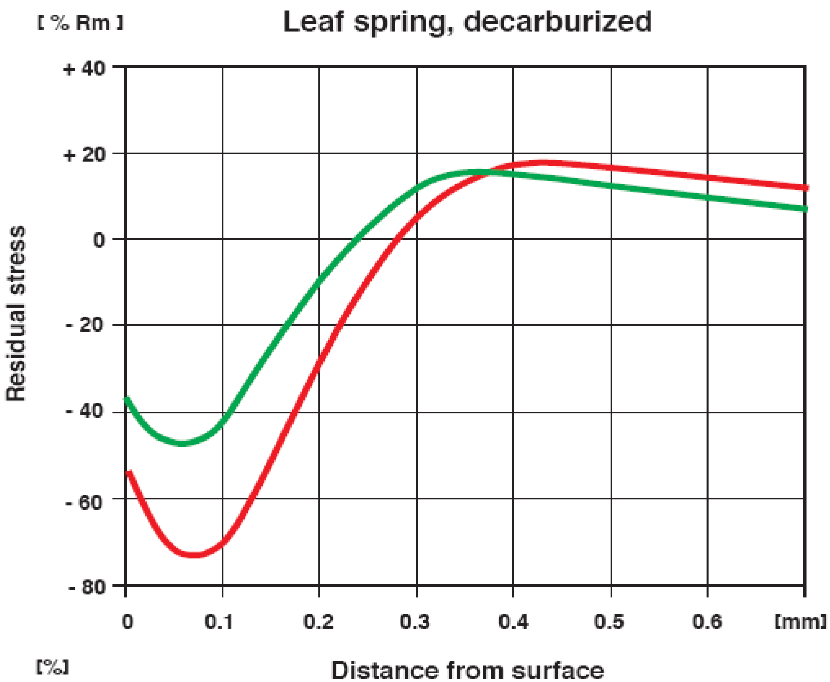
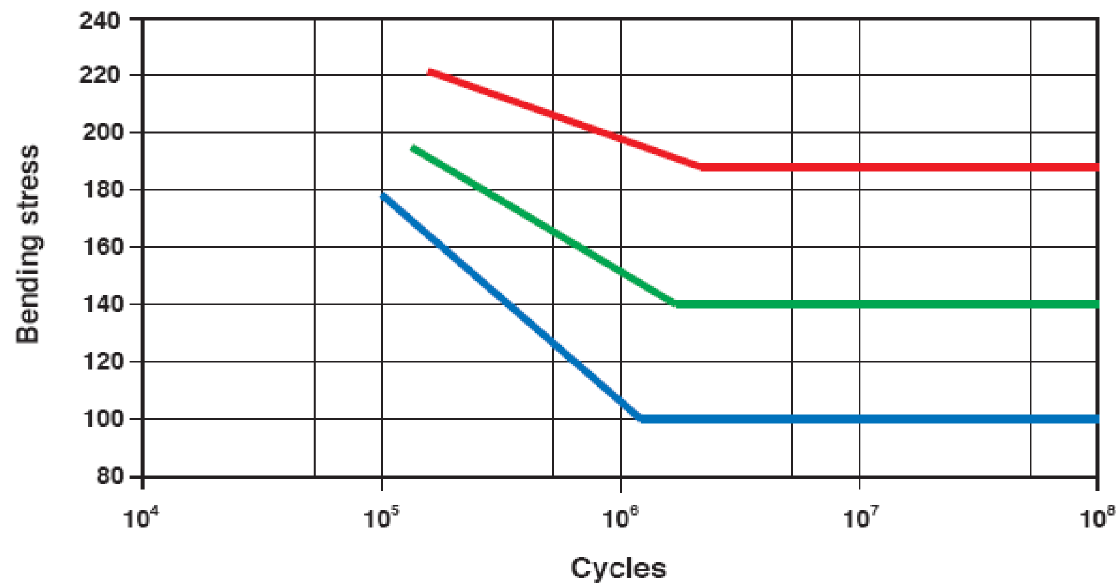
New technologies

Stress peening





= not shot peened

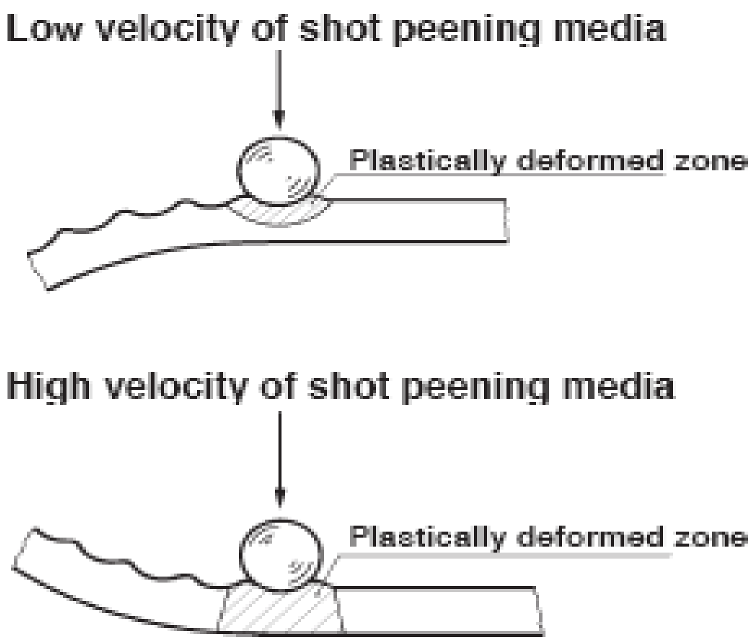
= shot peened (normal)

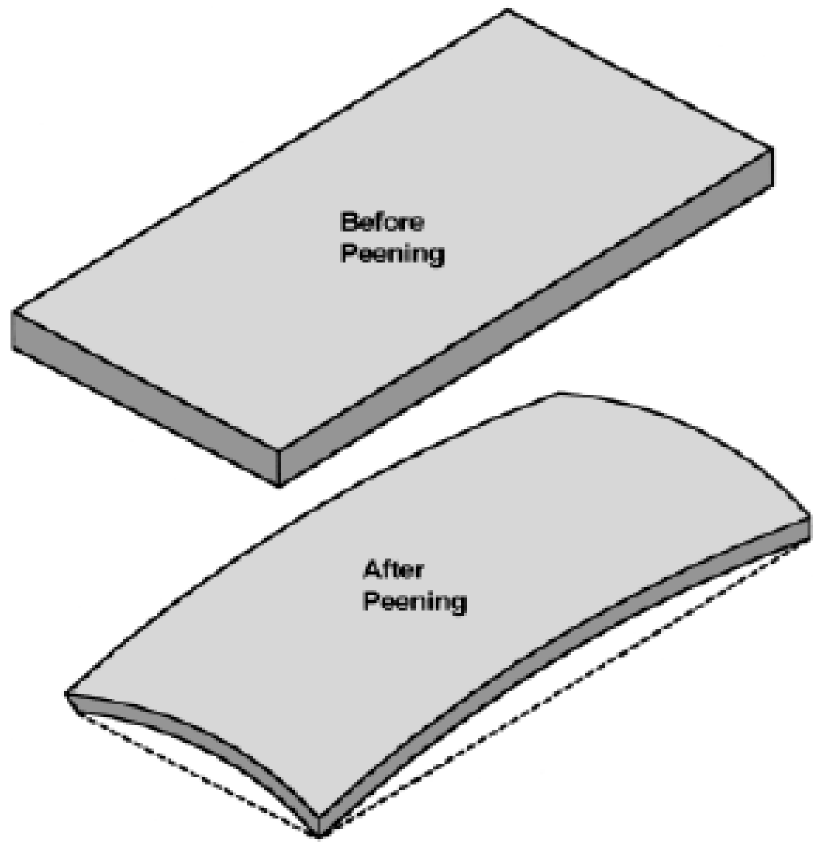
= stress-peened (externally loaded with about 50% of Rm)

Rocker arm in a toggle lever prestress fixture

New technologies

Peen Forming



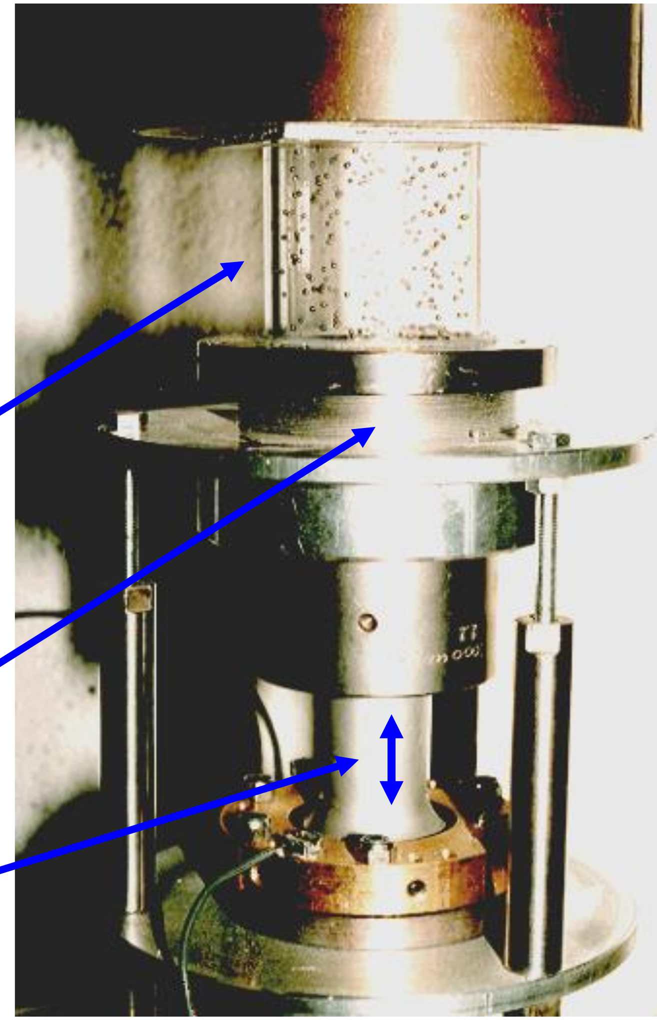


parts with relatively thin cross section may be formed only on one side. The advantages are: no tooling, no development time, no heat

New technologies

Ultrasonic peening

The bearing balls are put in movement by a Sonotrode, vibrating at an ultrasonic frequency.
the balls are contained inside a housing enclosed by the Sonotrode surface and the part to treat.
Longitudinal vibrations of the Sonotrode randomly throw the balls inside the housing as molecules in a gas. Therefore, the treatment is homogeneous on all surfaces of the enclosure on the part to treat.



New technologies

Ultrasonic peening advantages

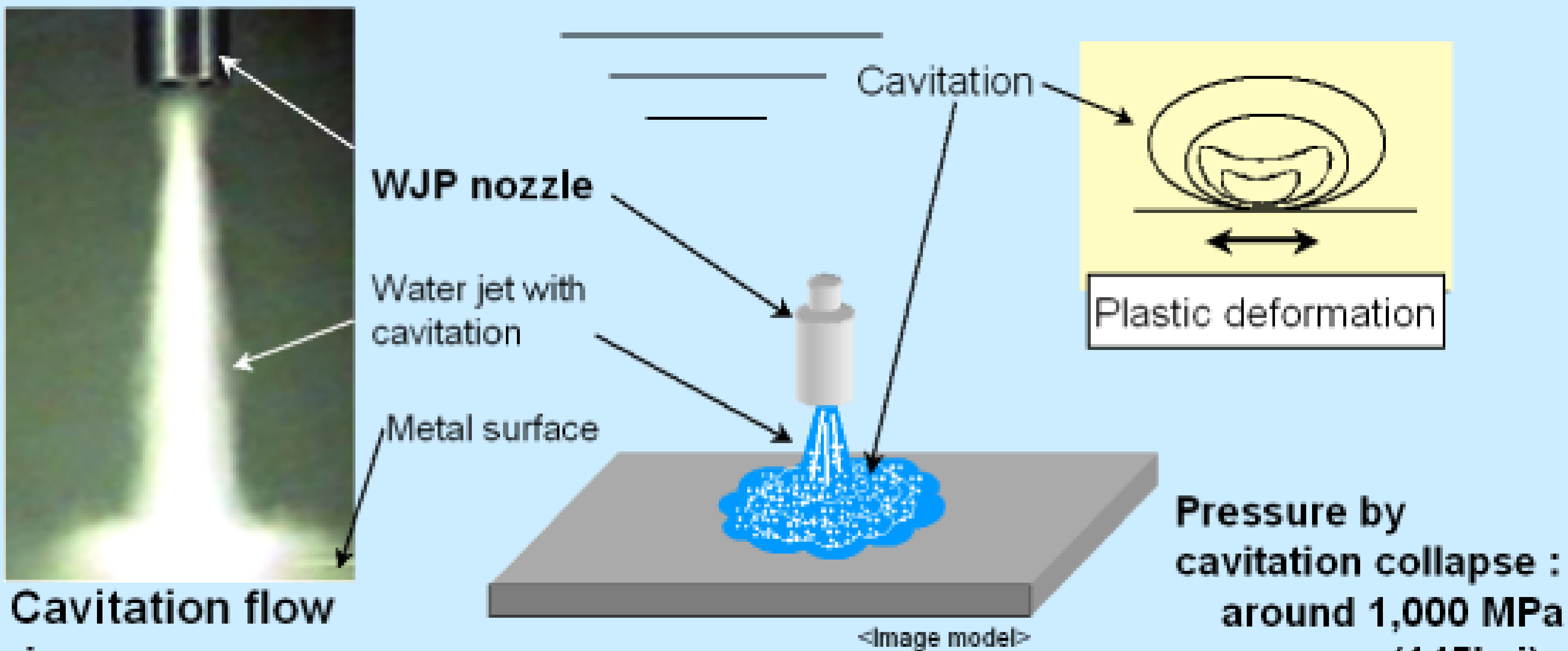
- A very consistent and repeatable peening process
- A clean, simple and lean process
- The use of small quantities of media
- A reduction or elimination of masking
- The elimination of decontamination
- Machines are small, quiet and easy to operate
- Increased flexibility
- Much improved surface finish
- Introduce very deep compressive residual stresses
- A highly optimized fatigue life
- Peening complicated geometries (threads, notches, ID of holes or the inside of hollow parts)

Ultrasonic Peening Floor Model

Portable Model with Peening Head

New technologies

Water jet peening

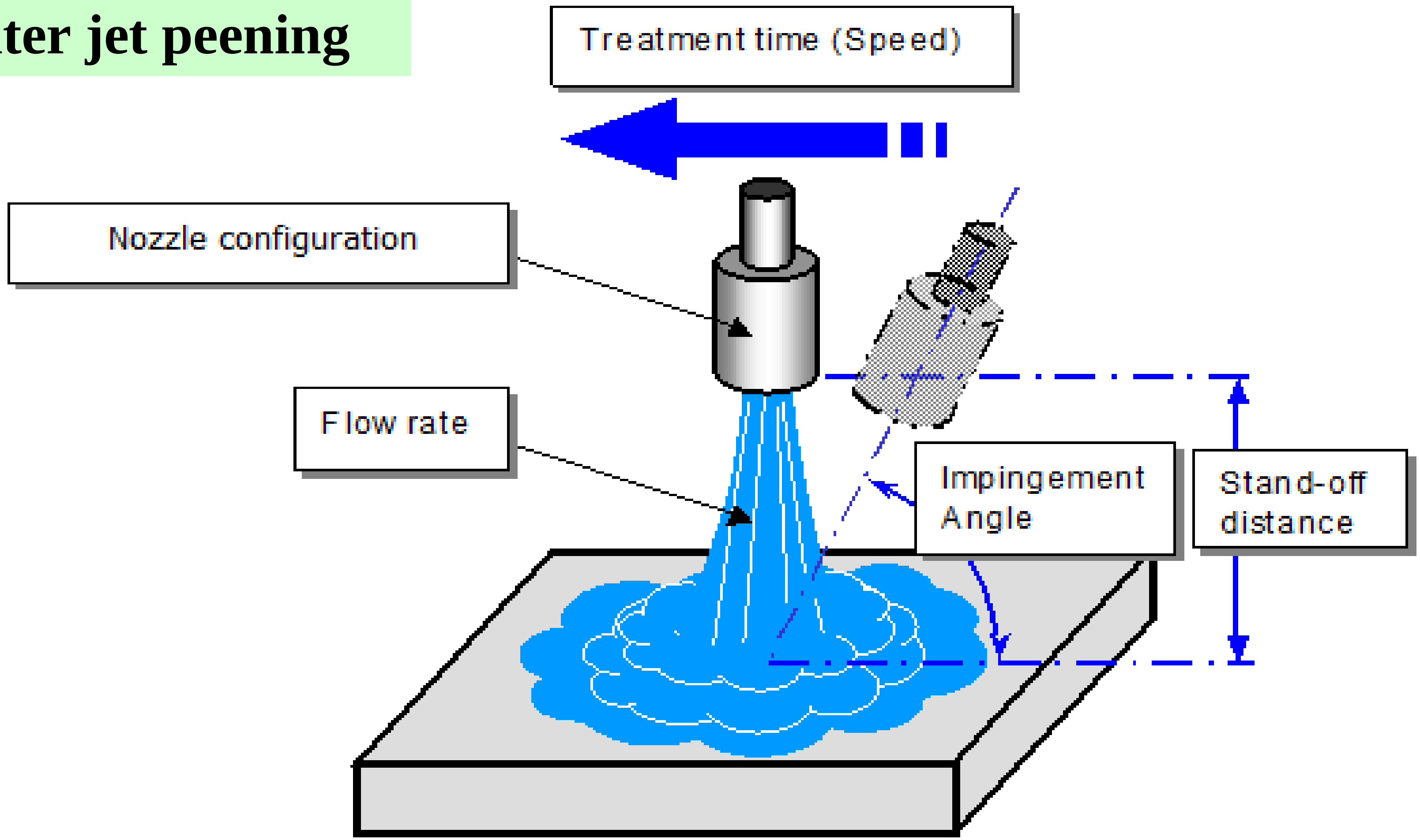


Cavitation flow image

Mechanism of residual stress improvement with Water jet peening

New technologies

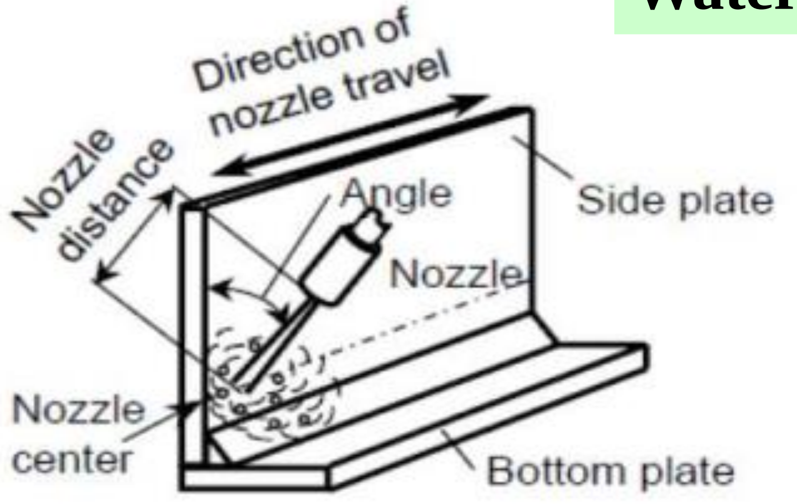
Water jet peening

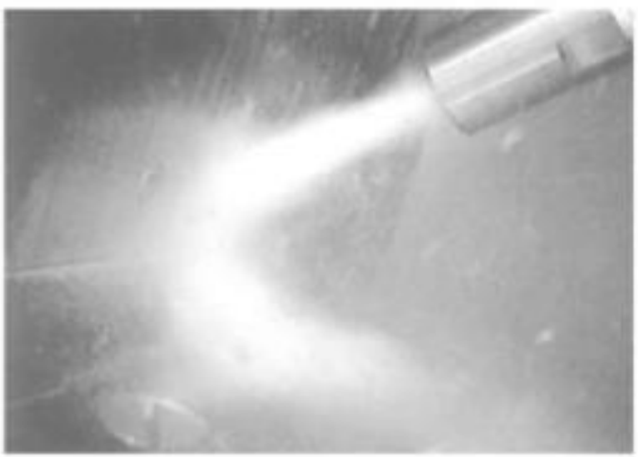


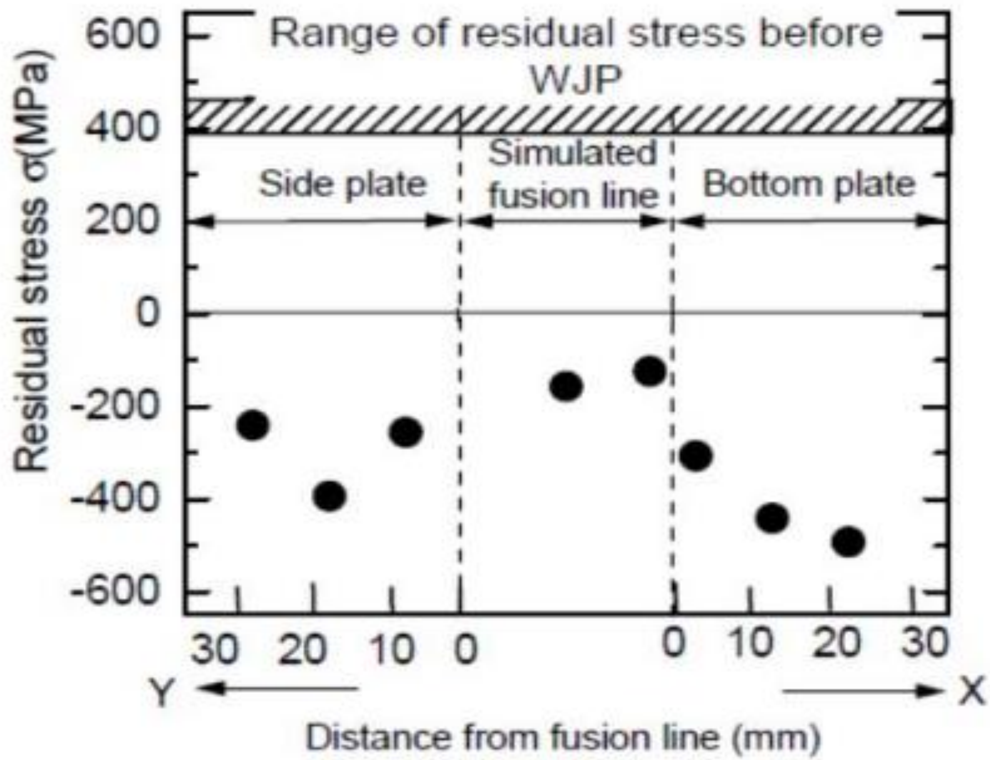
Essential variables of water jet peening

New technologies

Water jet peening





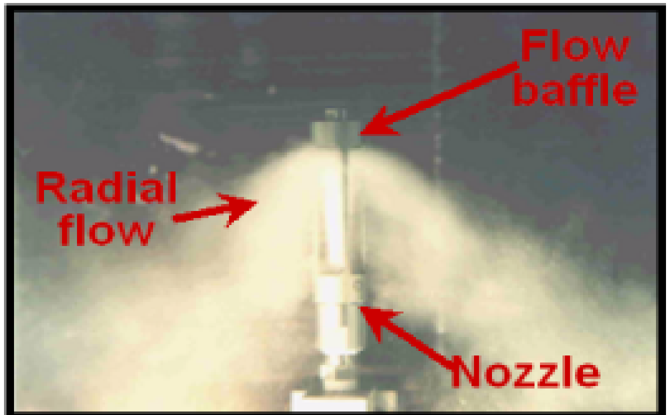


Side plate : Direct flow

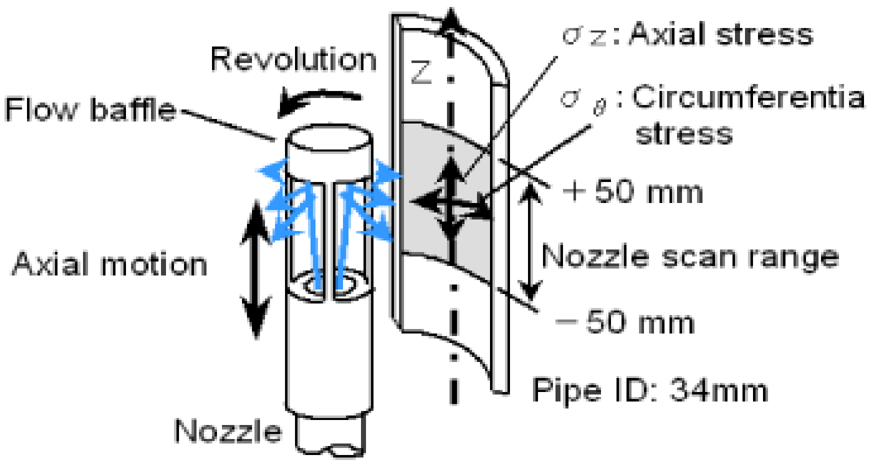
Bottom plate : Reflected flow around corner

New technologies

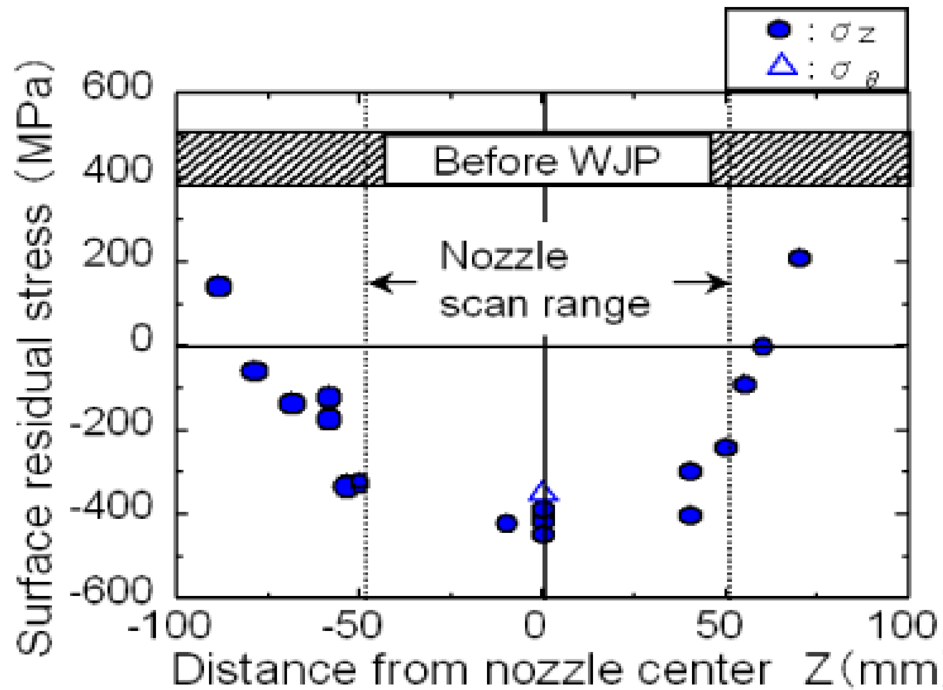
Water jet peening



Radial cavitation flow by a flow baffle



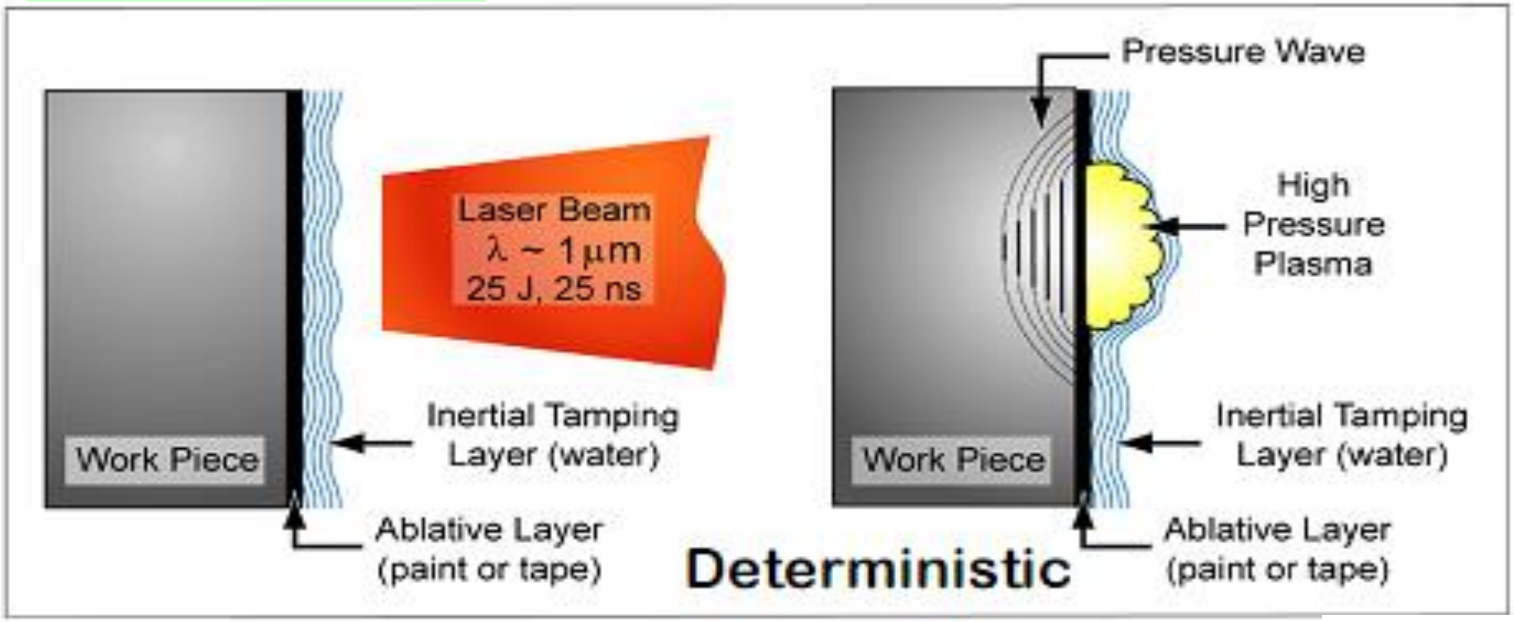
WJP procedure for small diameter pipe ID

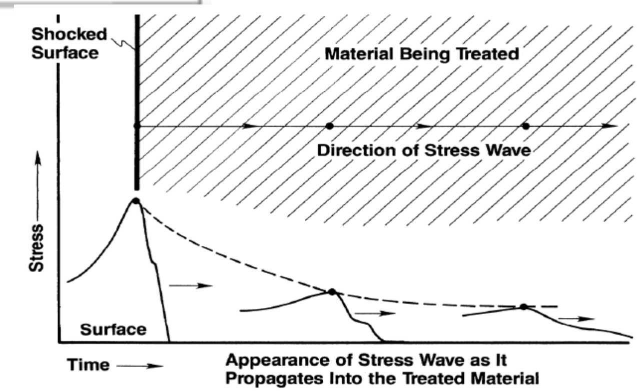


Stress distribution of pipe ID

New technologies

Laser peening





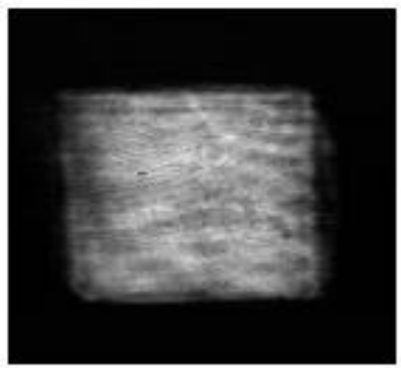
New technologies

Laser peening

➔ Extension of conventional shot peening

➔ Laser peening provides

* Highly compressive surface residual stress
* Deep layer of compressive residual stress
* Smooth surface
* Deterministic, precise process control

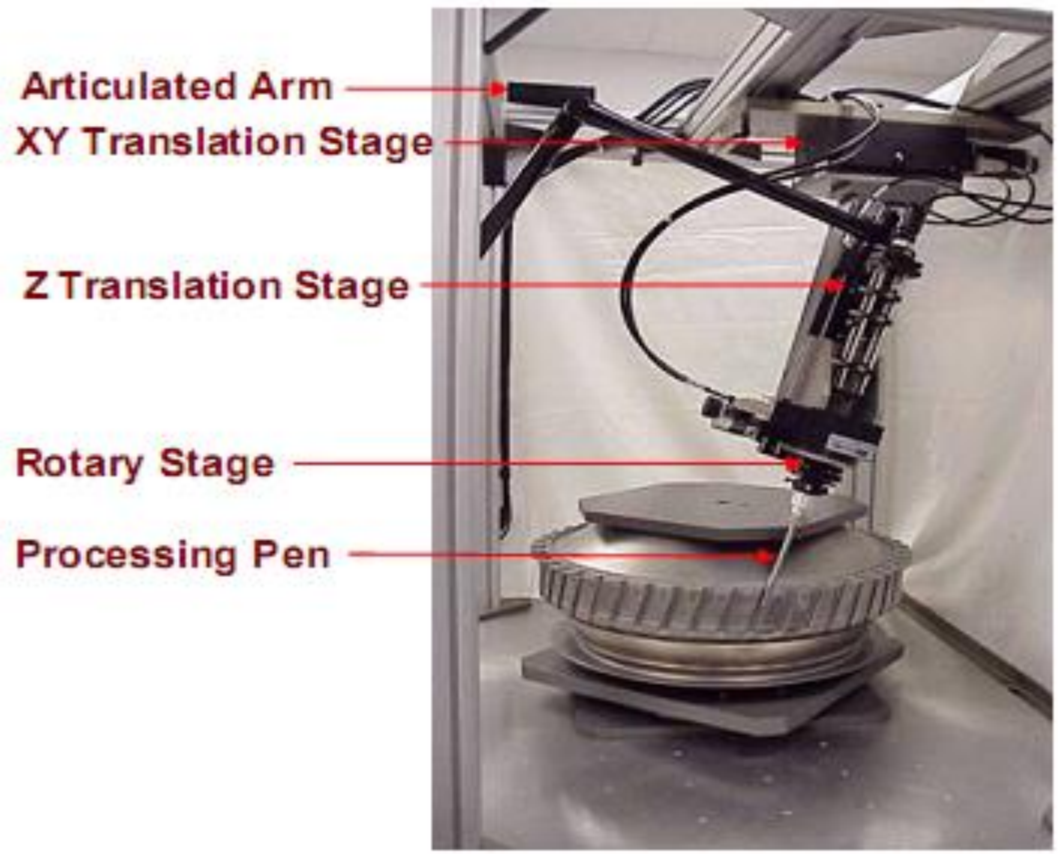


Laser near field image

Laser peened aluminum

New technologies

Laser peening



F110- GE-400 2nd stage fan disk

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New technologies

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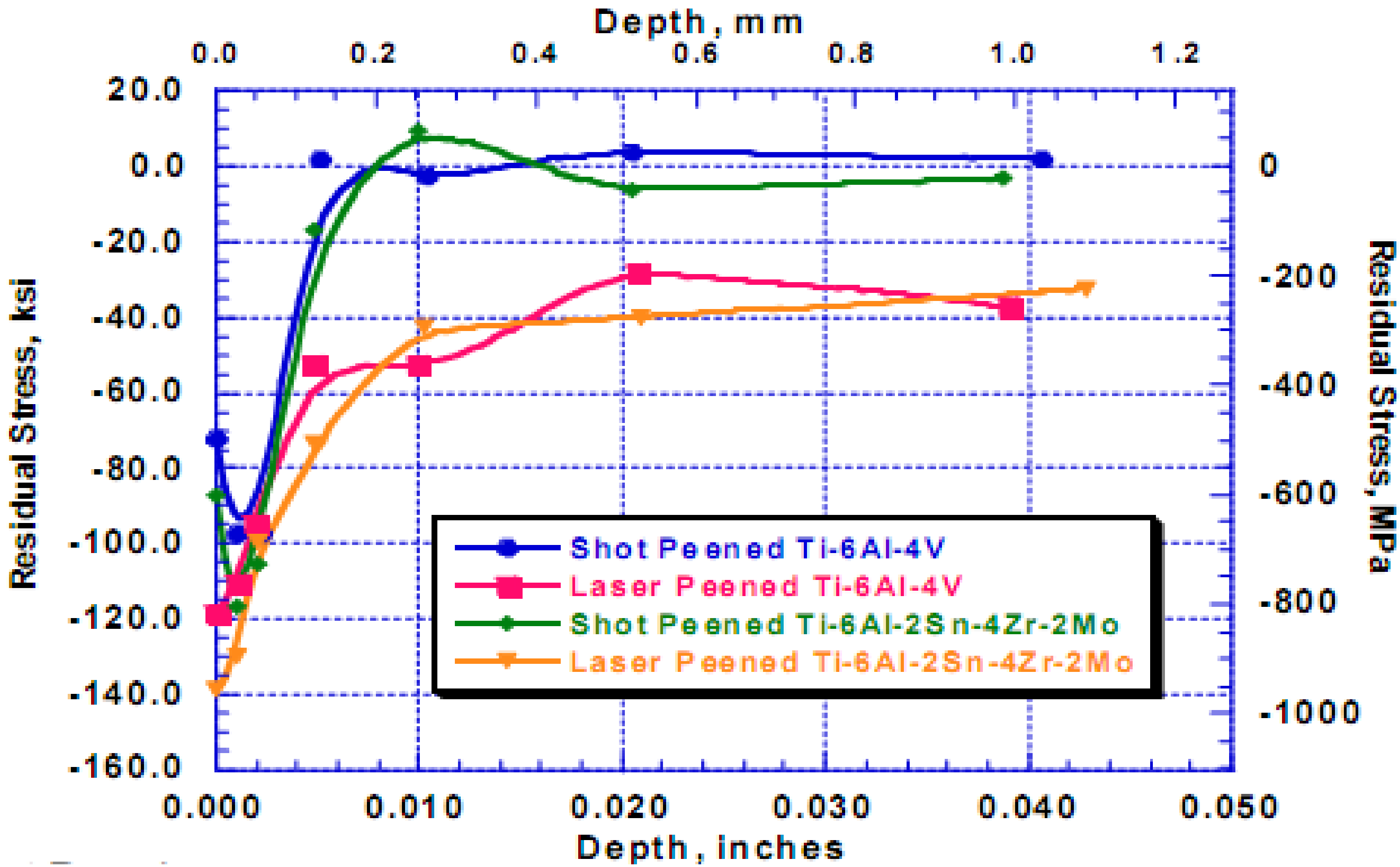
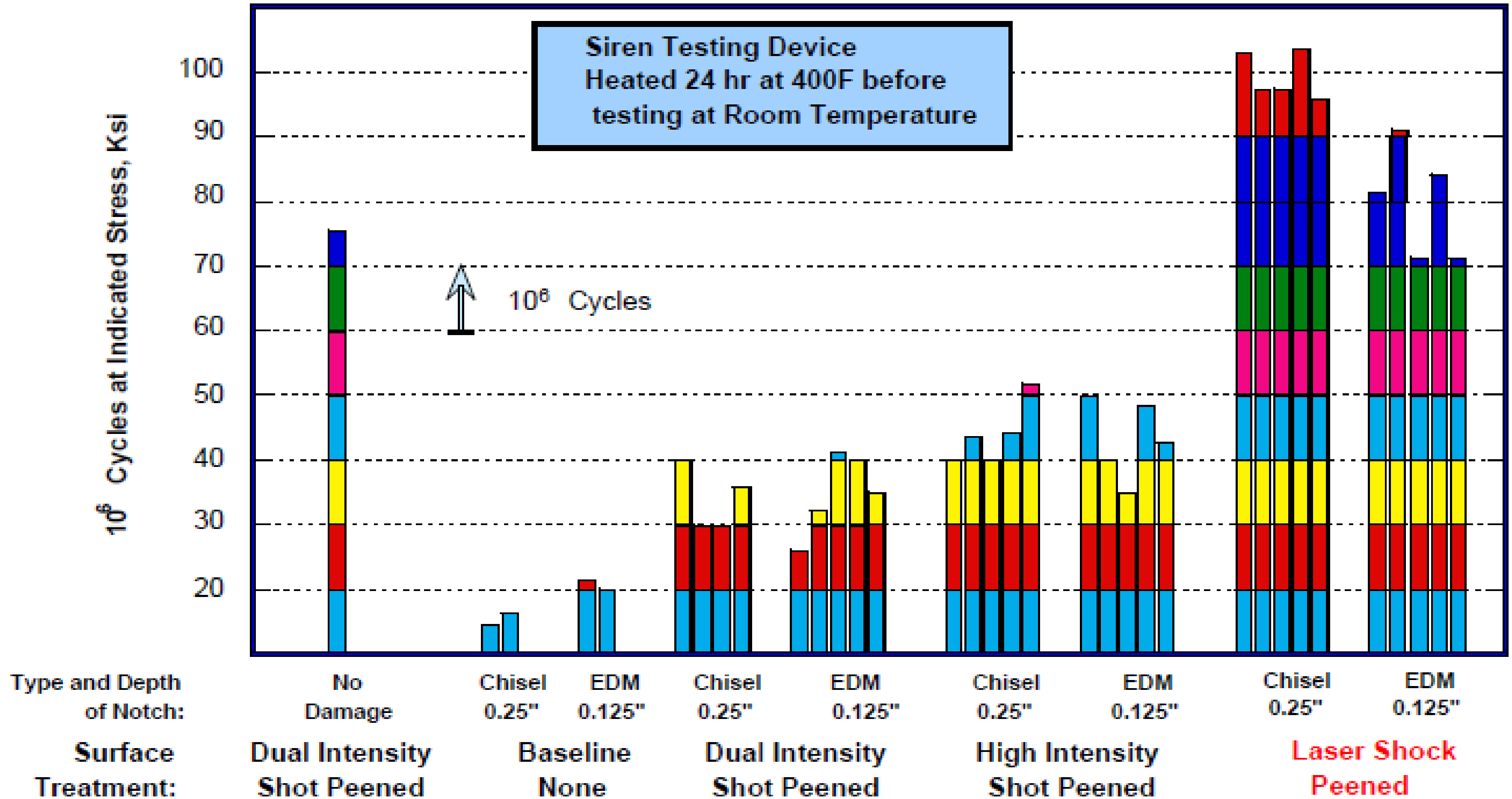
Laser peening



New technologies

Laser peening



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New technologies

Laser peening

B1-B Lancer, F101-GE-102 Engine

F/A-22 Raptor, F119-PW-100 Engine

F-16 Falcon, F110-GE-100,129 Engines

New technologies

Laser peening

- Chinook Transmissions
  - Engine - Gear tooth root
  - Forward - Planetary gears
  - Aft - Spiral bevel gear
- Apache
  - Main rotor transmission shaft – Upper and lower splines

Chinook

Apache