Cross-property connections in structural health monitoring

Main directions of research

Summer 2009-Summer 2010

- **Health monitoring of bolted joints**
- **Clusters of defects and mechanical properties of materials**
- **Quantification of strength-conductivity connections**

Publications

Sevostianov, I. Incremental elastic compliance and electric resistance of a cylinder with partial loss in the cross-sectional area. *International Journal of Engineering Science* **48** (2010), 582-591.

Cramer, M. and Sevostianov, I. Effect of pore distribution on elastic stiffness and fracture toughness of porous materials. *International Journal of Fracture* **160** (2009), 189-196.

Sevostianov, I. and Kushch, V.I., Effect of pore clusters on the statistics of peak stress and overall properties of porous material. *International Journal of Solids and Structures* **46** (2009) 4419-4429.

Argatov, I. and Sevostianov, I. On relations between geometries of microcontact clusters and their overall properties. *International Journal of Engineering Science* **47** (2009), 959-973.

Ervin, J. and Sevostianov, I. Effect of mutual positions of individual contacts on the overall resistance and elastic stiffness of a cluster. *International Journal of Fracture* **160** (2009), 101-108.

Sevostianov I. and Kachanov M. Local minima and gradients of stiffness and conductivity as indicators of strength reduction of brittle-elastic materials. *International Journal of Fracture* (DOI: 10.1007/s10704-010-9485-6).

Sevostianov, I., Zagrai, A., Kruse, W.A., and Hardee, H. Connection between strength reduction, electric resistance and electro-mechanical impedance in materials with fatigue damage. *International Journal of Fracture* (DOI: 10.1007/s10704-010-9487-4).

Sevostianov, I. Explicit cross-property connections for materials with anisotropic constituents. *Journal of Mechanics of Materials and Structures* (accepted for publication).

Argatov, I and Sevostianov, I. Health monitoring of bolted joints via electrical conductivity measurements. *International Journal of Engineering Science* (accepted for publication).

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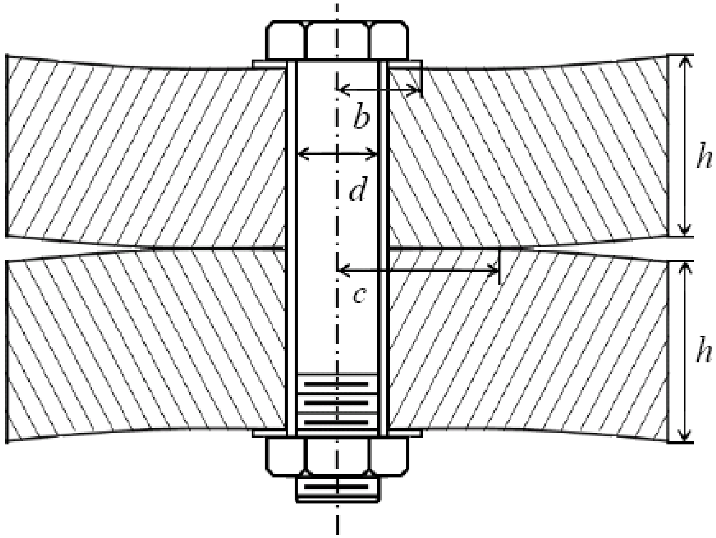
Health monitoring of bolted joints



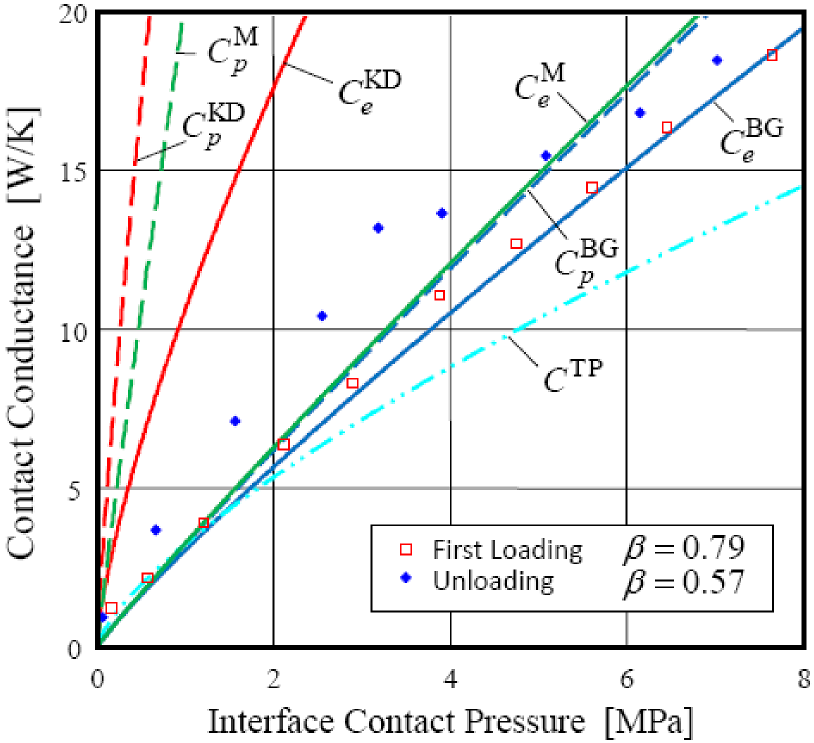
- Electrical resistance depends on the area of contact between two contacting plates;
- The area of contact depends on the applied force;
- Can we evaluate loosening of a bolted joint via resistance measurement?

Several theories have been adopted and checked against experimental data

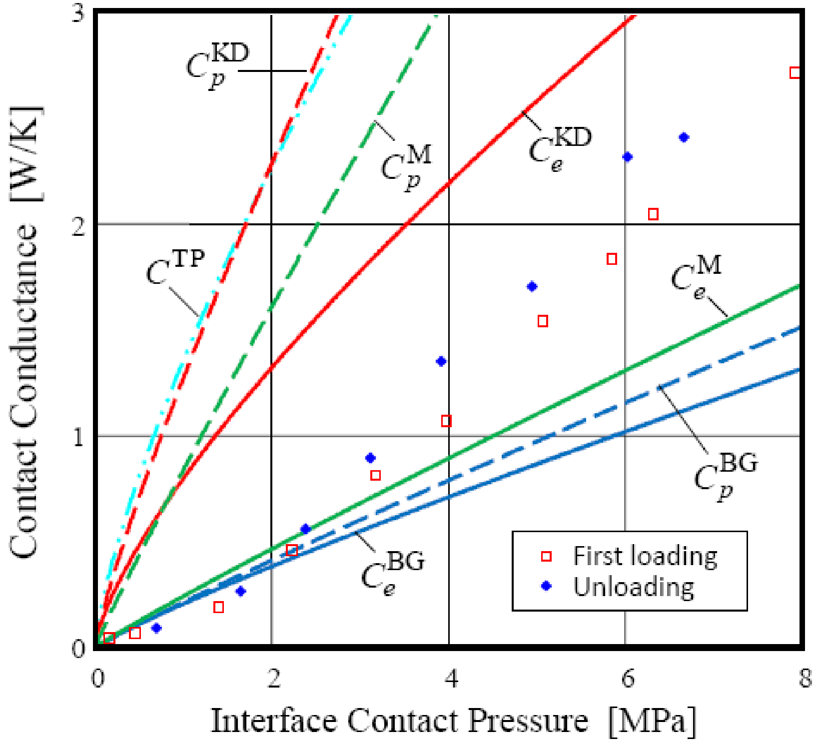
Thomas and Probert (1972)
Kragelsky and Demkin (1960)
Bush and Gibson (1979)
McWald and Marshall (1992)

No fully comprehensive theory exists

Contact conductance versus contact pressure

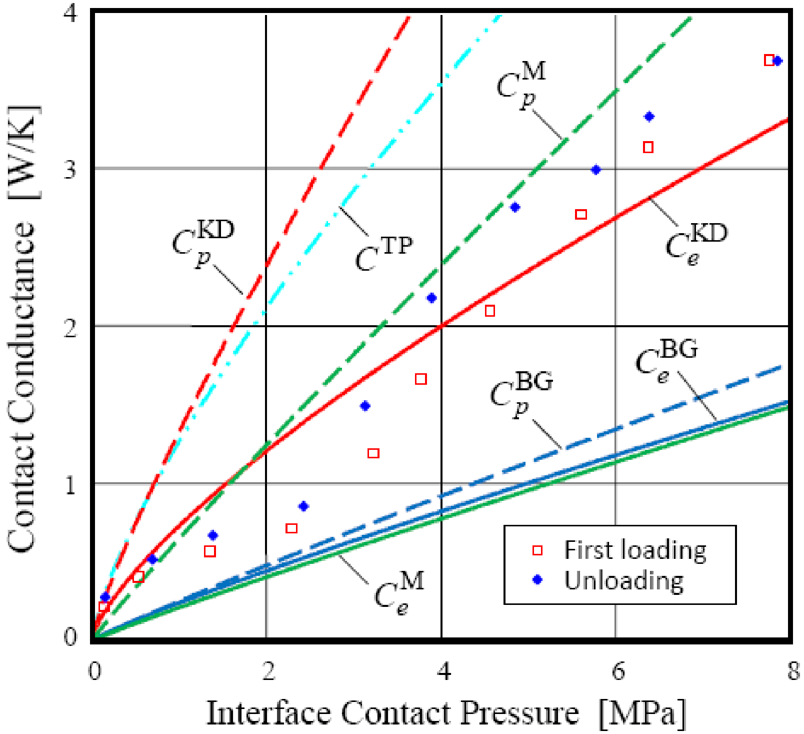


Aluminum surfaces bed-blasted with small beds

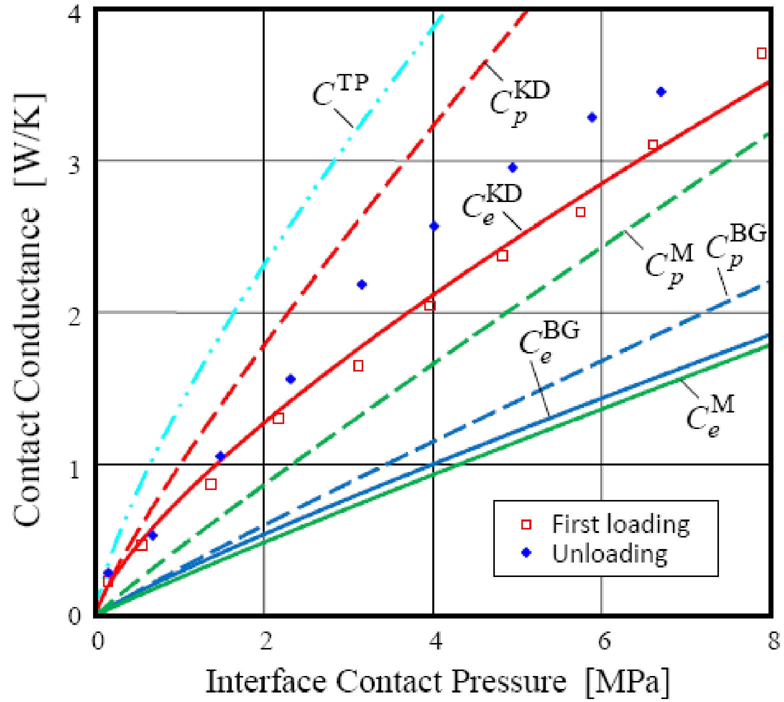


Steel surfaces bed-blasted with small beds

Contact conductance versus contact pressure



Ground steel specimens with their lays oriented parallelly

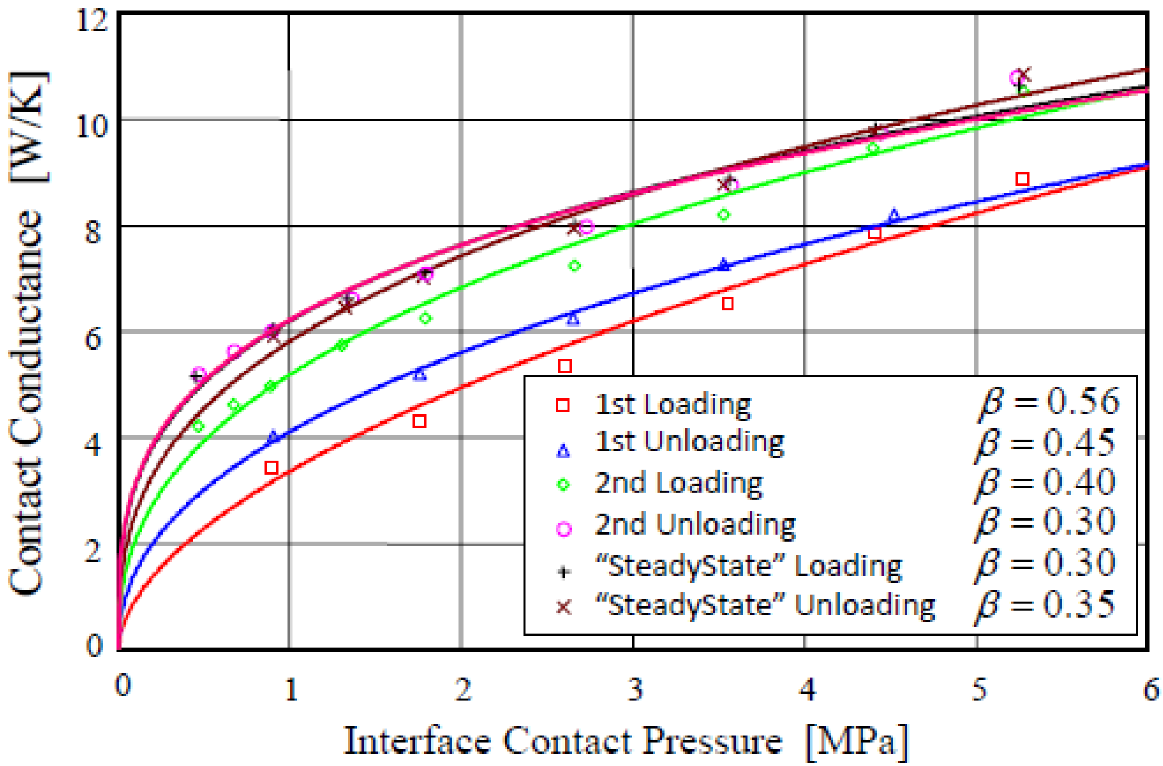


Ground steel specimens with their lays oriented perpendicularly

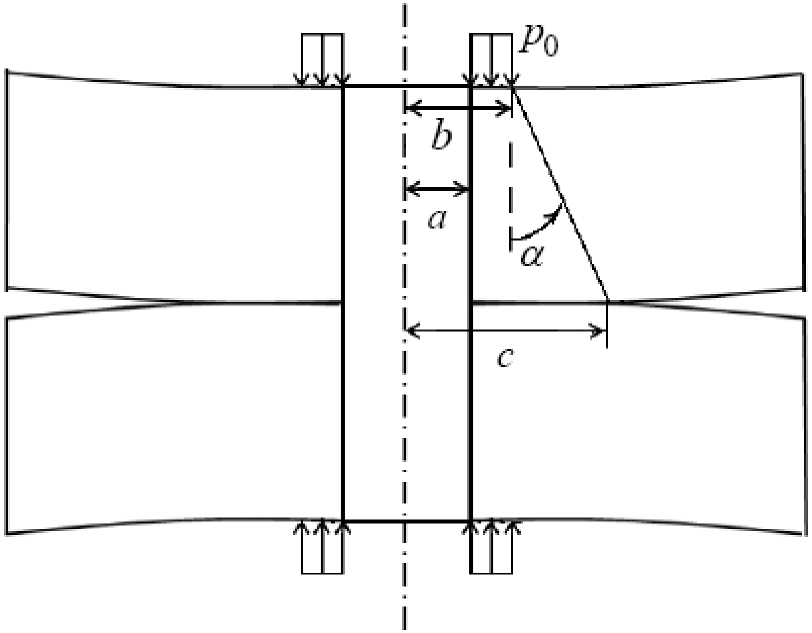
Using cross-property connection to evaluate conductivity exponent

$$h_c = \text{const}\frac{k}{R_p}(\Theta p_c)^{\frac{4\nu-3}{4\nu-1}}$$

$$\beta = \frac{4\nu - 3}{4\nu - 1}$$



Interface contact pressure in bolted joints



Fernlund-Motosh approximation

$$p(r) = C_4\left(\frac{r}{a}\right)^4 + C_3\left(\frac{r}{a}\right)^3 + C_2\left(\frac{r}{a}\right)^2 + C_1\frac{r}{a} + C_0.$$

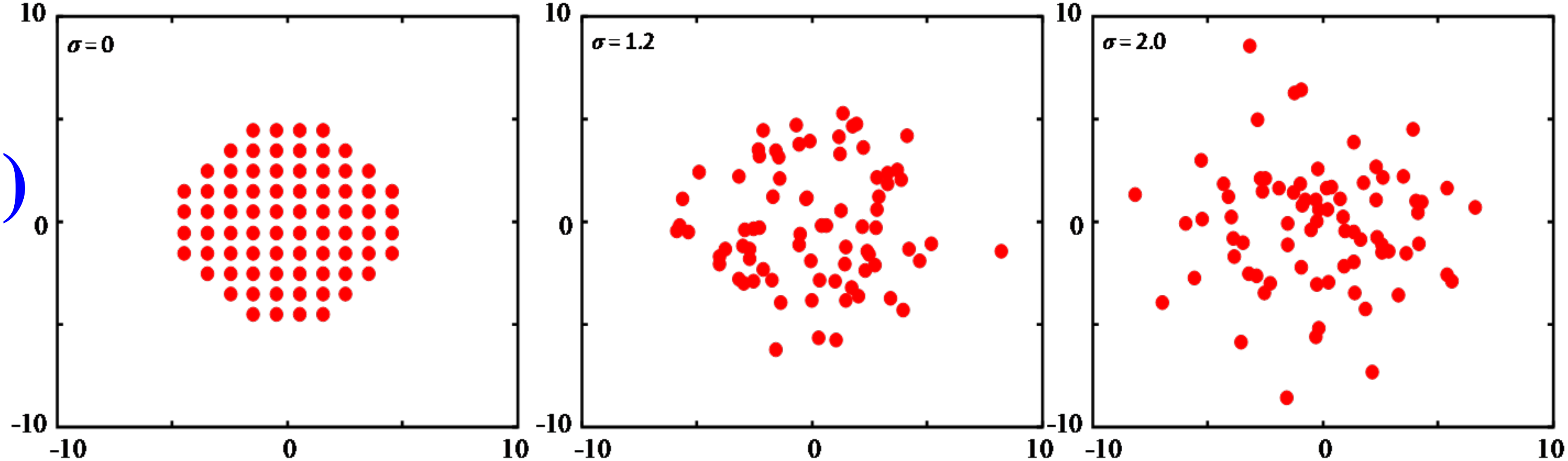
Rötscher relation

$$c = b + h\tan\alpha.$$

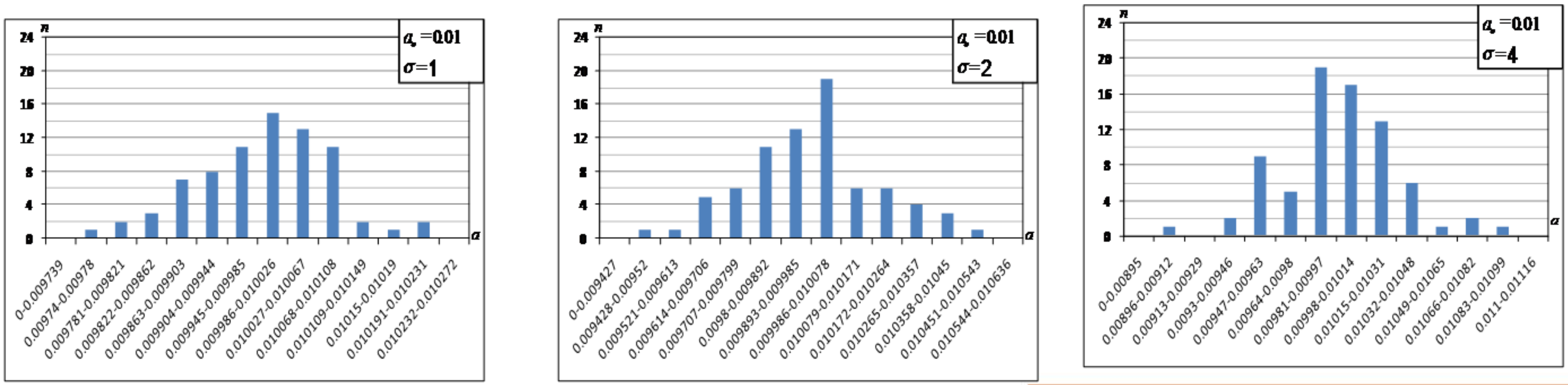
$$\alpha = 40^\circ \quad \text{or less for} \quad (h/a) < 2,$$
$$\alpha = 45^\circ \quad \text{for} \quad 2 \le (h/a) < 4,$$
$$\alpha = 50^\circ \quad \text{or more for} \quad (h/a) \ge 4.$$

Dependence of overall resistance on cluster geometry

(A)



(B)

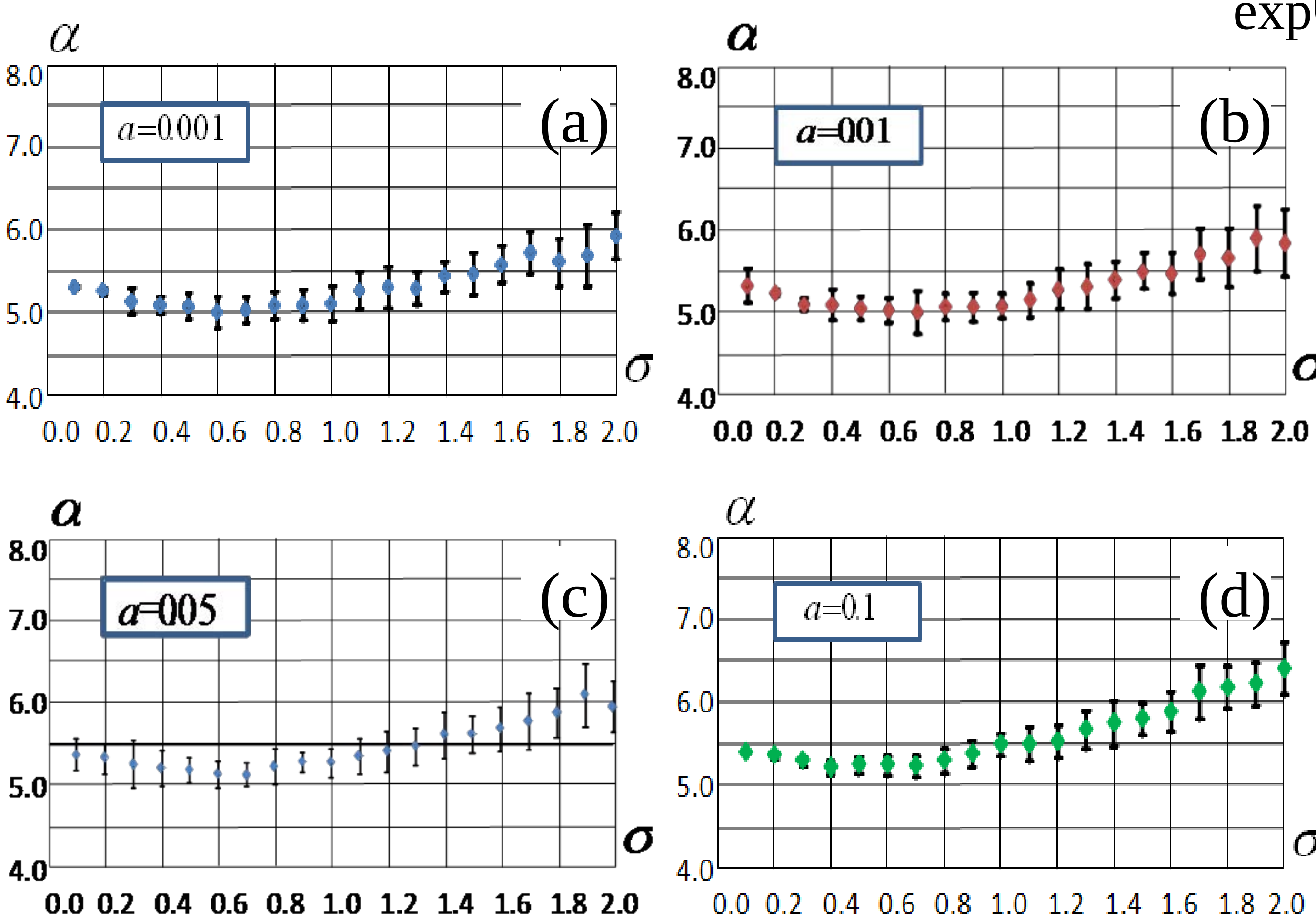


Effect of mutual positions

$$\exp\left(-x_0^2/2\sigma^2\right)/\left(\sqrt{2\pi}\sigma\right)$$

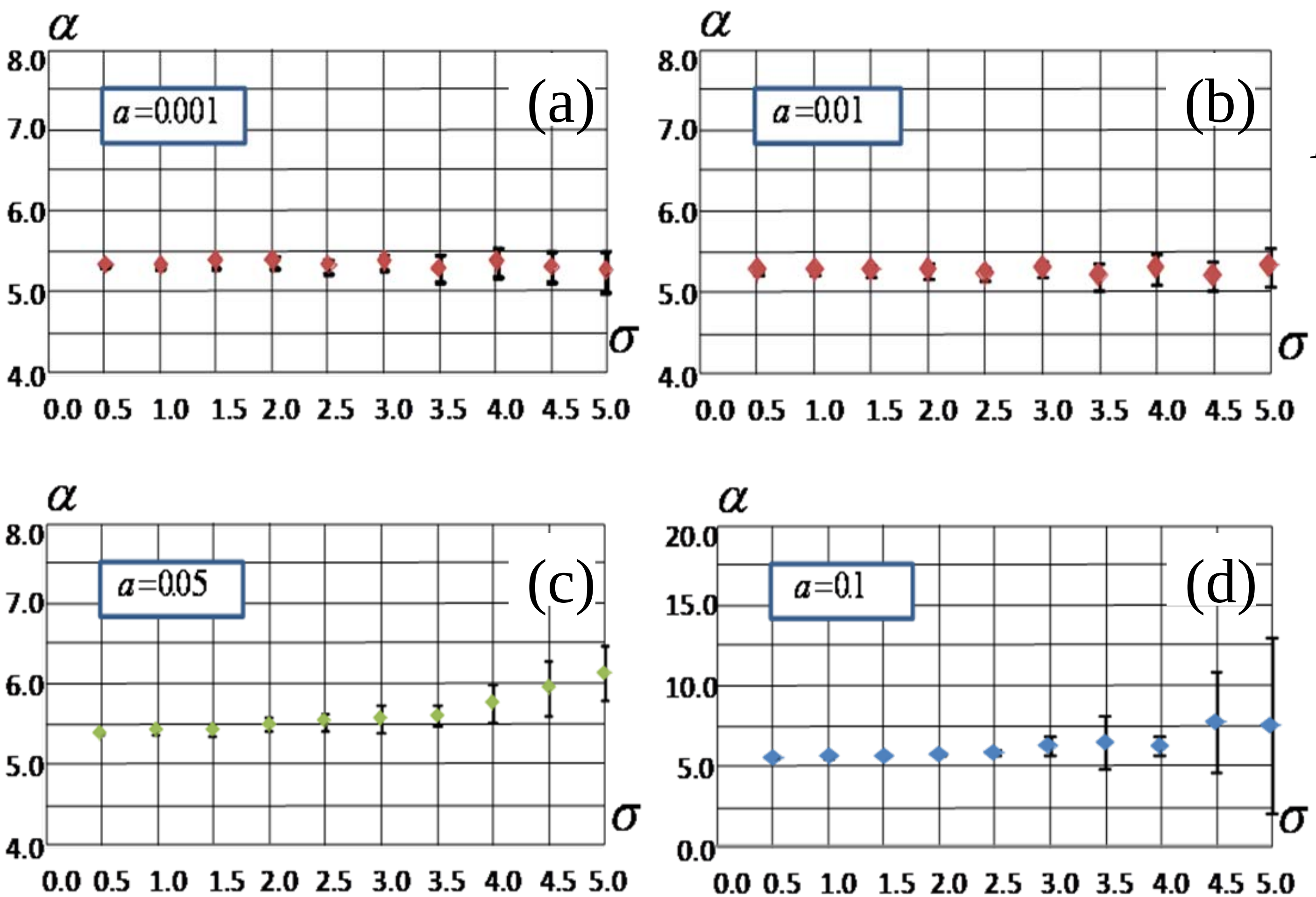
$$\exp\left(-y_0^2/2\sigma^2\right)/\left(\sqrt{2\pi}\sigma\right)$$

$$R=\rho\left(\frac{1}{2Na}+\frac{1}{2\alpha}\right)$$



Effect of variation in radii

$$\exp\left(-\left(1/r_0\right)^2/2\sigma^2\right)/\left(\sqrt{2\pi}\sigma\right)$$

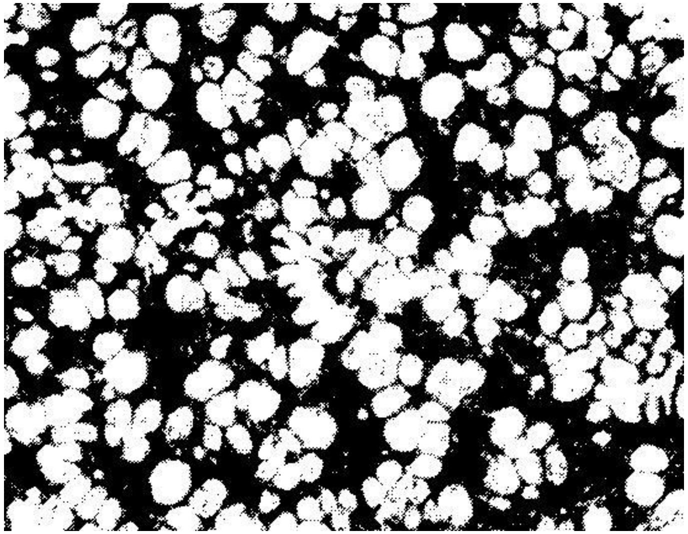


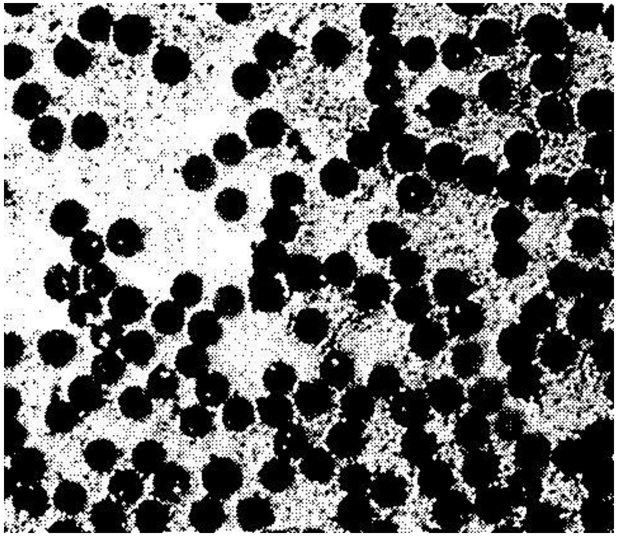
$$R = \rho\left(\frac{1}{2Na} + \frac{1}{2\alpha}\right)$$

Clusters of defects and mechanical properties

Most of the results in microstructure-property relationships are obtained for either uniform or periodic distribution of inhomogeneities.

Real materials (both natural and man-made) rarely have uniform microstructure.

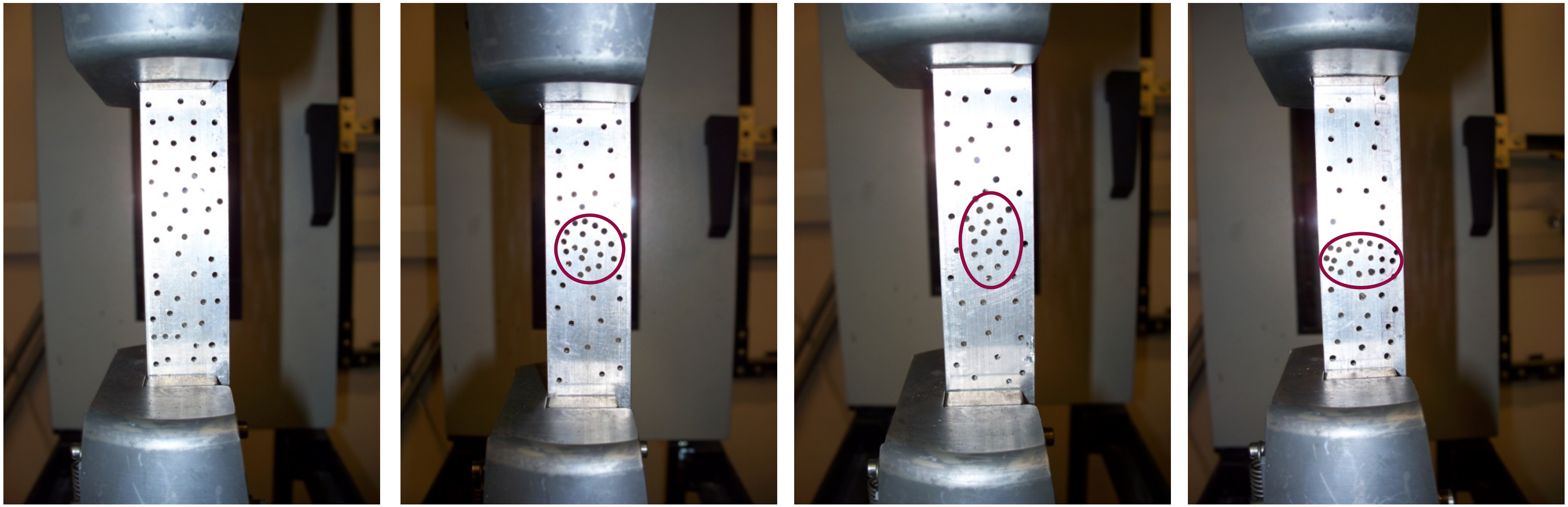


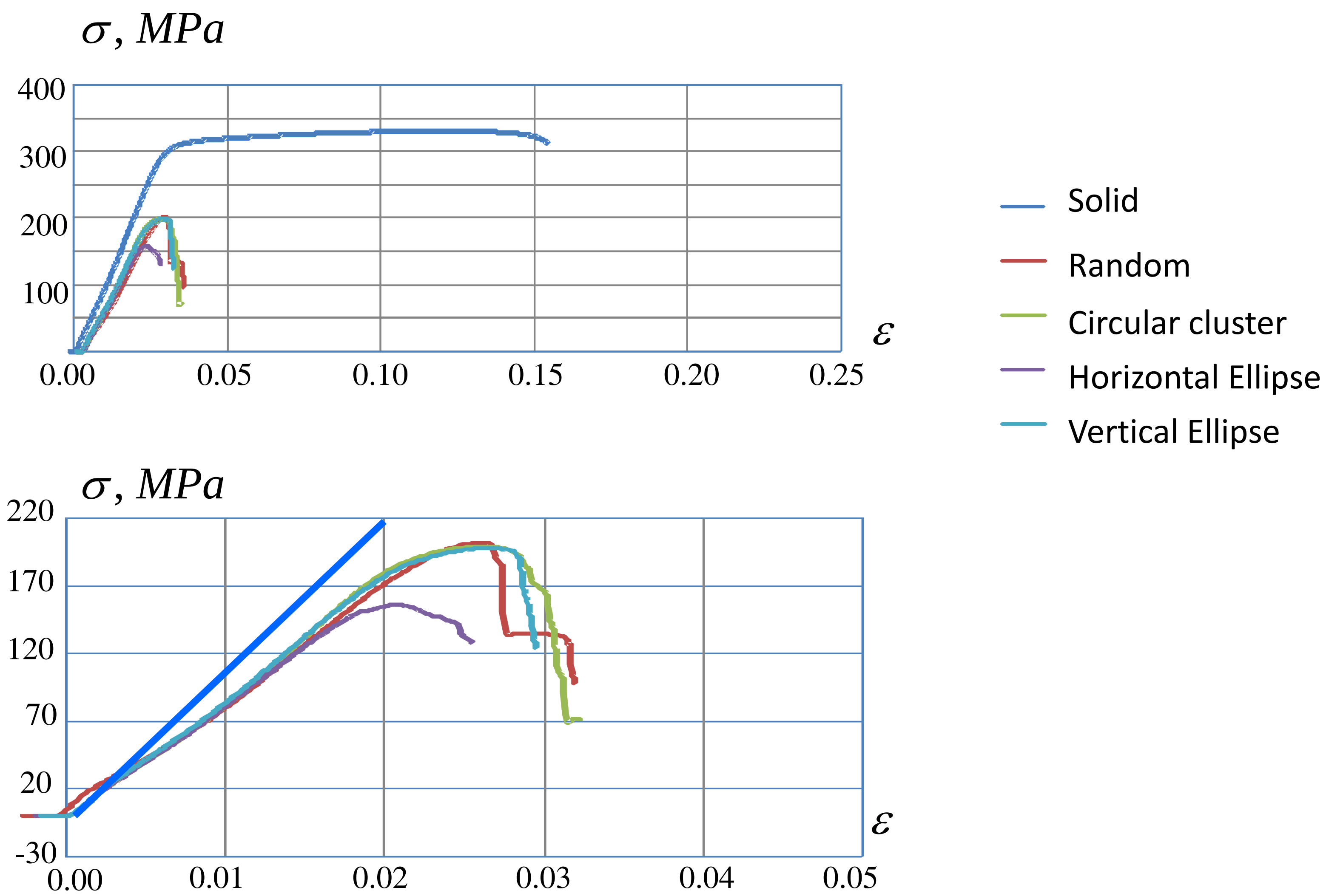


(1) Zinc alloy; (2)Aluminum alloy reinforced with boron;

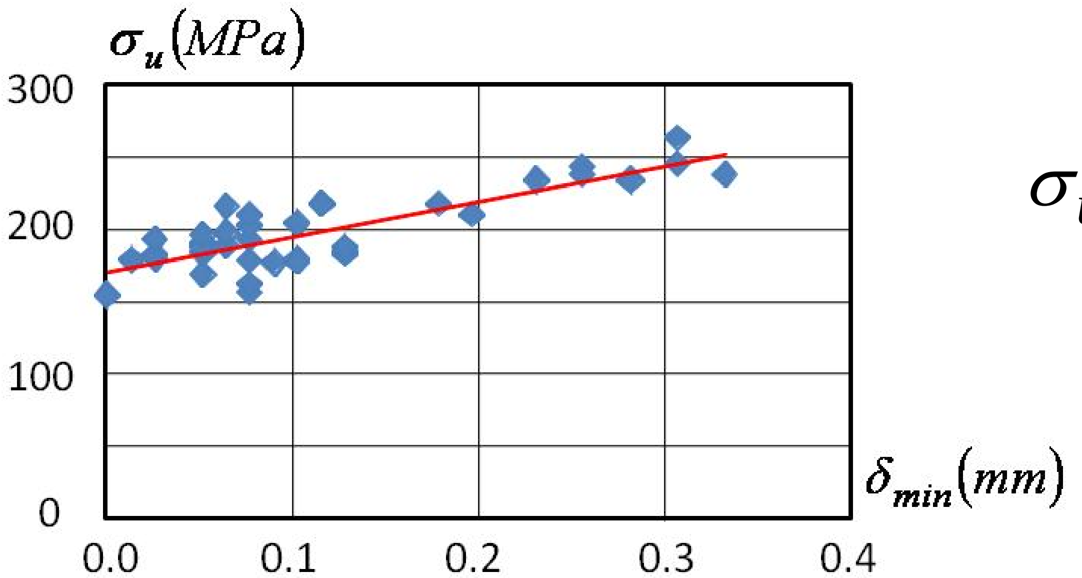
Clusters of different shape

The microstructures of the specimens have been first generated on a computer. For this aim, the 2D version of the molecular dynamics (MD) algorithm of growing particles is utilized.

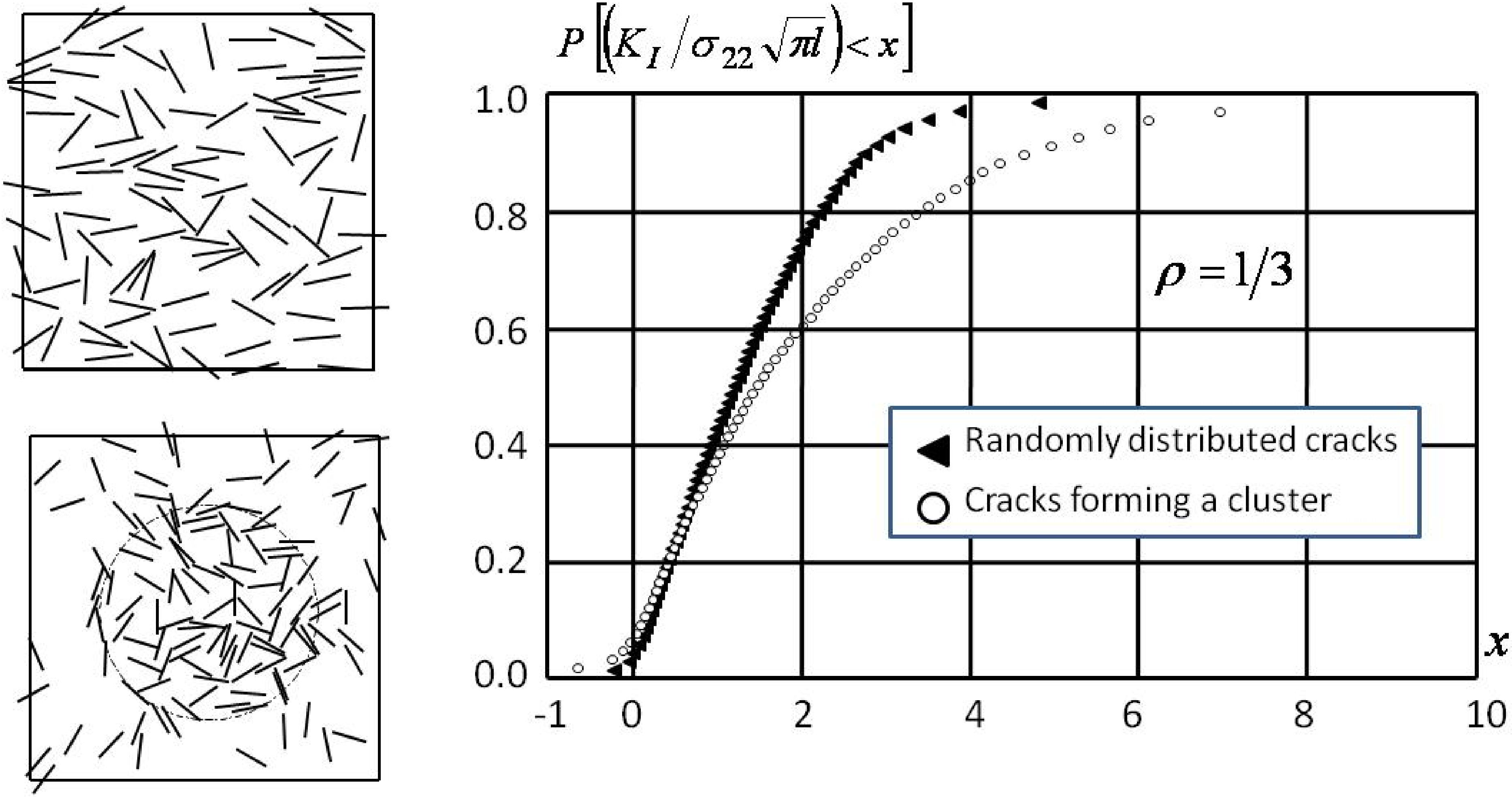



σ, MPa
400
300
200
100
0.00
0.05
0.10
0.15
0.20
0.25
ε
Solid
Random
Circular cluster
Horizontal Ellipse
Vertical Ellipse
σ, MPa
220
170
120
70
20
-30
0.00
0.01
0.02
0.03
0.04
0.05
ε

	Pore-Free	Random pore distribution	Elliptic cluster, major axis along the loading direction	Circular cluster	Elliptic cluster, major axis normal to the loading direction
$E^*(GPa)$	70.0	39.9	38.2	37.8	37.4
$\sigma_{fr}(MPa)$	326	240	206	185	166



$$\sigma_u = 38.175\delta + 167.2$$



$P\left[\left(K_I / \sigma_{22}\sqrt{\pi l}\right) < x\right]$
1.0
0.8
0.6
0.4
0.2
0.0
-1
0
2
4
6
8
10
x
$\rho = 1/3$
Randomly distributed cracks
Cracks forming a cluster

Quantification of strength-conductivity connections

It is often suggested in literature to use change in the effective elastic properties (stiffness loss) as an indicator of reduction of strength due to defects such as cracks and pores. We argue that the key parameter is not the reduction of the average (over the specimen) stiffness but its *local* minimal values caused by formation of defect clusters. These defect clusters can be identified by the emergence of spatial *gradients* of elastic stiffness on a smaller scale. A convenient tool of detecting these gradients is provided by the elasticity-conductivity connection: the electric conductance gradient is usually easier to measure than the stiffness gradient. This concept is supported by computational and experimental results reported in two accompanying papers published in the present issue

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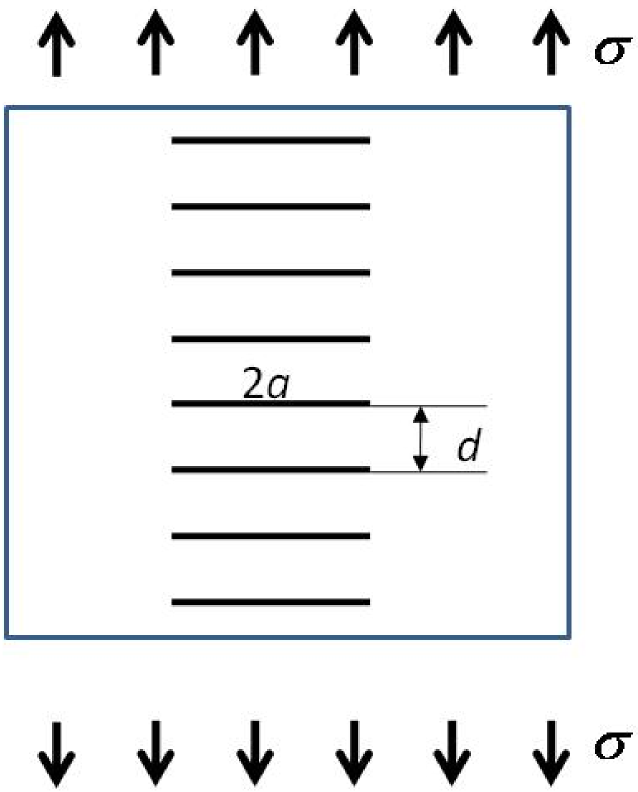
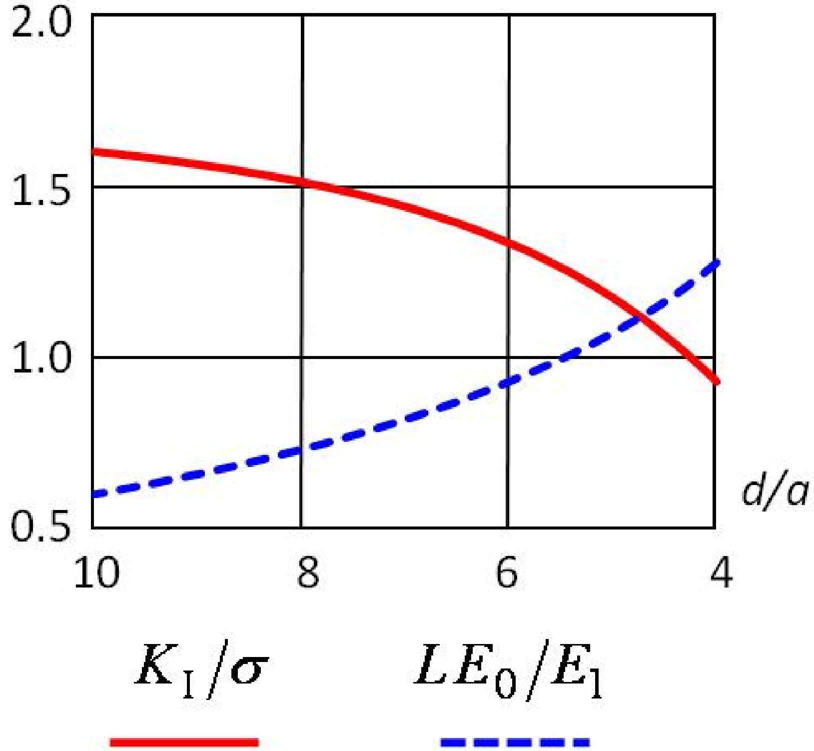
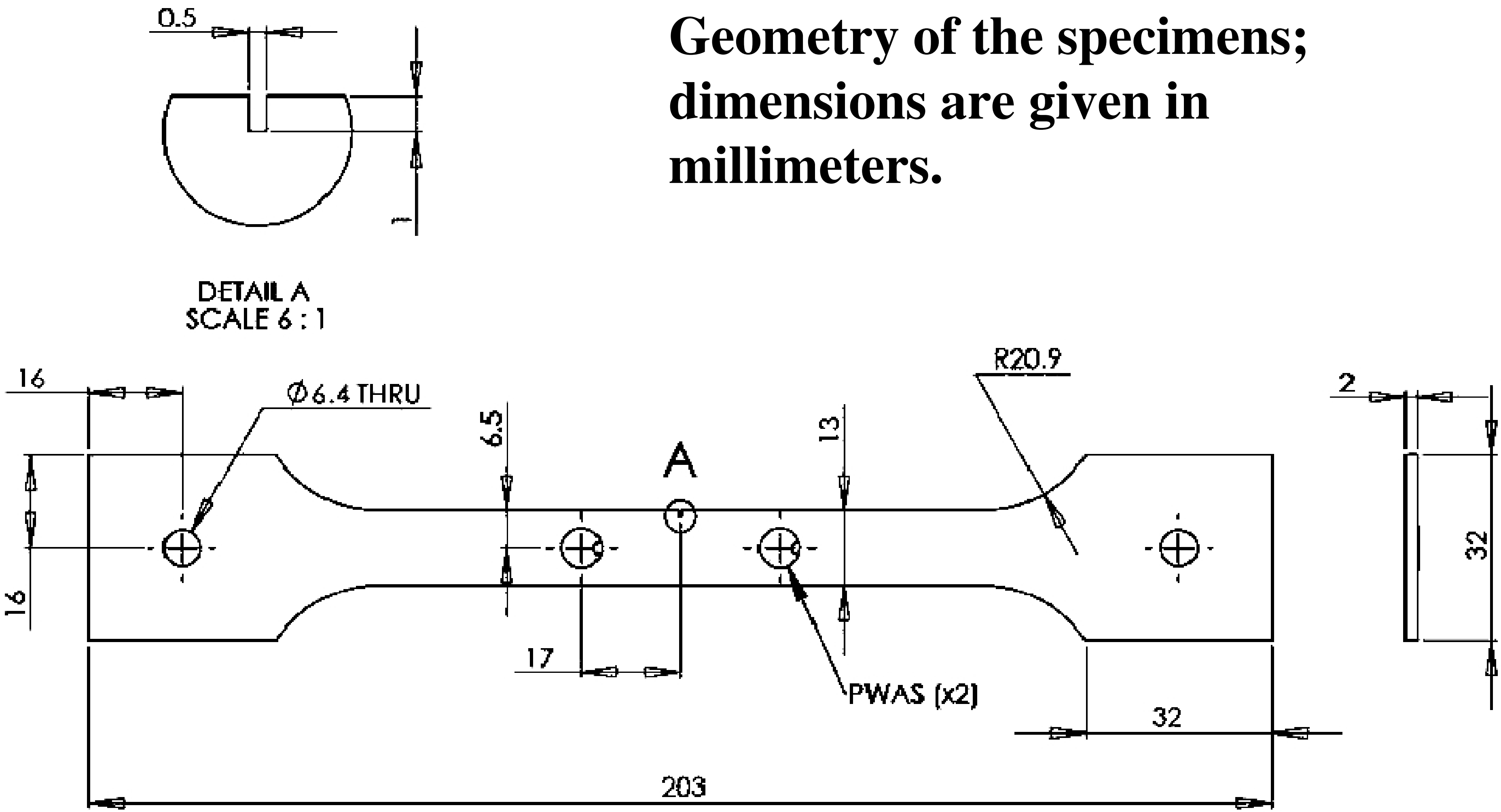
Quantification of strength-conductivity connections

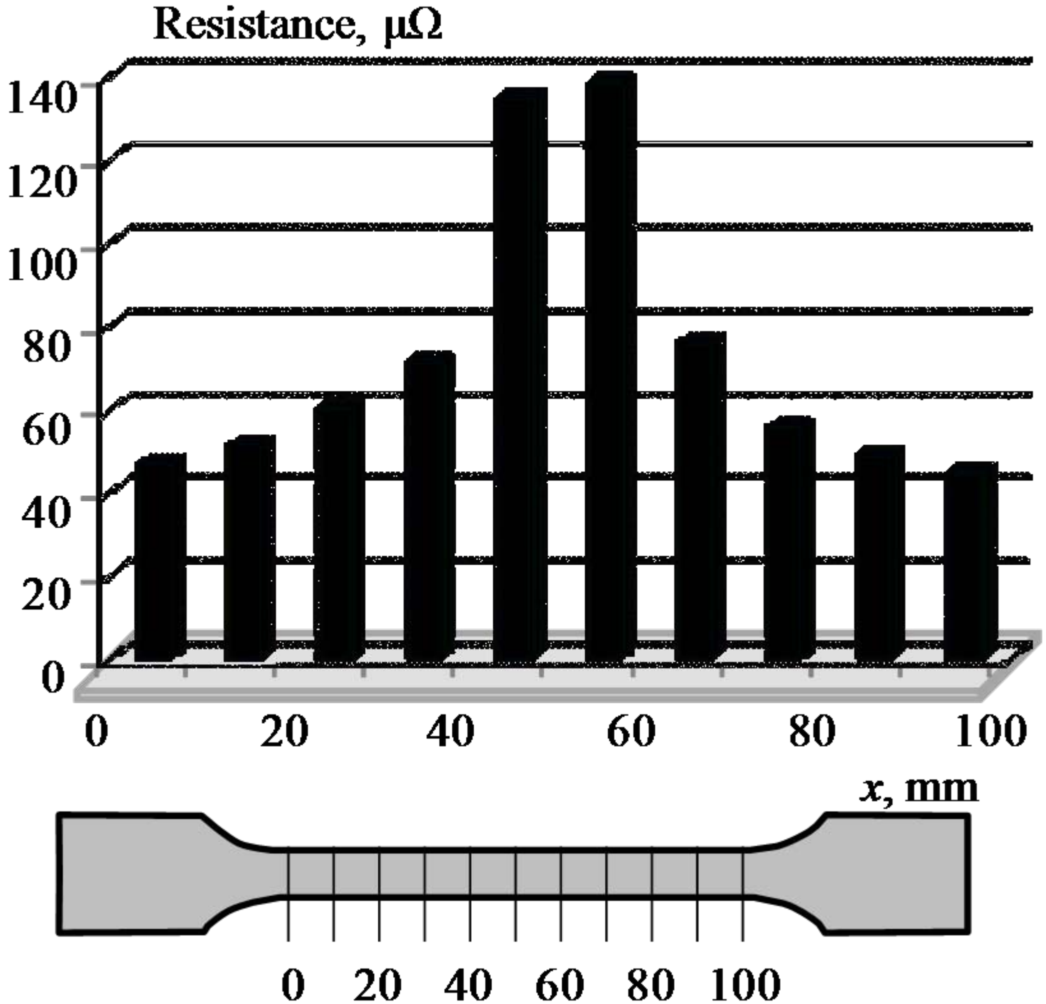




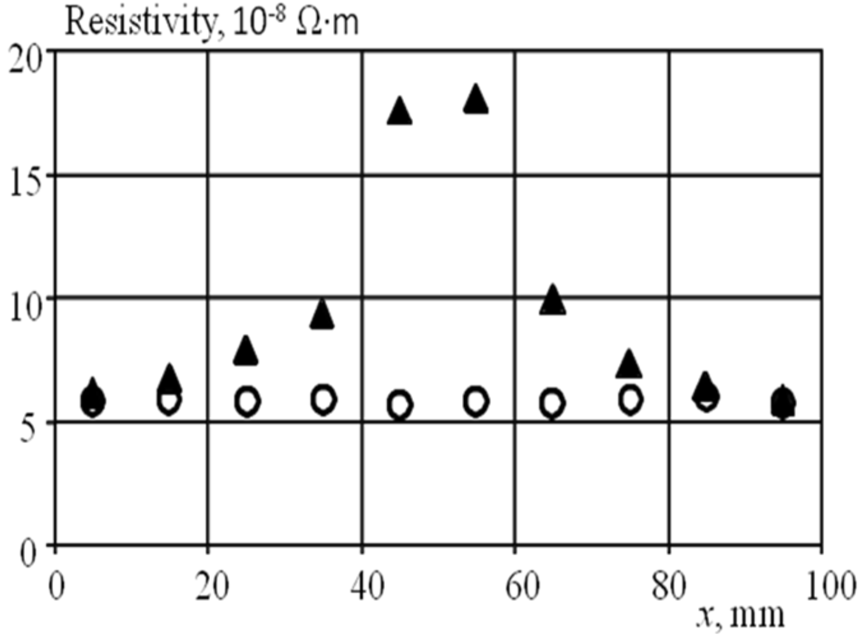
Parallel cracks: “Paradoxical” connection between stiffness reduction due to introduction of new cracks (modeled by reduction of spacing between cracks) and <u>decrease</u> of SIFs.

Geometry of the specimens; dimensions are given in millimeters.

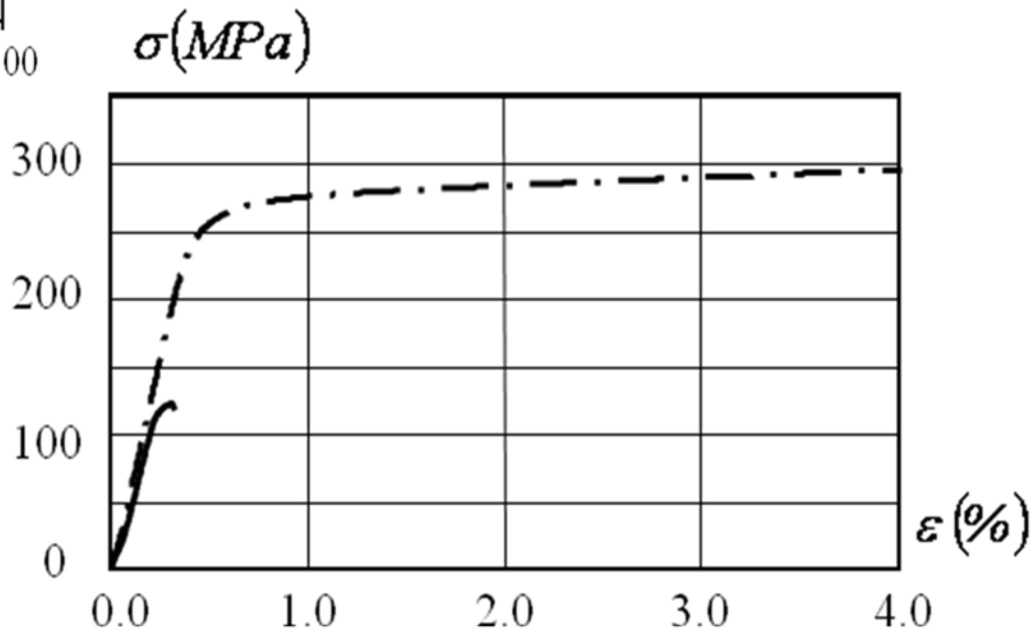




Variation of local resistance in a specimen after 44000 loading cycles. Note substantial increase of resistance (drop of conductivity) near the notch, where the clusters of microcracks are suspected.

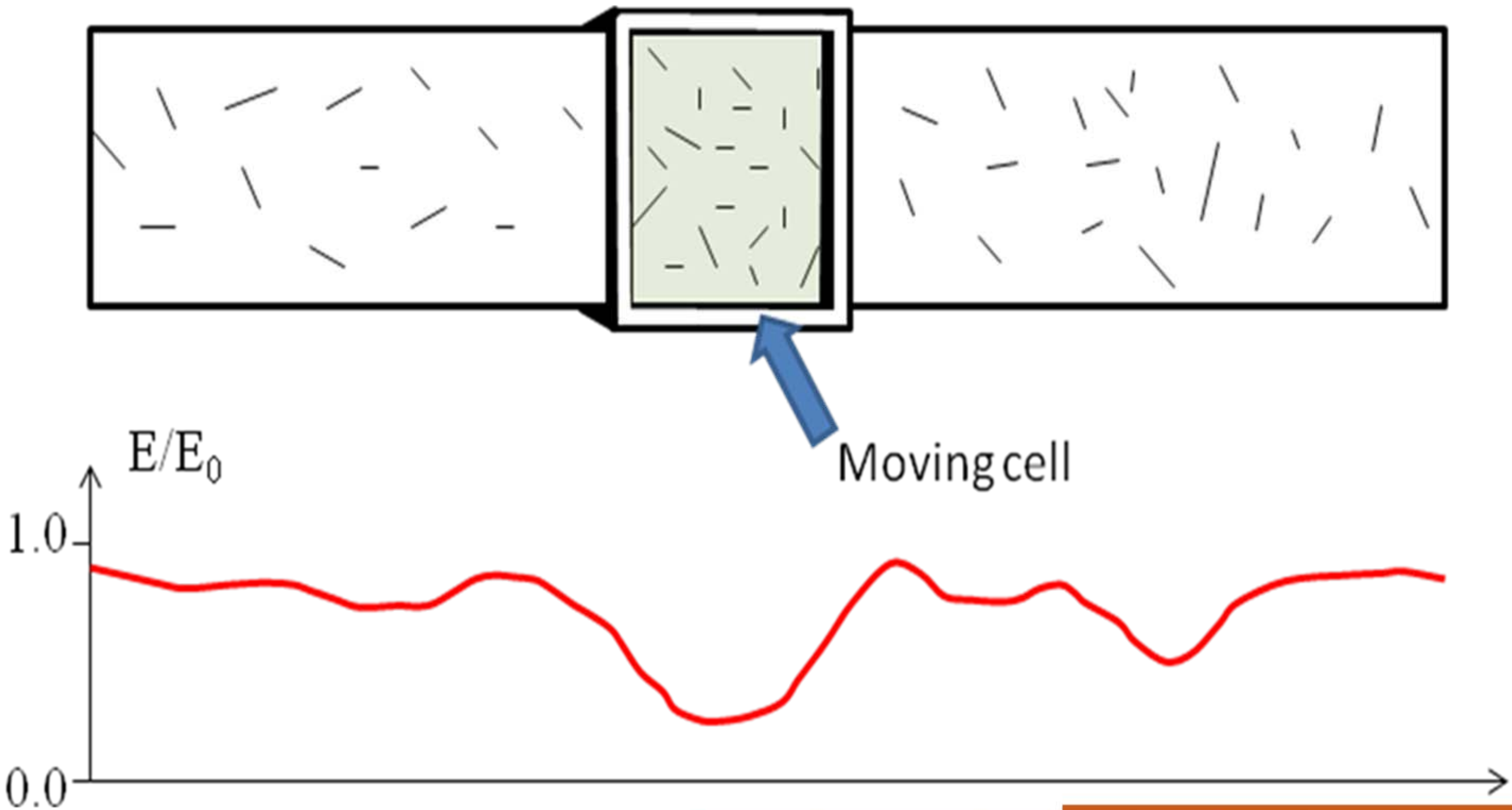


Variation of local resistivity in a specimen after 44000 loading cycles (solid triangles) compared with local resistivity in a non-loaded specimen (white circles).



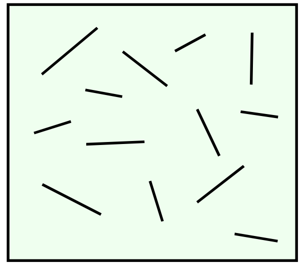
Stress-strain curves for a specimen after 44000 loading cycles (solid line) in comparison with those for non-loaded specimen (dash-dot line).

Defect clusters produce local minima of the elastic stiffness (its average over a moving observation cell)

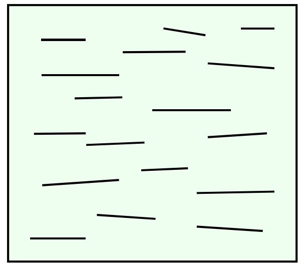


Using cross-property connections

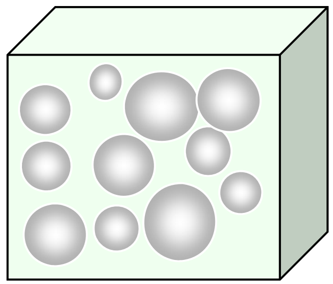
$$\frac{E_0 - E(\boldsymbol{x})}{E(\boldsymbol{x})} = \frac{2\left(1-\nu_0^2\right)\left(10-3\nu_0\right)}{5\left(2-\nu_0\right)} \frac{k_0 - k(\boldsymbol{x})}{k(\boldsymbol{x})}$$



$$\frac{E_0 - E_3(\boldsymbol{x})}{E_3(\boldsymbol{x})} = 2\left(1-\nu_0^2\right)\frac{k_0 - k_3(\boldsymbol{x})}{k_3(\boldsymbol{x})}$$



$$\frac{E_0 - E(\boldsymbol{x})}{E(\boldsymbol{x})} = \frac{\left(1-\nu_0\right)\left(9+5\nu_0\right)}{7-5\nu_0} \frac{k_0 - k(\boldsymbol{x})}{k(\boldsymbol{x})}$$



Stiffness and conductivity gradients as indicators of microdefect clusters

Defect clustering produces local minima of the elastic stiffness and of the conductivity – more precisely, minima of averages over a moving observation cell. This implies that, upon approaching a cluster, a gradient of the said properties is observed. Therefore, such gradients indicate the presence of clusters and hence can be used as detection tools.

The cross-property connection relates gradients of the two properties.

$$\nabla \frac{E_0}{E} = \frac{2\left(1-\nu_0^2\right)\left(10-3\nu_0\right)}{5\left(2-\nu_0\right)} \nabla \frac{k_0}{k}$$

$$\nabla \frac{E_0}{E_3} = 2\left(1-\nu_0^2\right) \nabla \frac{k_0}{k_3}$$

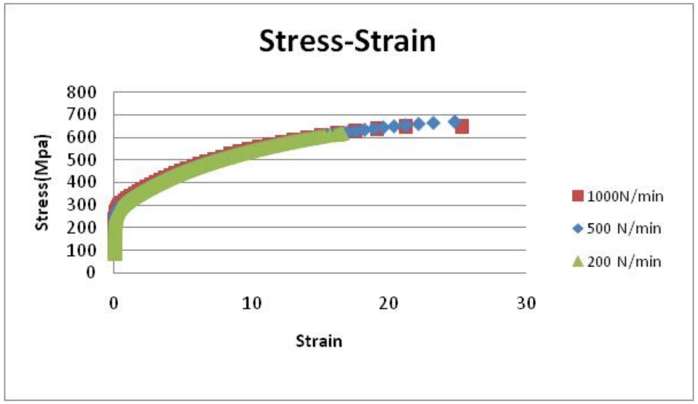
$$\nabla \frac{E_0}{E} = \frac{\left(1-\nu_0\right)\left(9+5\nu_0\right)}{7-5\nu_0} \nabla \frac{k_0}{k}$$

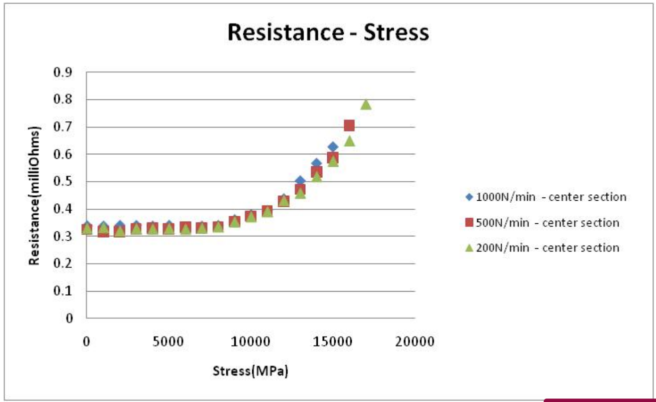
Thus, the cross-property connections allow one to replace detection of stiffness gradients – that may be a difficult task – by the detection of conductivity gradients.

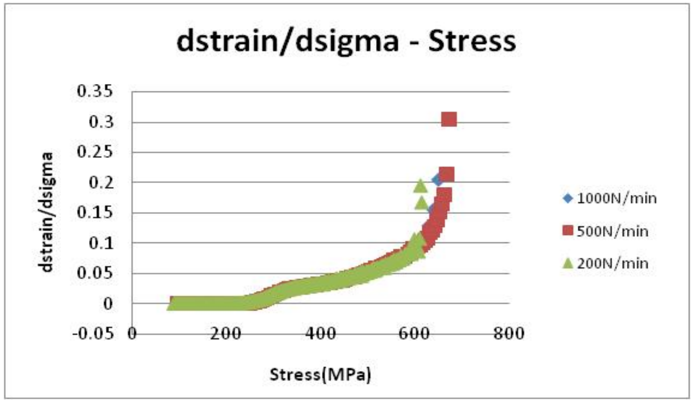
To quantify this effect – namely, to connect the maximum drop in conductivity with strength loss- additional substantial theoretical and experimental work is required.

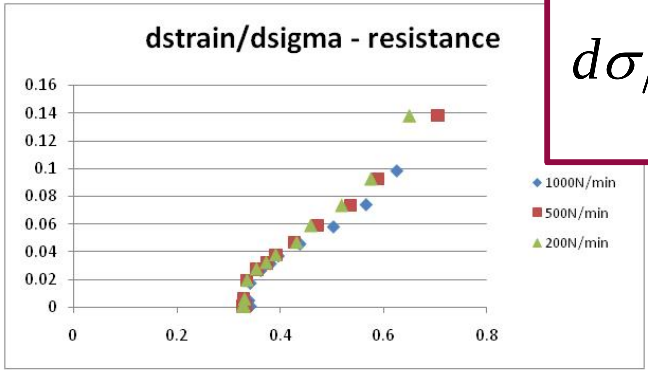
Work in progress

Quantitative connections between incremental stiffness and electrical resistance of stainless steel 304 in dependence on the stress level. The physical mechanism providing the background of this connection is dislocation density growth caused by the applied stresses.









$$d\sigma/d\varepsilon \propto \frac{1}{\sqrt{(\rho/\rho_0 - 1)}}$$