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International Spring School on Forefront Alloys and Advanced Materials for Extreme Conditions

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SEVERE PLASTIC DEFORMATION TECHNIQUES FOR METALLIC MATERIALS: POTENTIALS AND LIMITS

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- The **Hall-Petch** relationship
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- Potentials and Limits of ECAP and HPT (industrial scale-up)
- **Outlook**

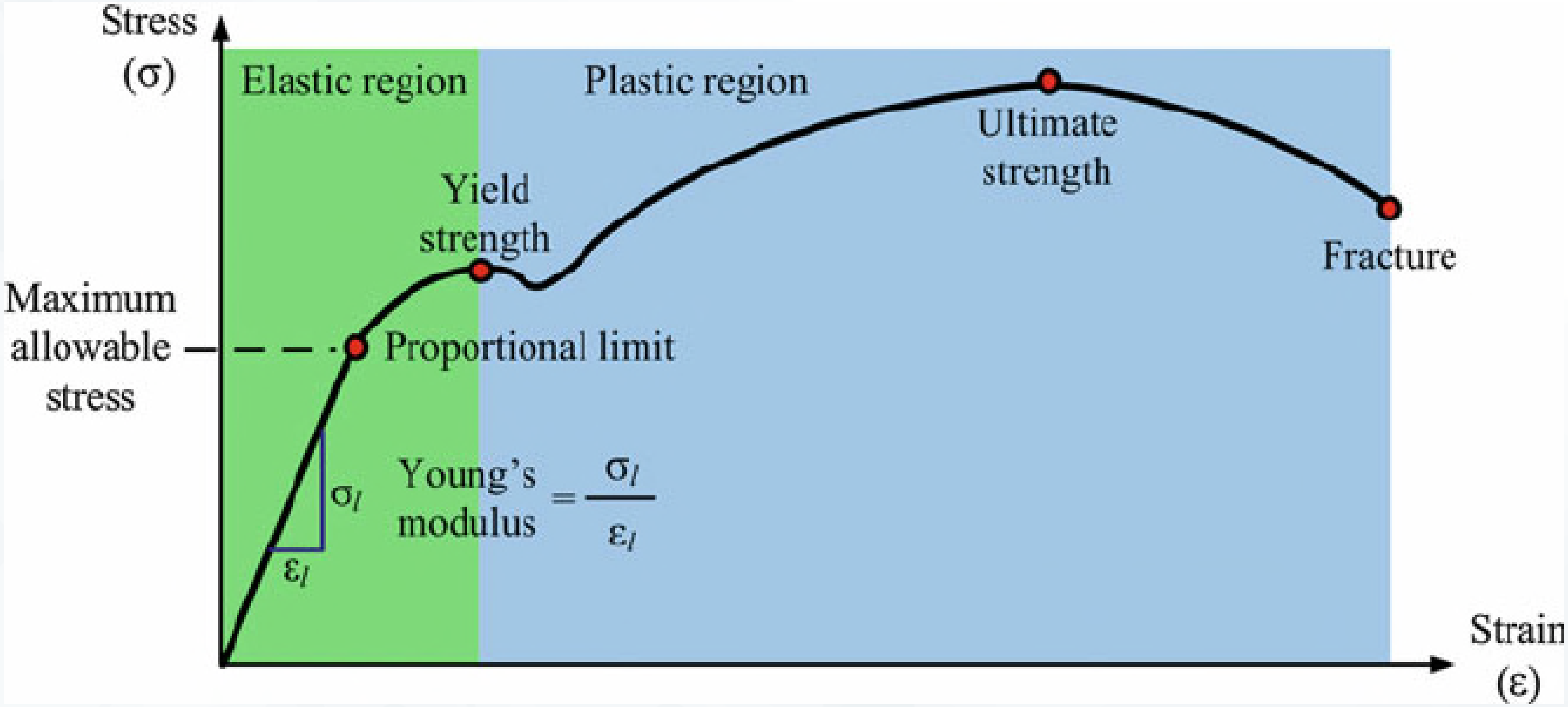
Technological meaningful metal properties

Yield strength

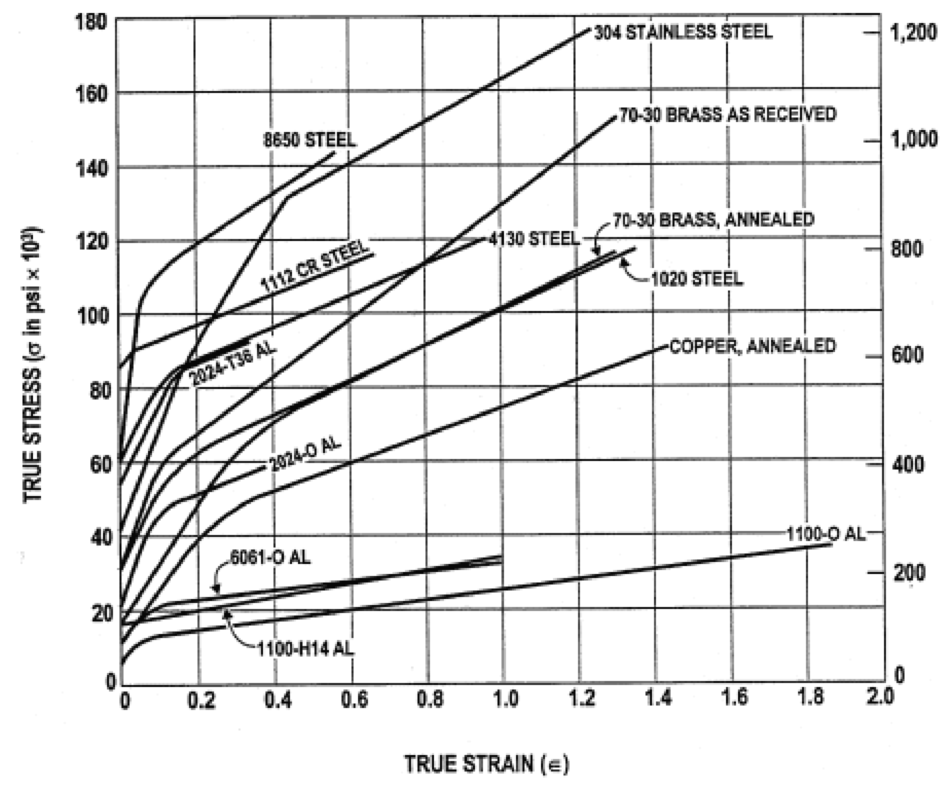
Ductility

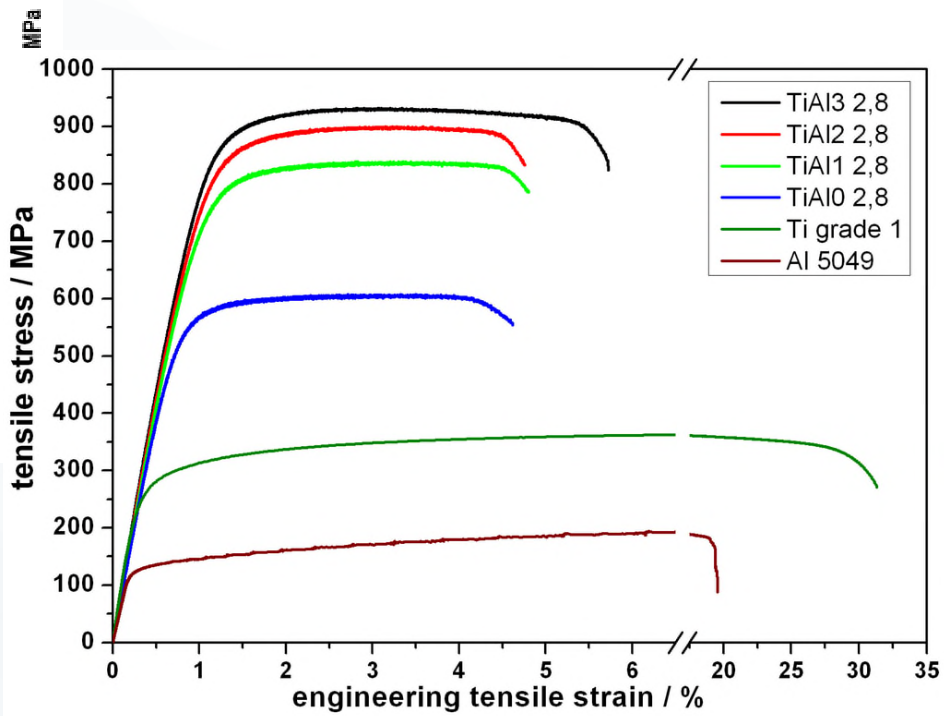
Young's modulus (Elastic modulus)

Technological meaningful metal properties



Technological meaningful metal properties

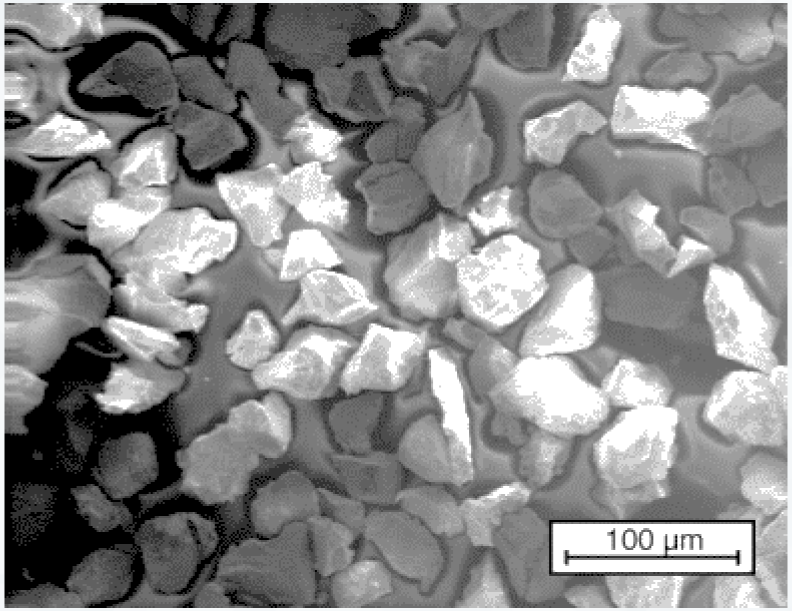




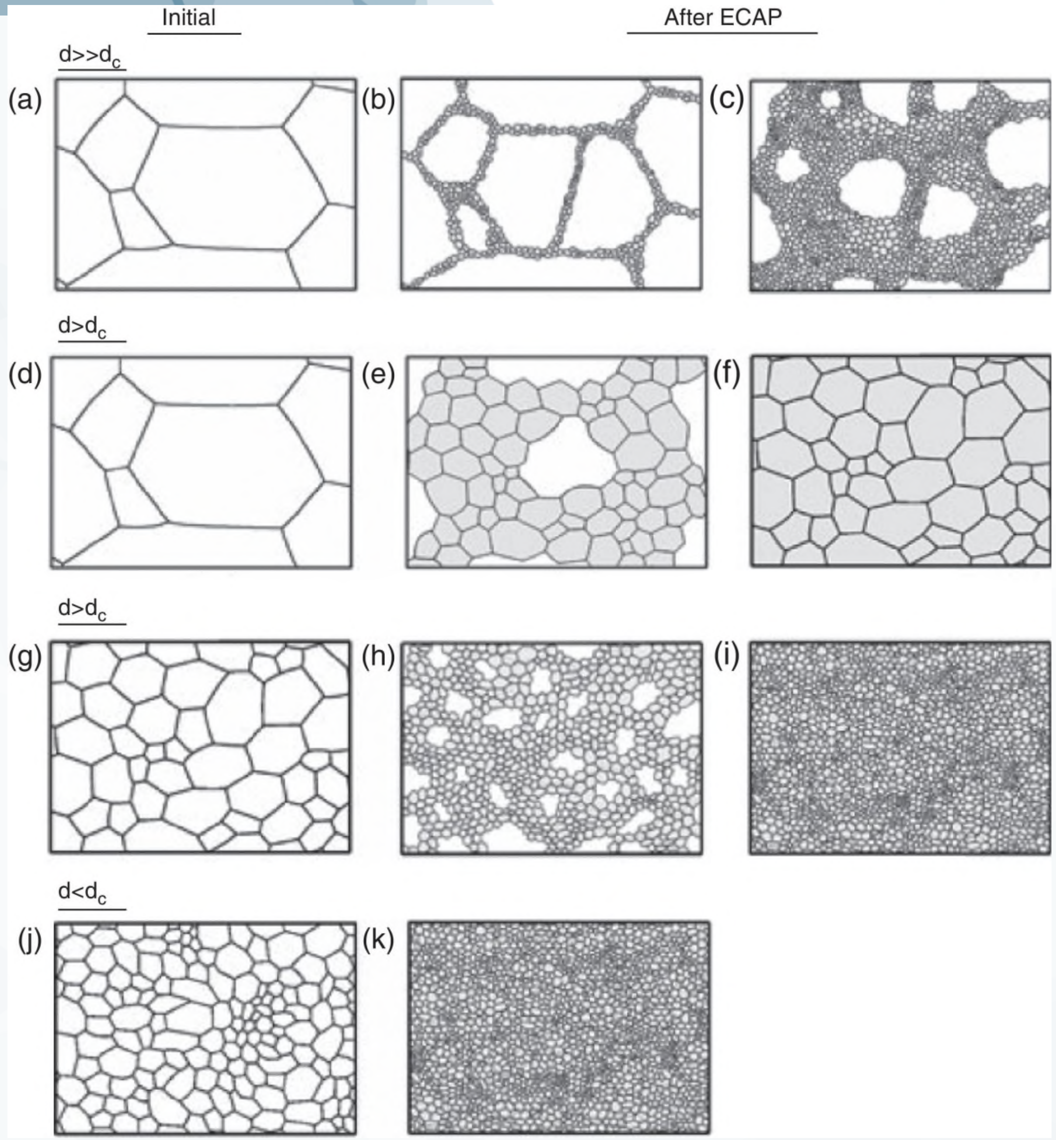
Hall-Petch relationship

Effect of grain size on the Yield strength and Young's modulus of elasticity of metallic material

$$\sigma = \sigma_o + K_{HP}/\sqrt{(d)}$$



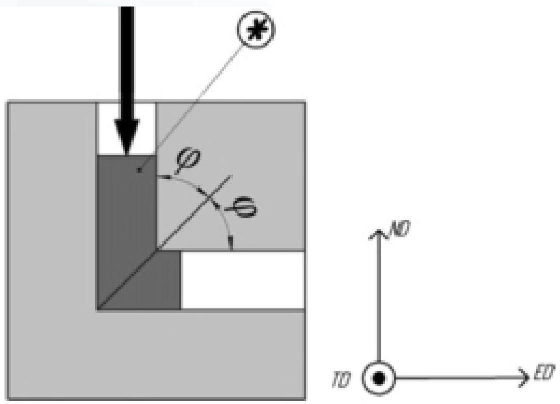
usefulness of grain size reduction



$$\sigma = \sigma_o + K_{HP}/\sqrt{(d)}$$

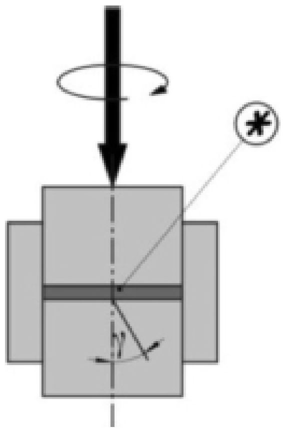
Severe Plastic Deformation techniques

Equal-channel angular pressing (ECAP)



$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\cot(\phi)$
N, the number of ECAP passes

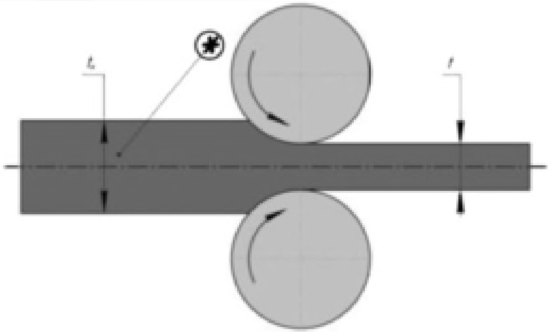
High-pressure torsion (HPT)



$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\frac{\pi r}{t}$
r, the distance from the axis, t, the thickness of the sample, N, the number of revolutions

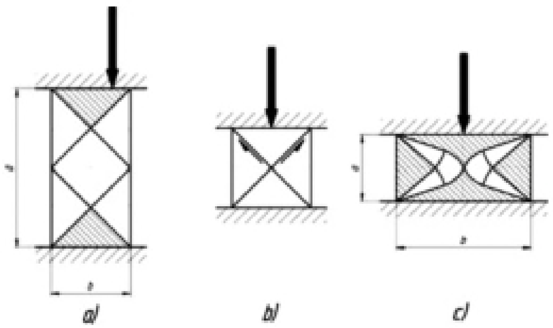
Severe Plastic Deformation techniques

Accumulative roll bonding (ARB)



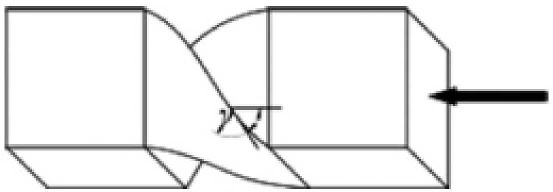
$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\ln(\frac{t_0}{t})$
t_0, the initial thickness of the sample, t, the thickness of the sample after rolling, N, the number of passes

Multi-axial forging



$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\ln(\frac{a}{b})$
Strain is non-uniform. N, the number of processing steps

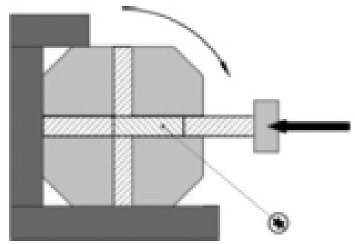
Twist extrusion (TE)



$\varepsilon_{eff}^{\min} \approx 0.4 + 0.1 tan\gamma$; $\varepsilon_{eff}^{\max} \approx N\frac{2}{\sqrt{3}} tan\gamma$
γ is the twist line slope; N is the number of passes. Deformation is non-uniform

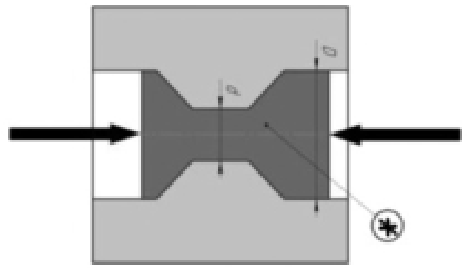
Severe Plastic Deformation techniques

Rotary-die ECAP



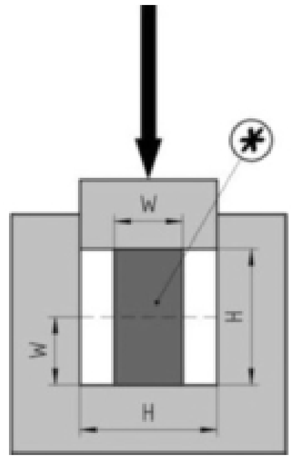
ECAP equivalent

Cyclic extrusion–compression (CEC)



$\varepsilon_{eff} = N 4 \ln(\frac{D}{d})$
N, number of cycles

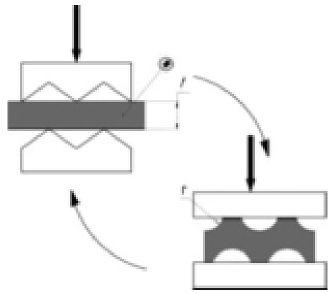
Cyclic close-die forging (CCDF)



$\varepsilon_{eff} = N \frac{2}{\sqrt{3}} \ln(\frac{H}{W})$
N, number of cycles

Severe Plastic Deformation techniques

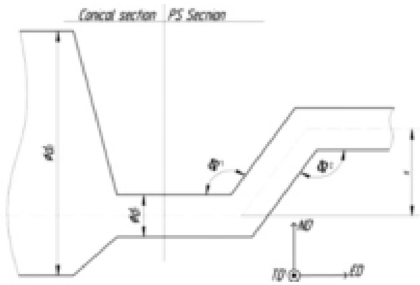
) Repetitive corrugation and straightening (RCS)

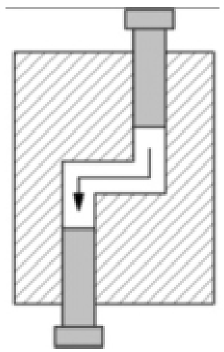


$\varepsilon_{eff} = N \frac{4}{\sqrt{3}} \ln(\frac{r+t}{r+0.5t})$

N, number of cycles

Integrated extrusion + ECAP

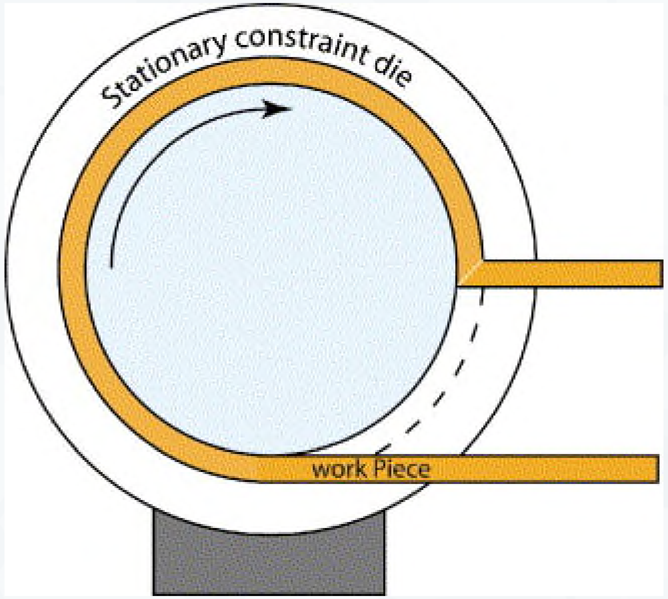


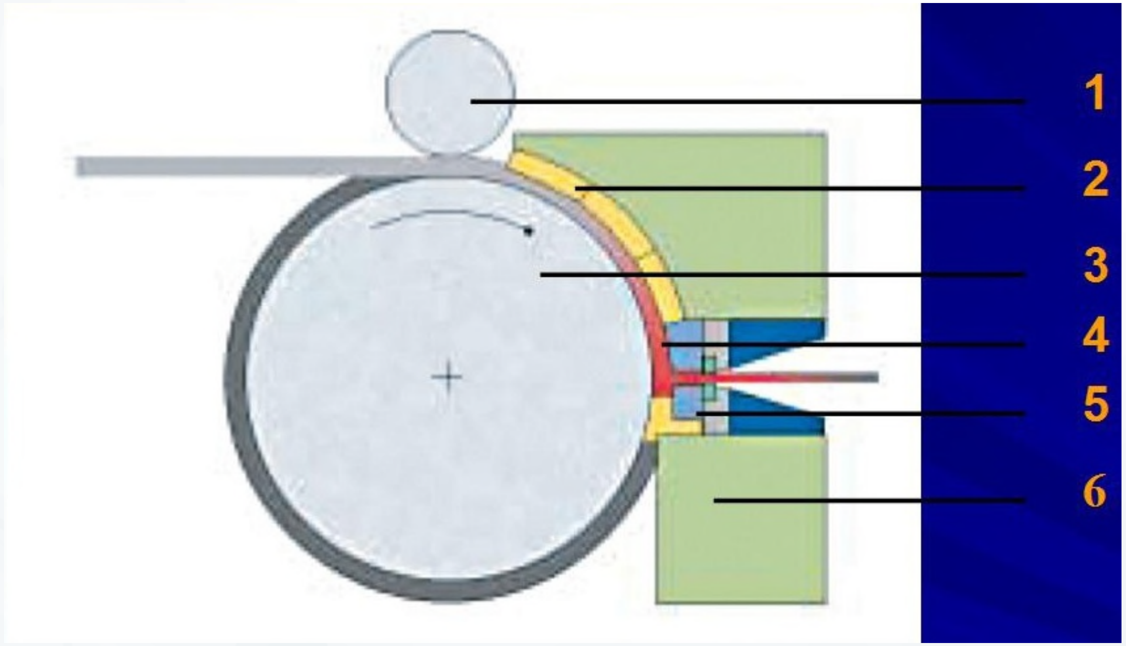


ECAP equivalent

Continuous processes (industrial scale up)

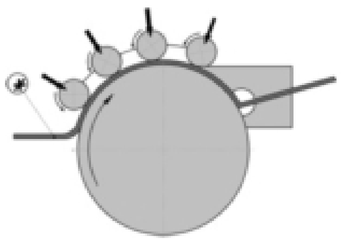
ECAP conform



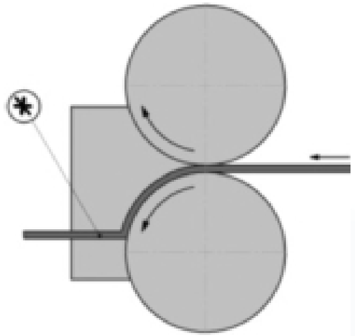


Severe Plastic Deformation techniques

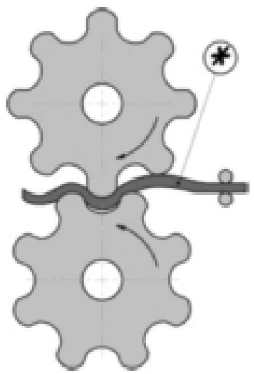
Con-shearing



Continuous confined strip shearing (C2S2)

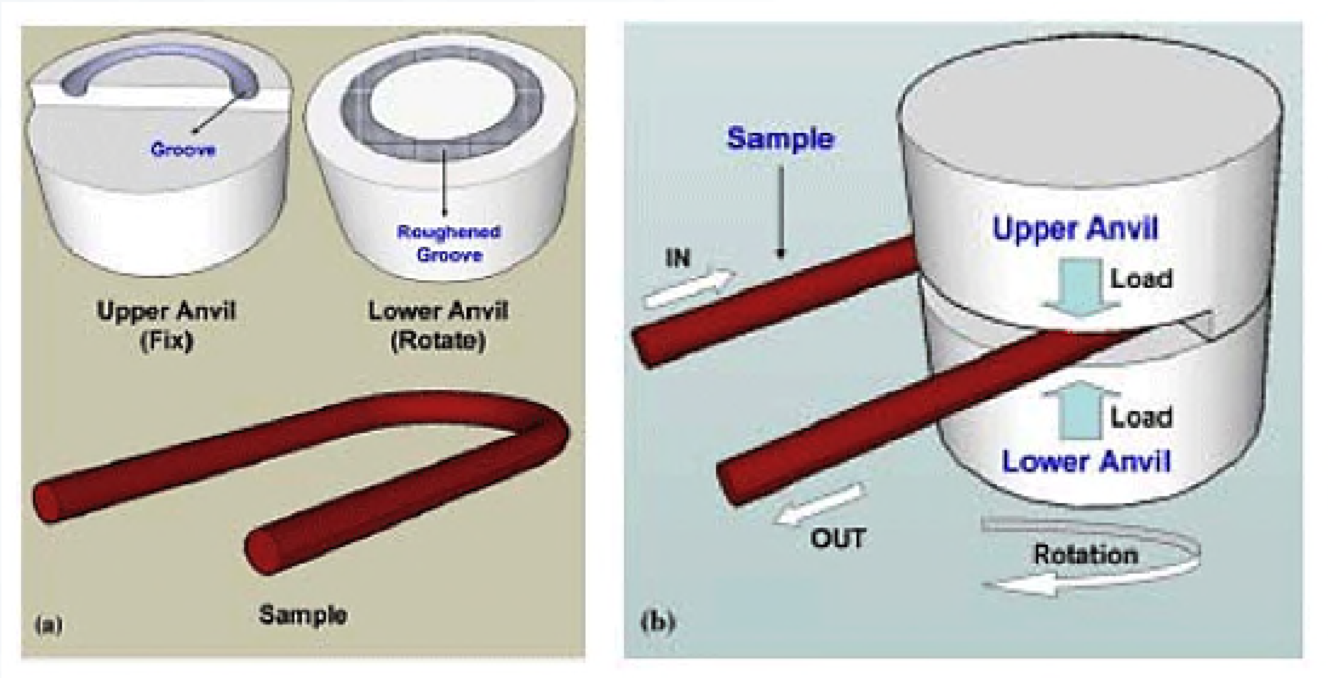


Continuous repetitive corrugating and straightening (RCS)



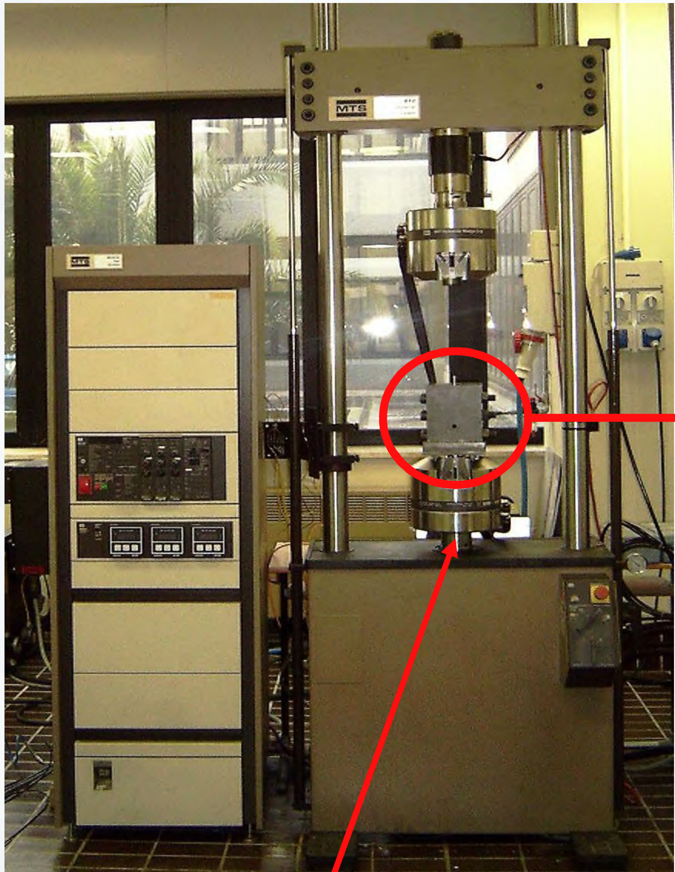
Continuous processes (industrial scale up)

Continuous HPT



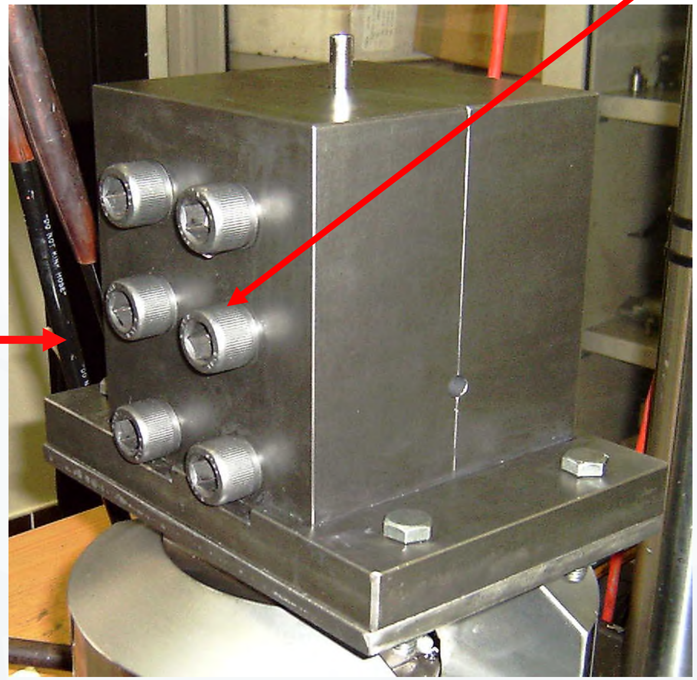
Equal-Channel Angular Pressing (ECAP)

Equal-Channel Angular Pressing (ECAP)



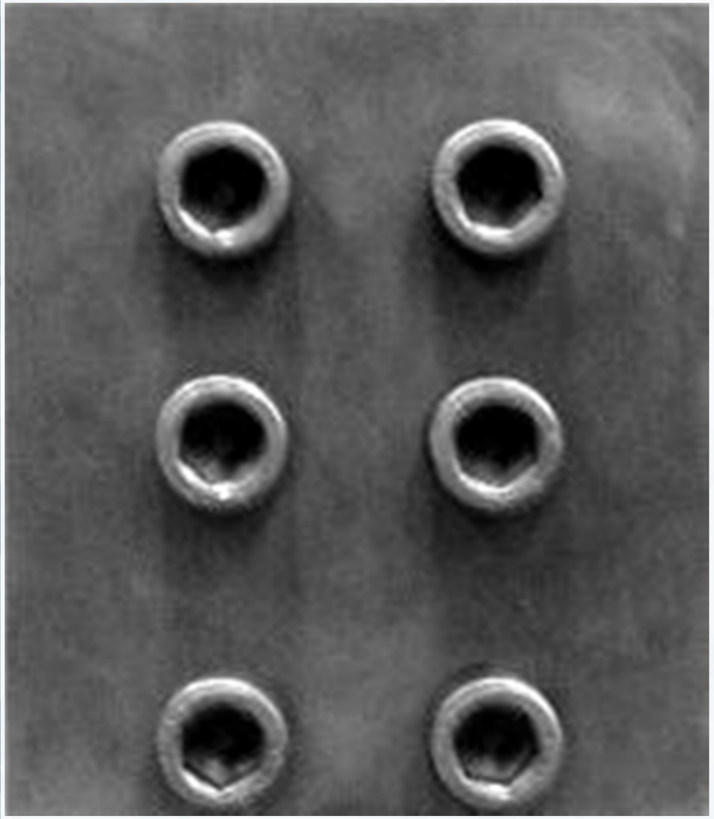
250 kN max pressure

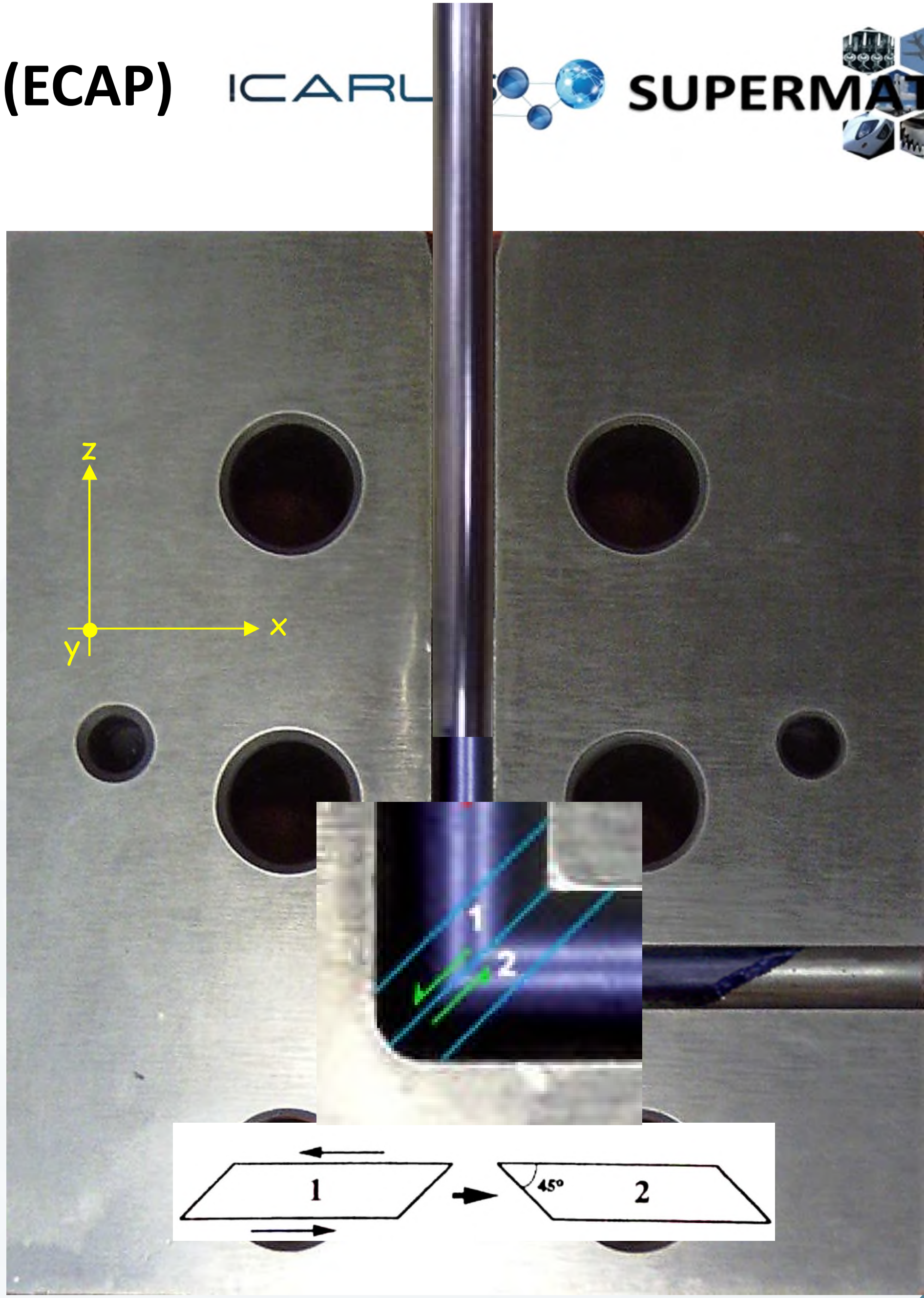
6 long screws



the die

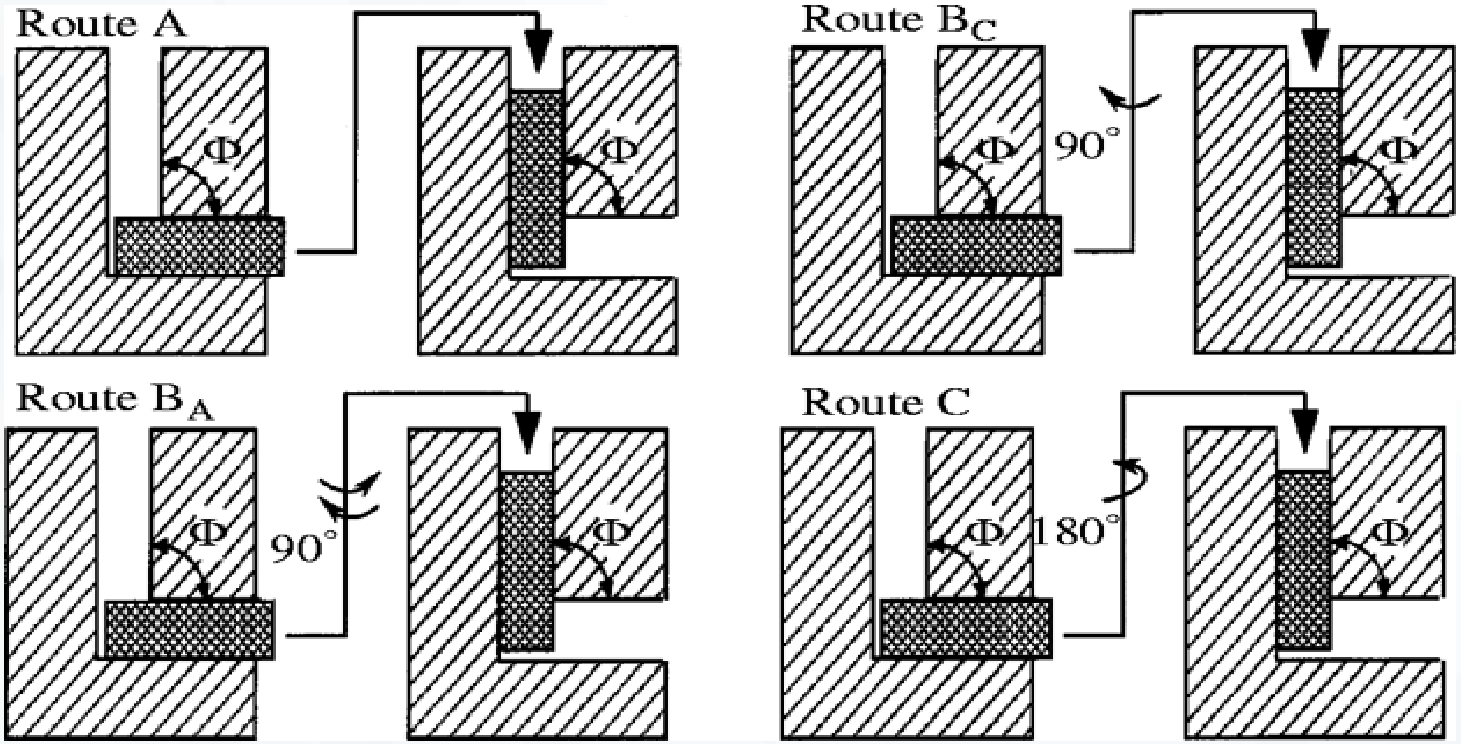
Equal-Channel Angular Pressing (ECAP)





Equal-Channel Angular Pressing (ECAP)

overview of routes scheme



After T.C. Langdon

Z. HORITA, T. FUJINAMI, M. NEMOTO AND T.G. LANGDON, Metall. Mater. Trans. A, 31A, (2000) p.691.
K. NAKASHIMA, Z. HORITA, M. NEMOTO AND T.G. LANGDON, Acta Mater., 46, 5, (1998) p.1589.
Y. IWAHASHI, M. FURAKAWA, Z. HORITA, M. NEMOTO AND T.G. LANGDON, Metall. Mater. Trans. A, 29A, (1998) p.2245.
M. FURUKAWA, Z. HORITA, M. NEMOTO, R.Z. VALIEV AND T.G. LANGDON, Acta Mater., 44, 11, (1996) p.4619.

Equal-Channel Angular Pressing (ECAP)

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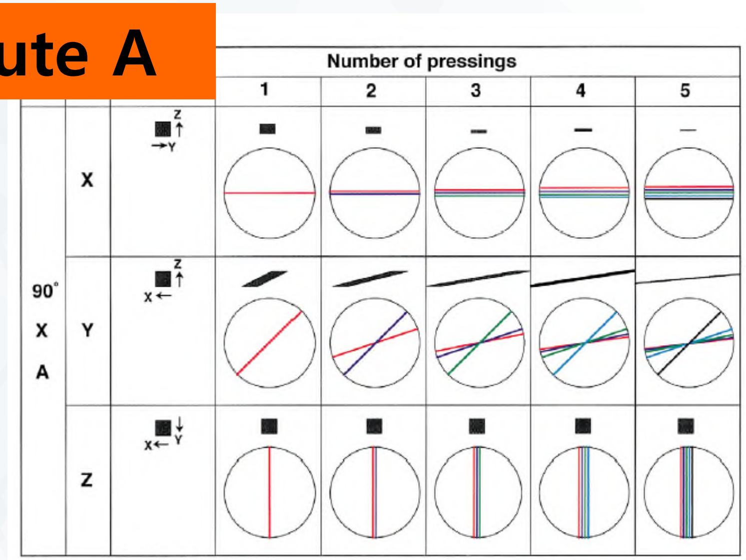
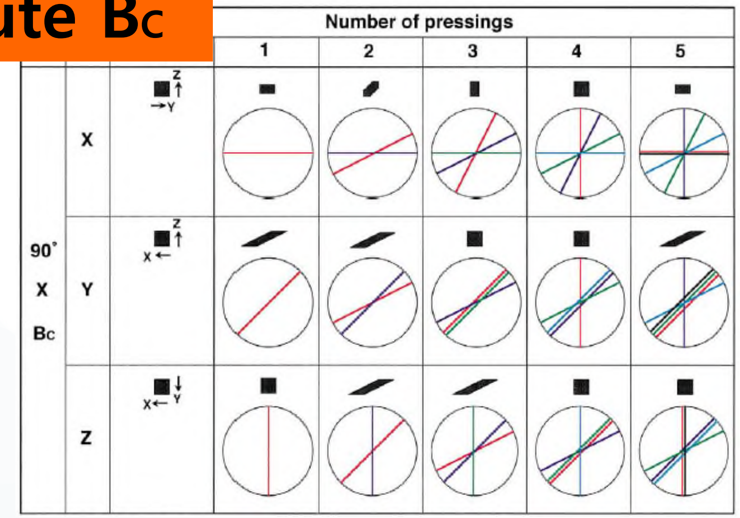
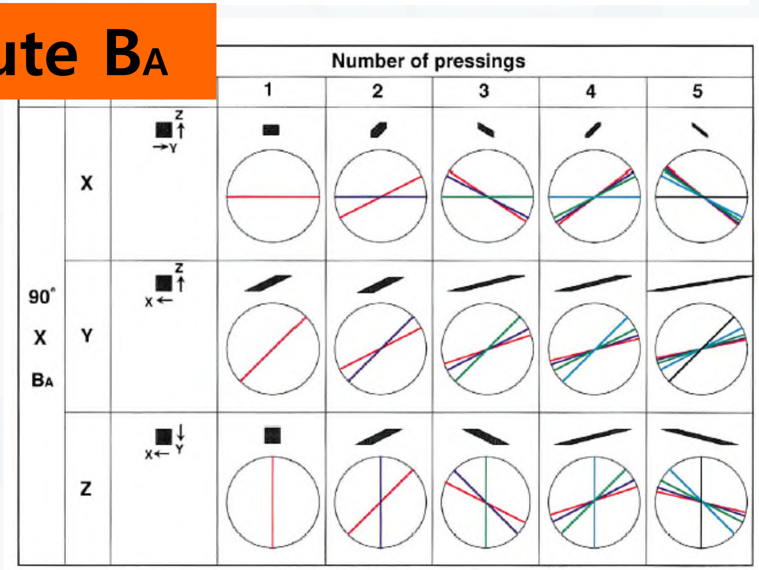
route A



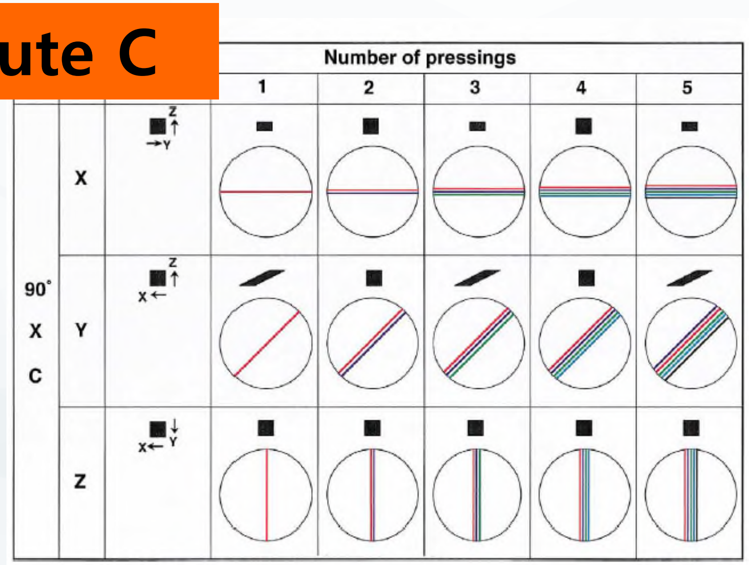
route Bc



route BA



route C



Equal-Channel Angular Pressing (ECAP)

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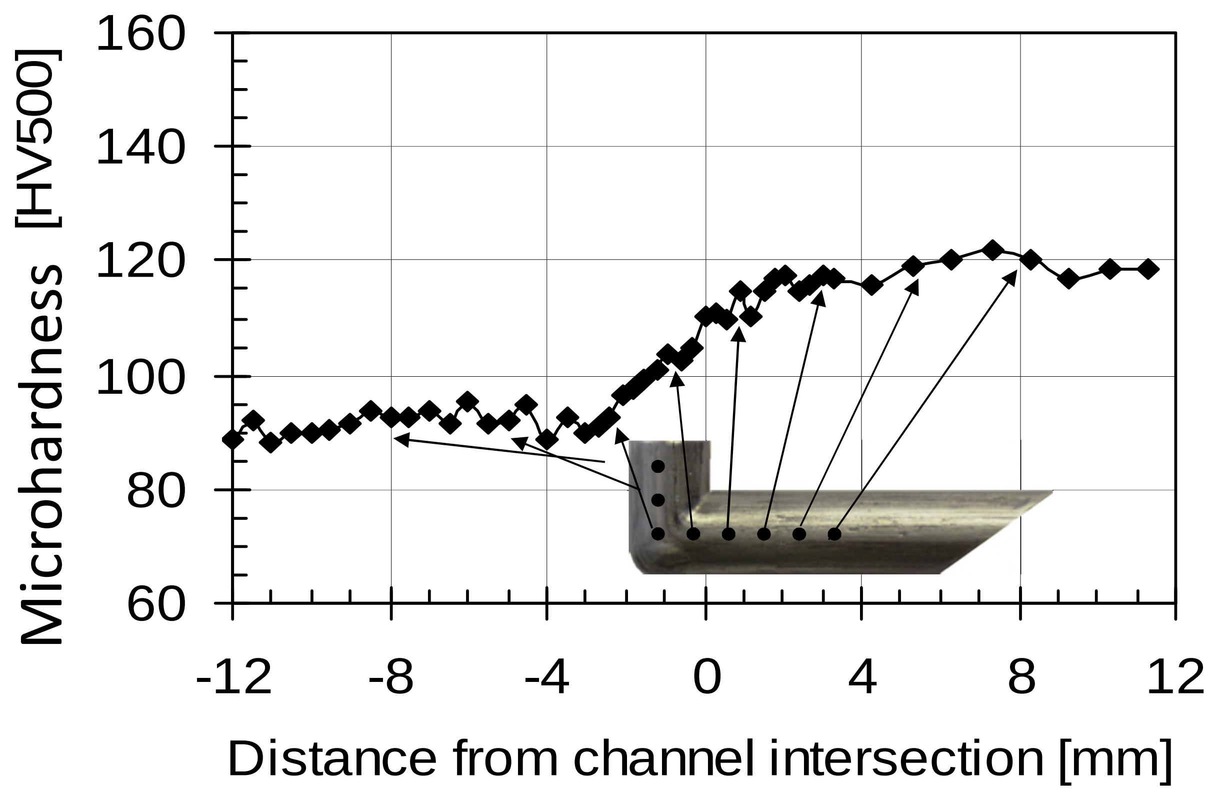
Typical microhardness profile along sample longitudinal axis

at the passage into the ECAP die



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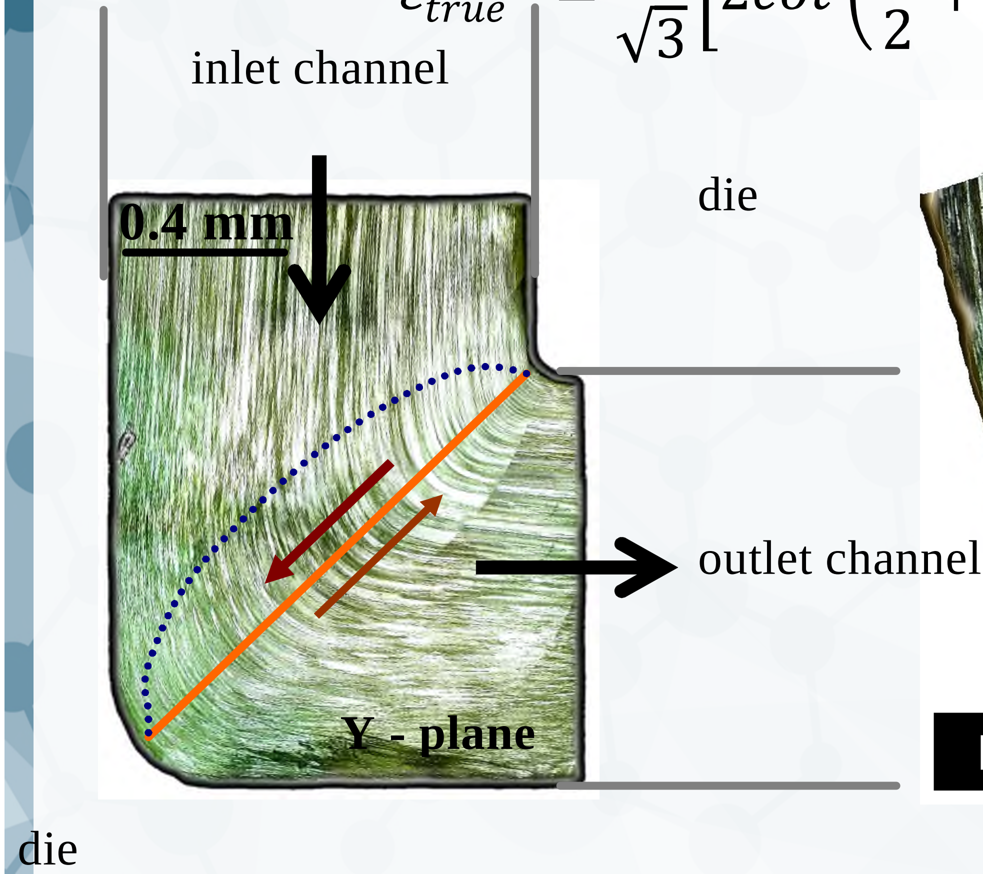
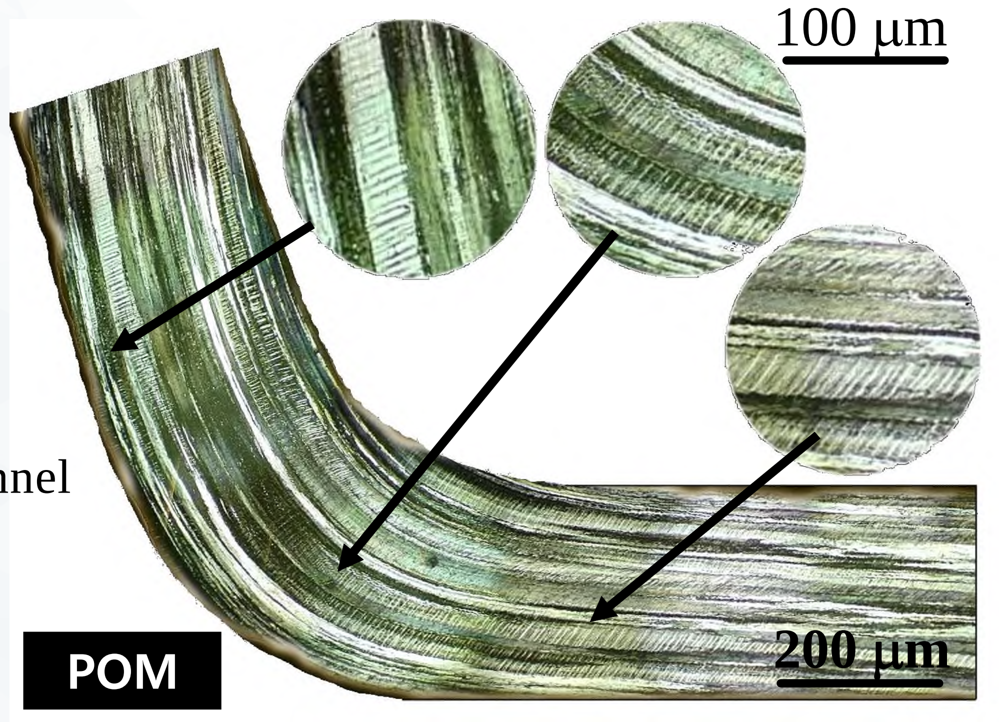
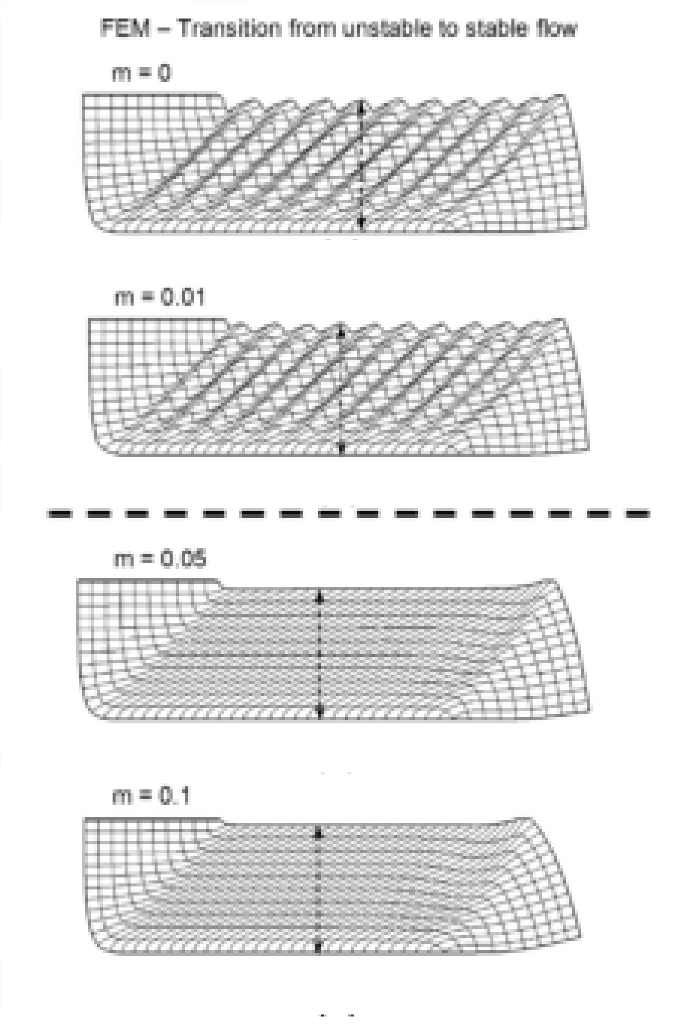
ECAP induced grain modifications

$$\varepsilon_{true}^{ECAP} = \frac{N}{\sqrt{3}}\left[2cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right) + \Psi cosec\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)\right]$$

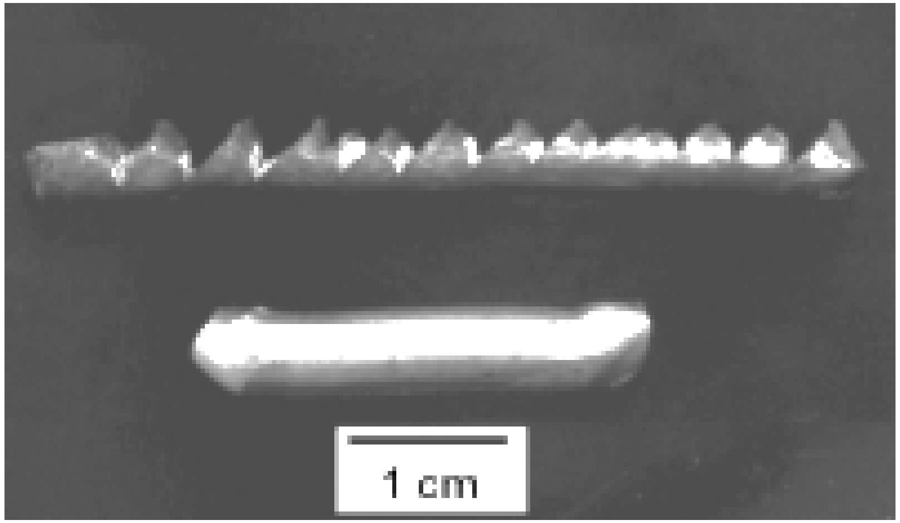




Equal-Channel Angular Pressing (ECAP)



Sample and set-up



Equal-Channel Angular Pressing (ECAP)

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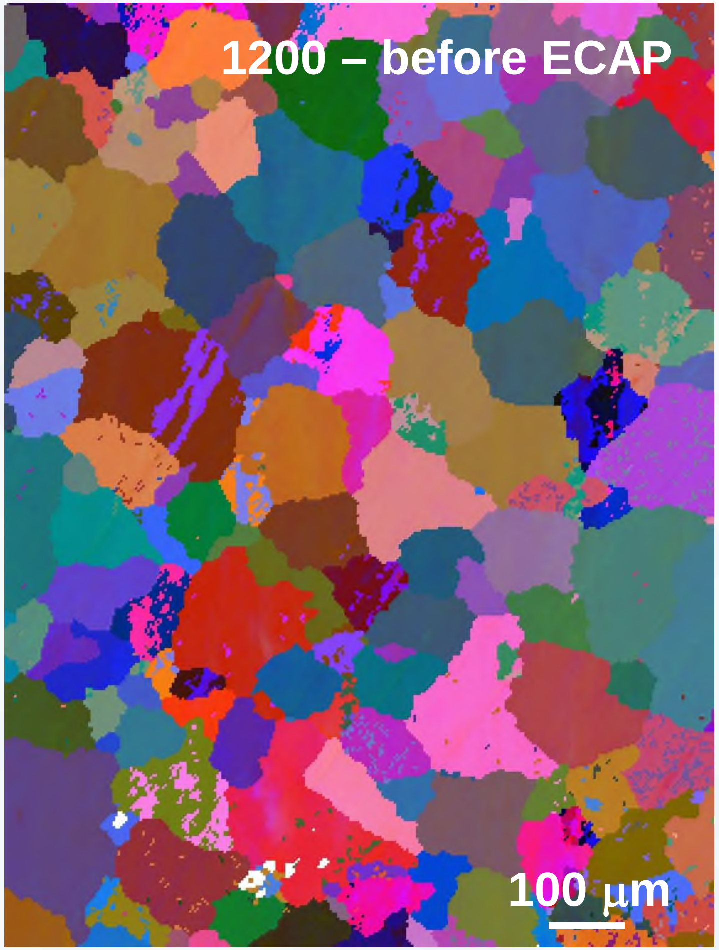
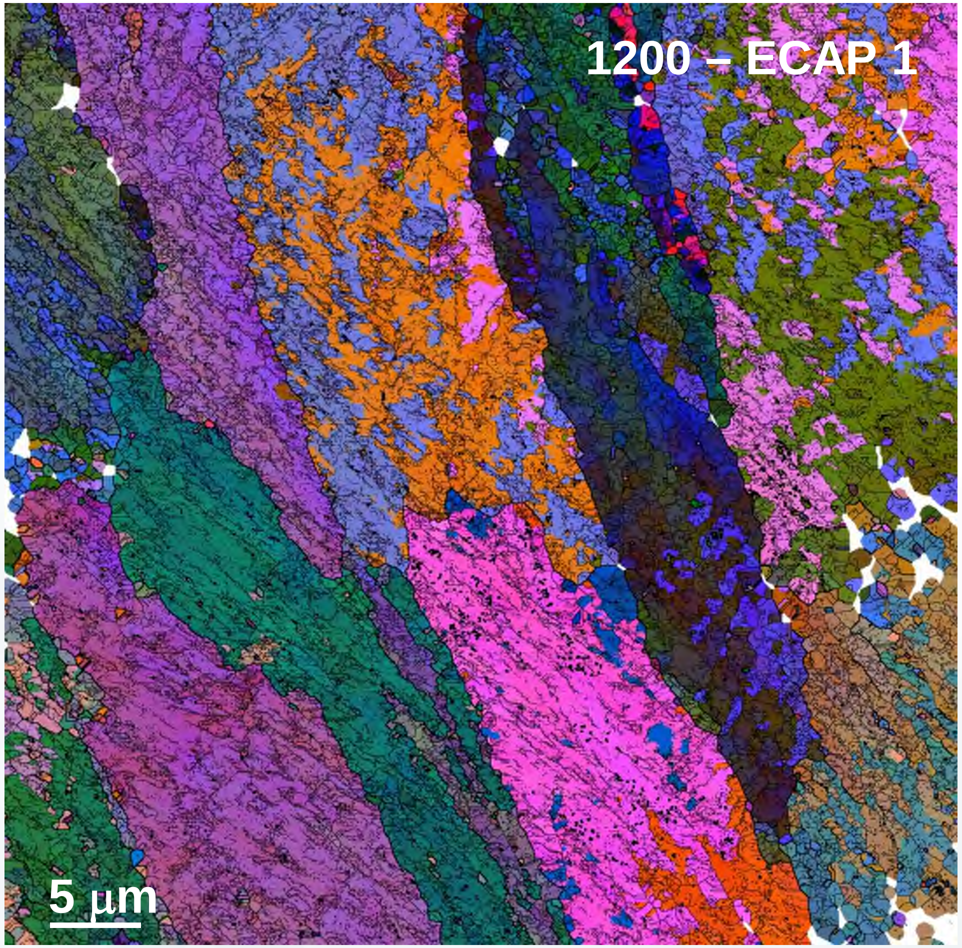
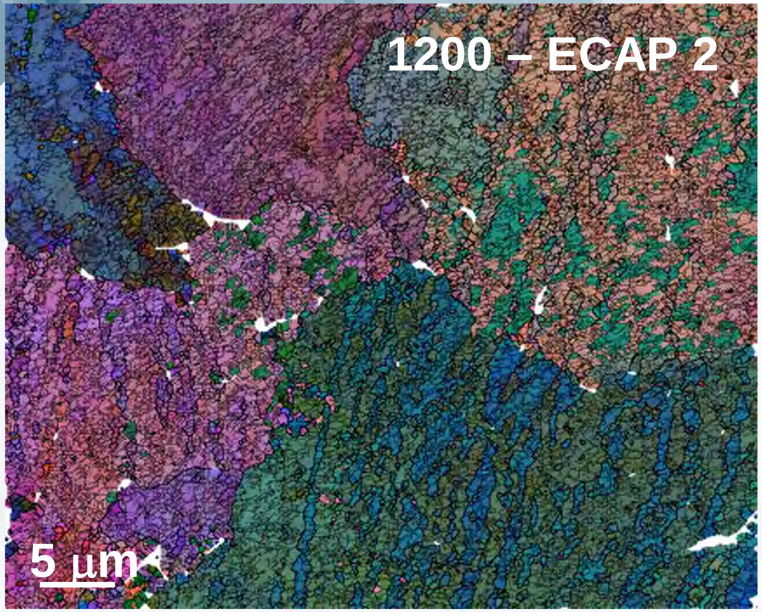
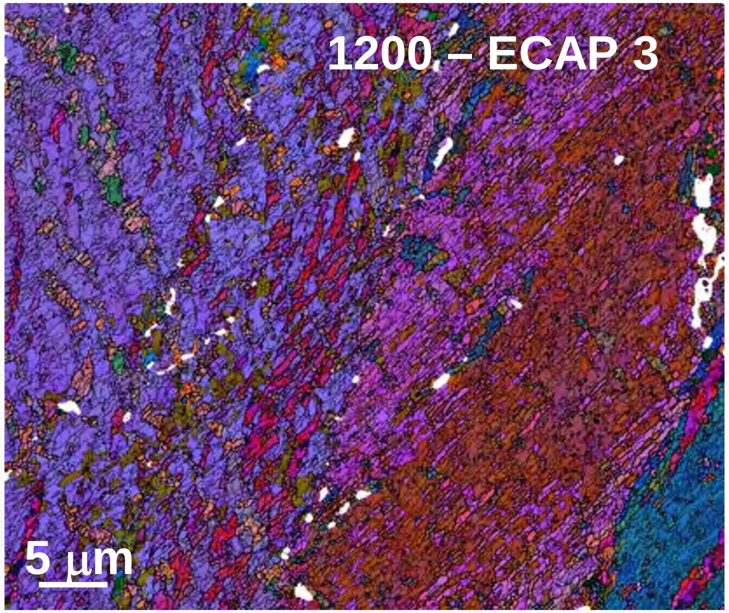
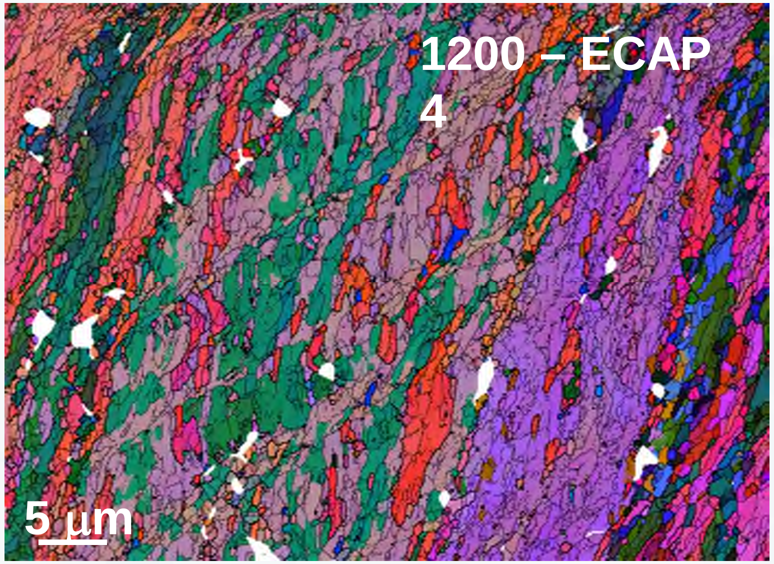


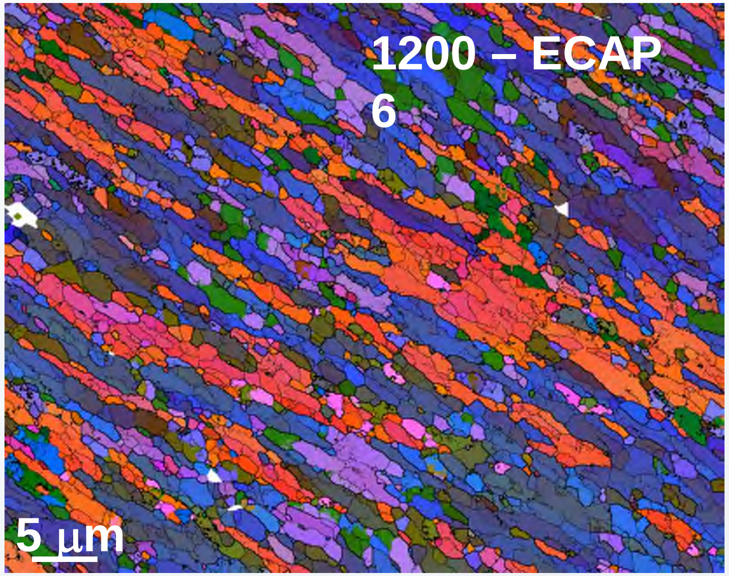


Equal-Channel Angular Pressing (ECAP)

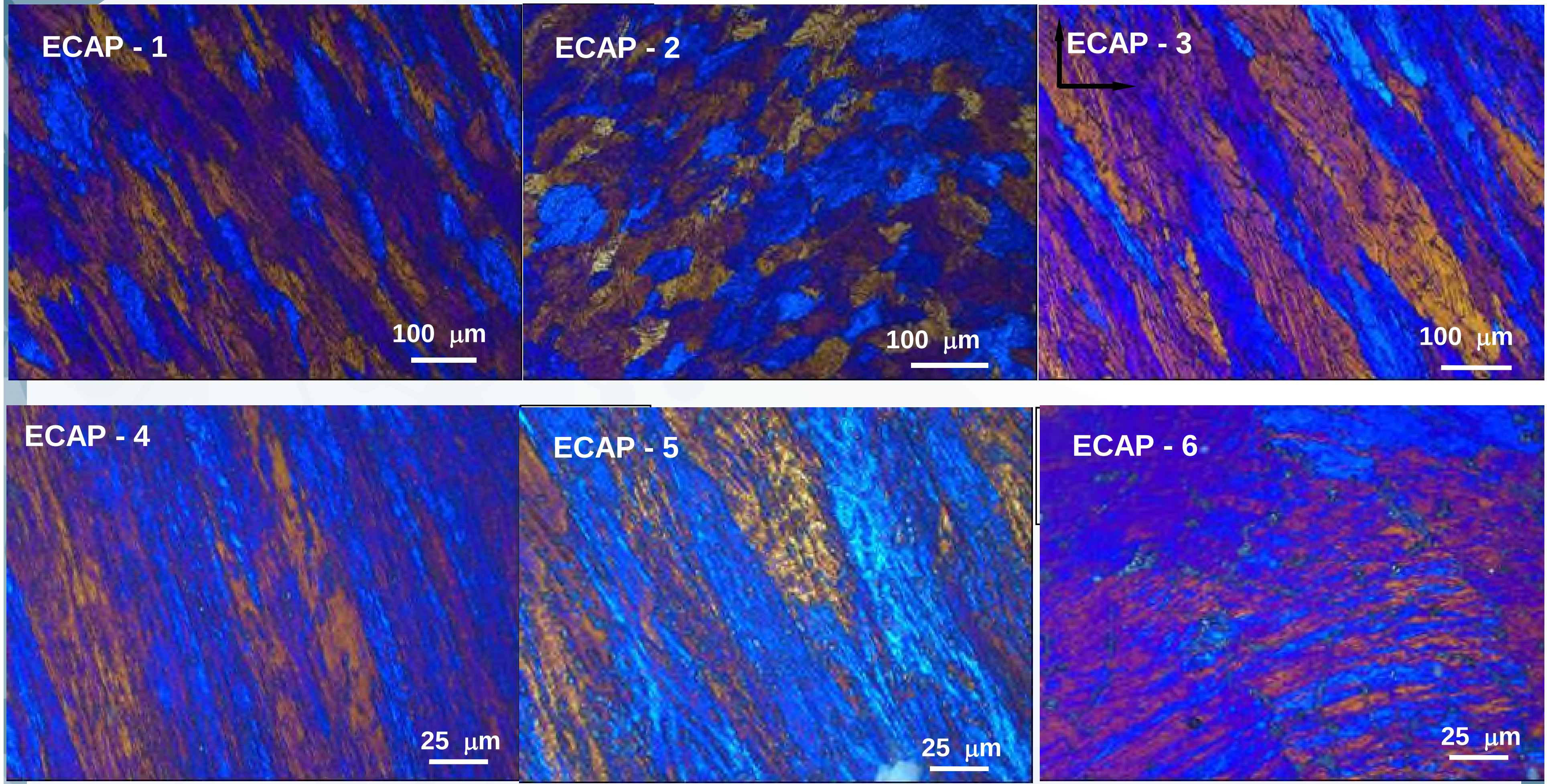






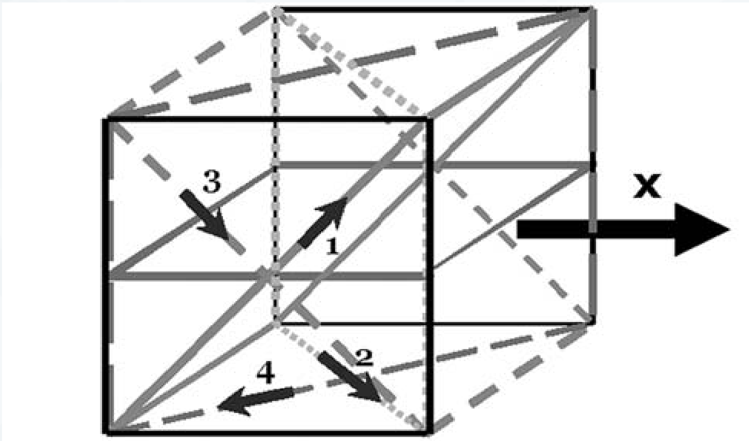


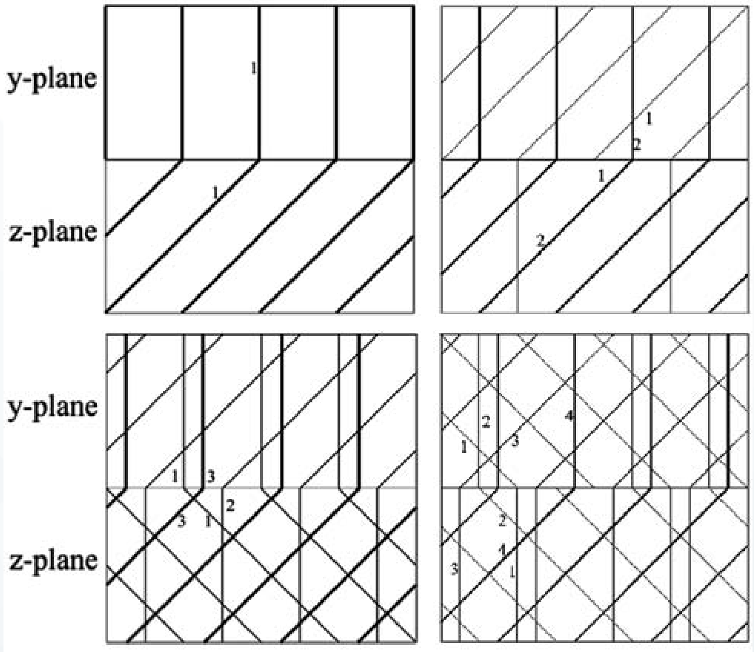
Equal-Channel Angular Pressing (ECAP)



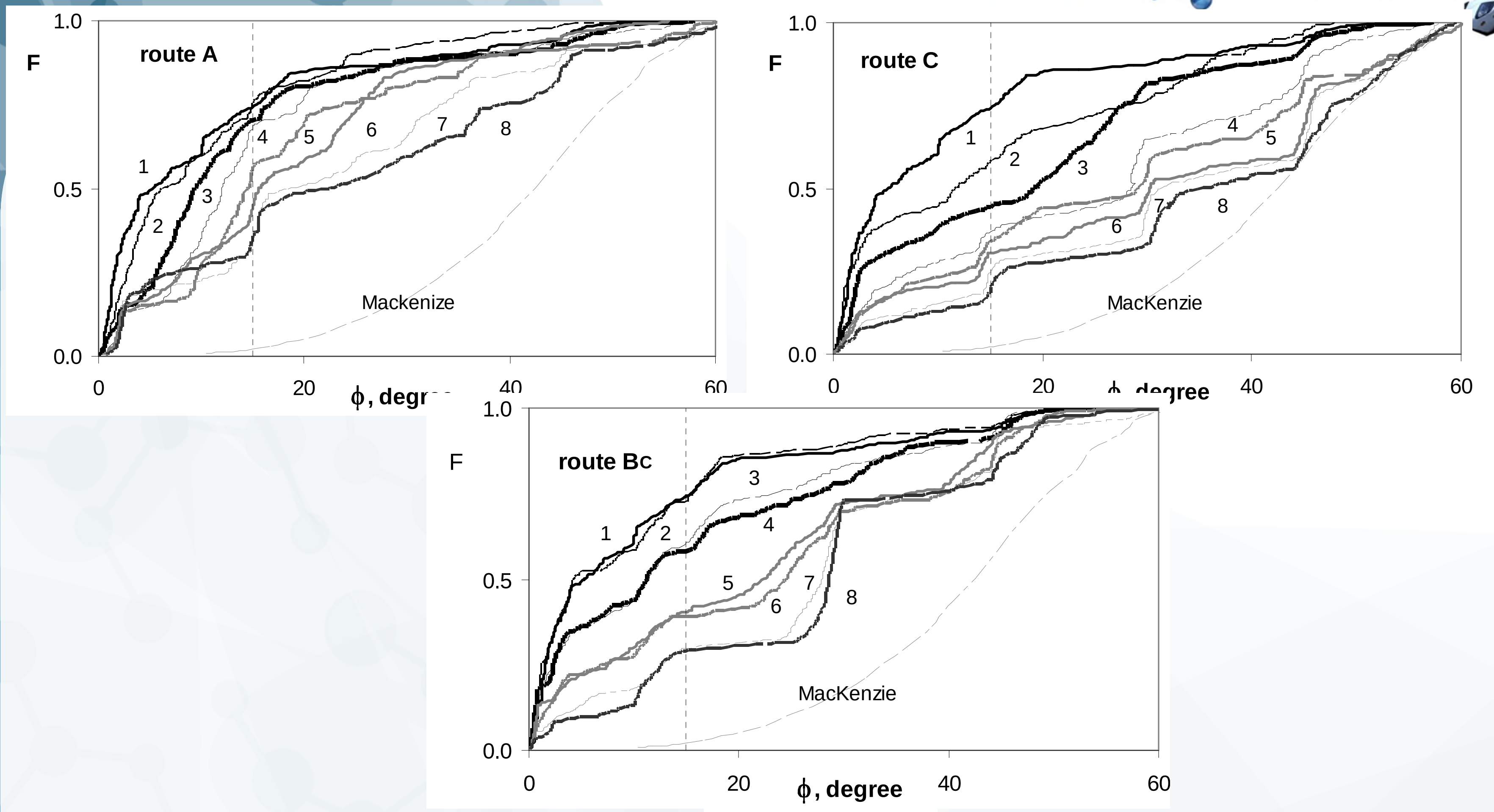
Equal-Channel Angular Pressing (ECAP)

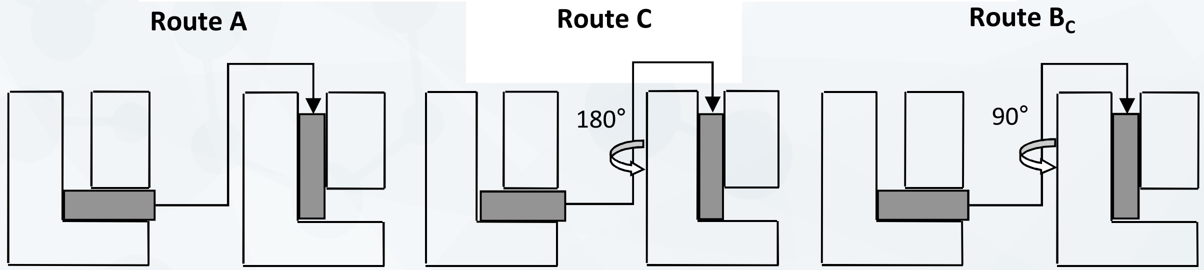
Shear plane deformation activated during ECAP Route Bc





Equal-Channel Angular Pressing (ECAP)





Equal-Channel Angular Pressing (ECAP)

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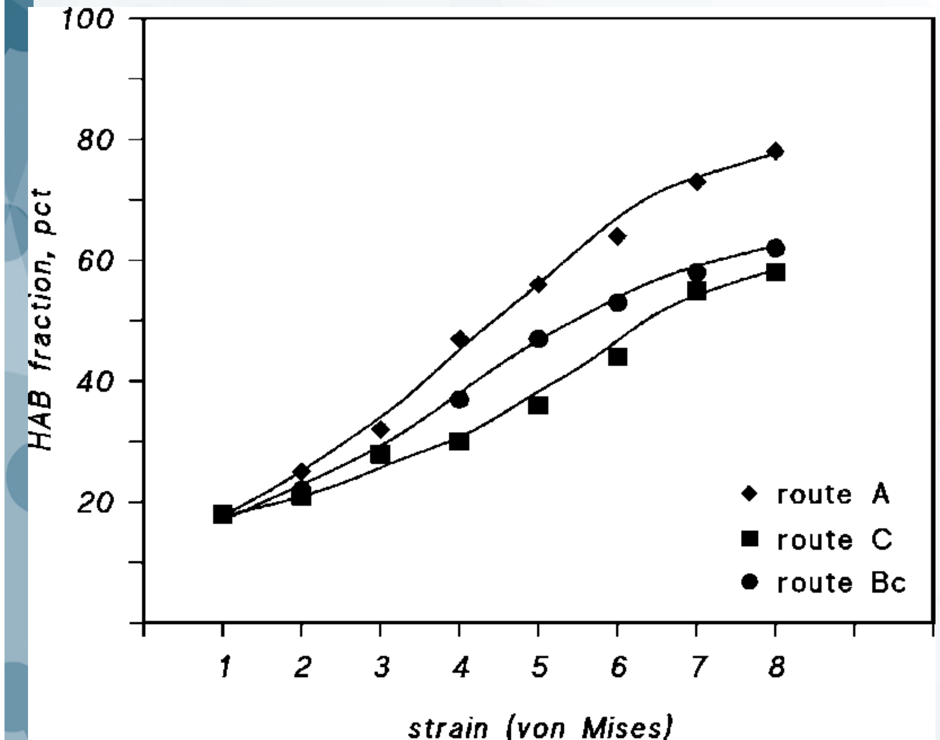
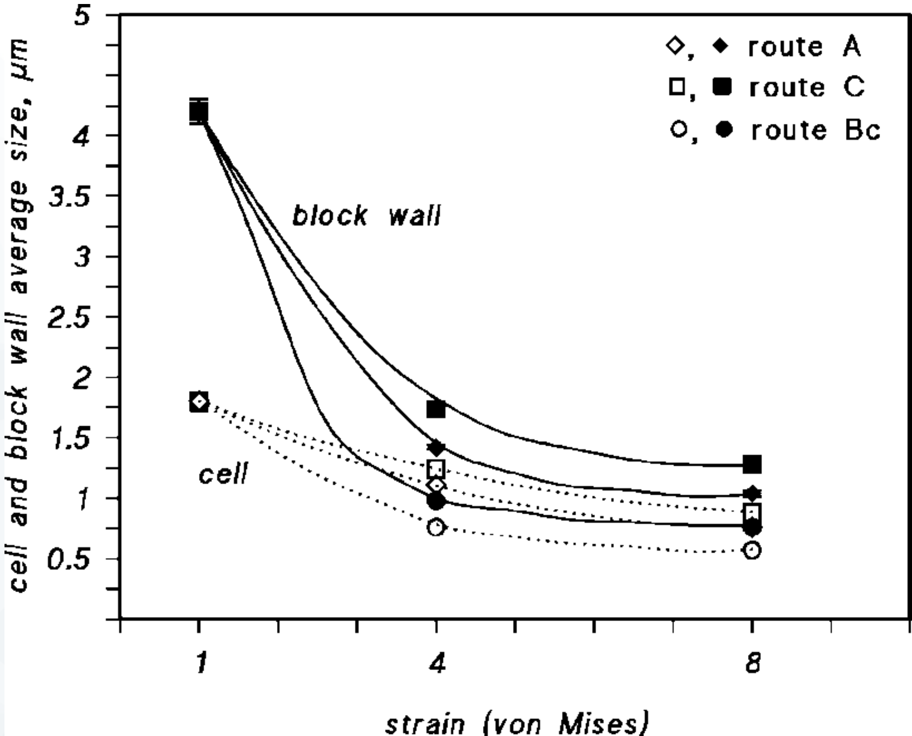
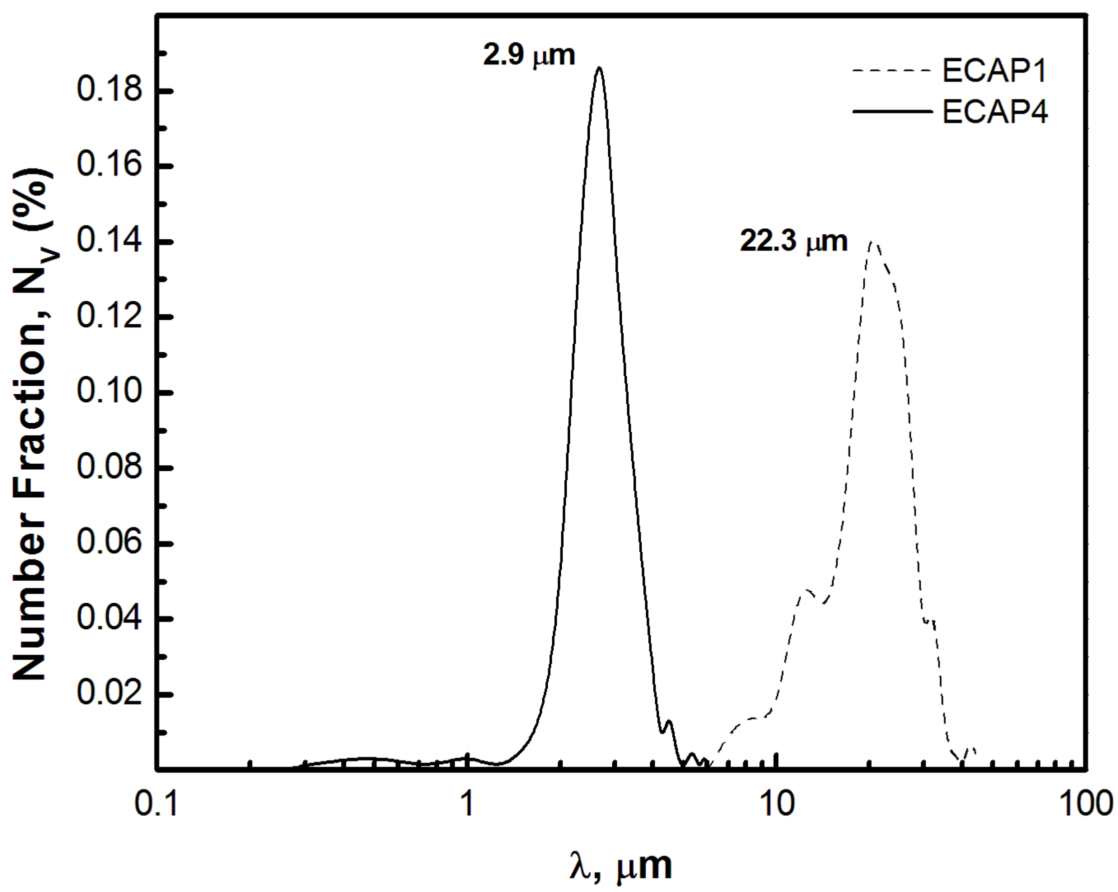
Grain size evolution





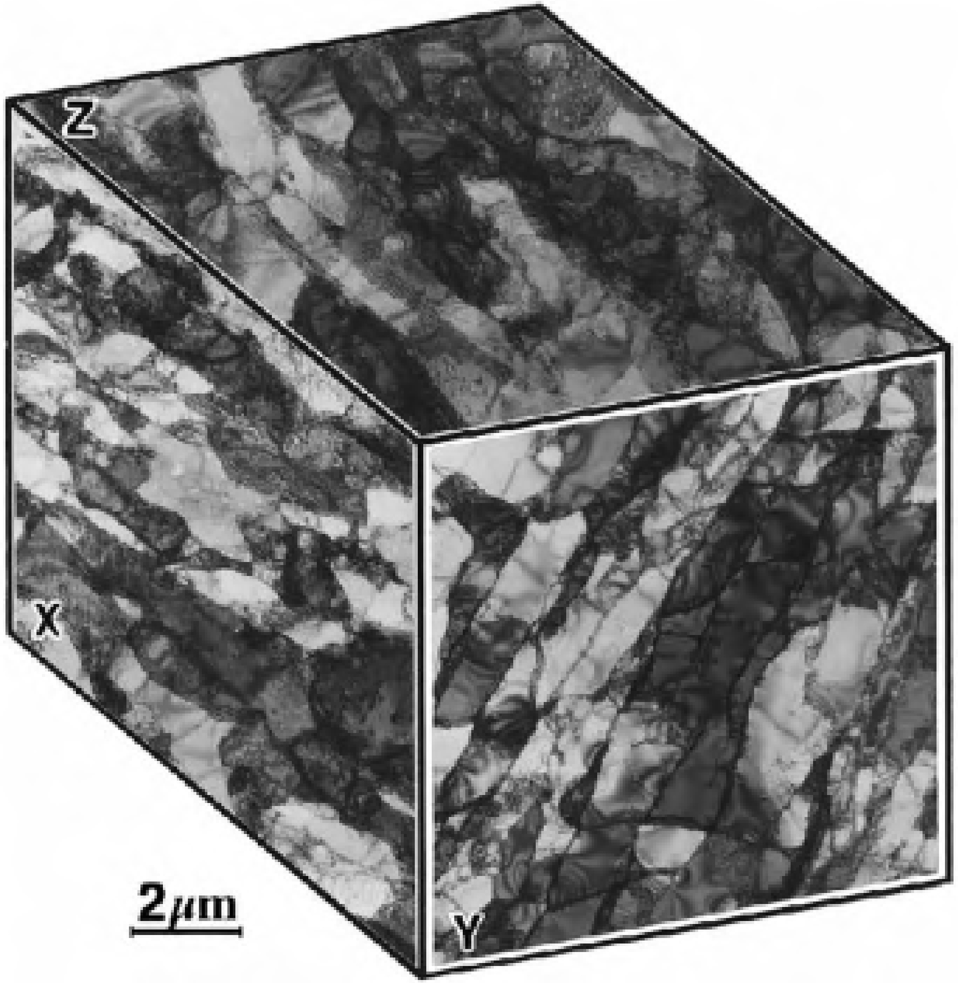
Equal-Channel Angular Pressing (ECAP)

Grain size evolution

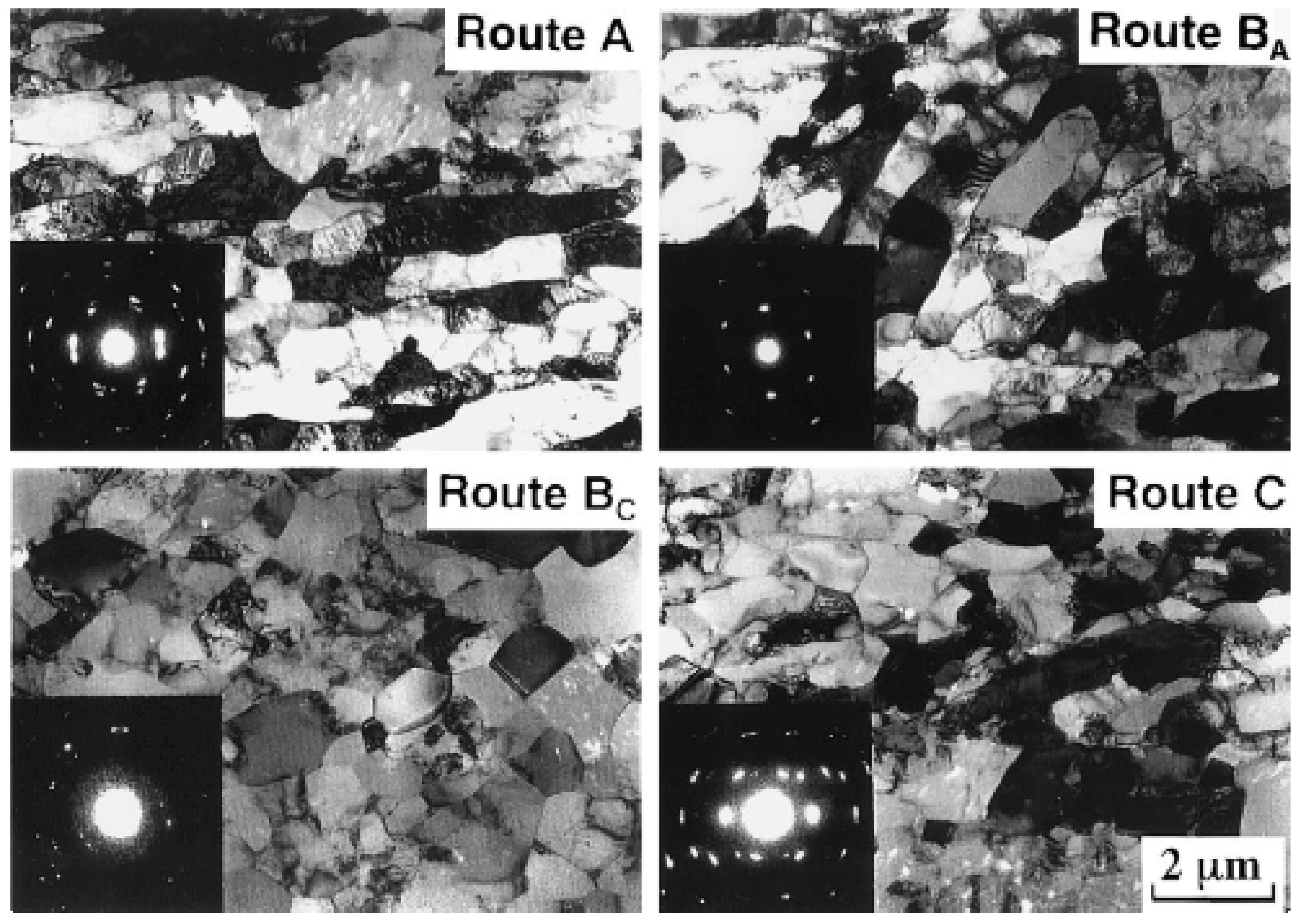


Equal-Channel Angular Pressing (ECAP)

Grain size evolution

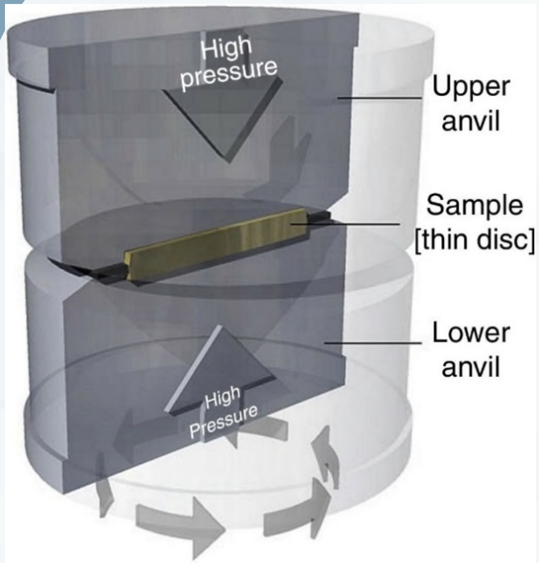


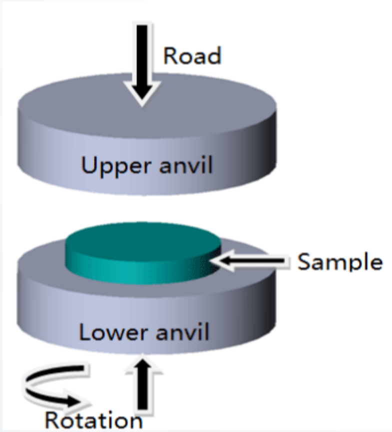
Grain size evolution

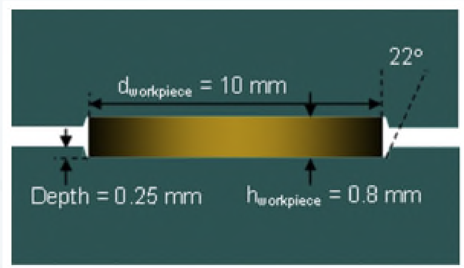


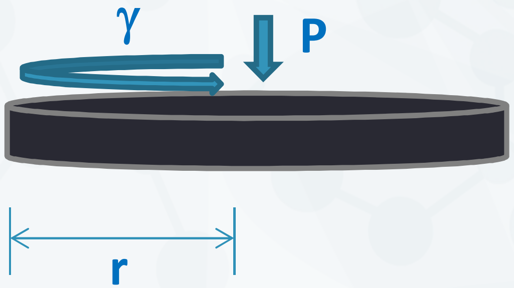
High-Pressure Torsion (HPT)

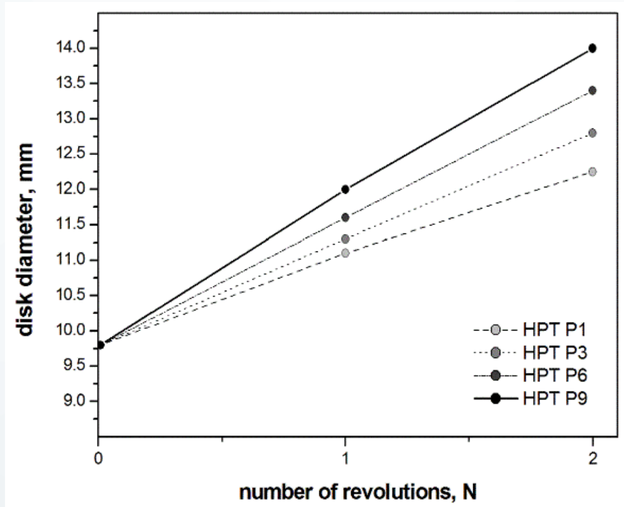
High-Pressure Torsion (HPT)











$t=f(\gamma,P)$ $d\gamma = r\cdot d\theta/t$

$$\varepsilon_{true}^{\ HPT} = \ln\left(1+\left(\frac{\theta r}{t}\right)\right) + \ln\left(\frac{t_0}{t}\right)$$

High-Pressure Torsion (HPT)

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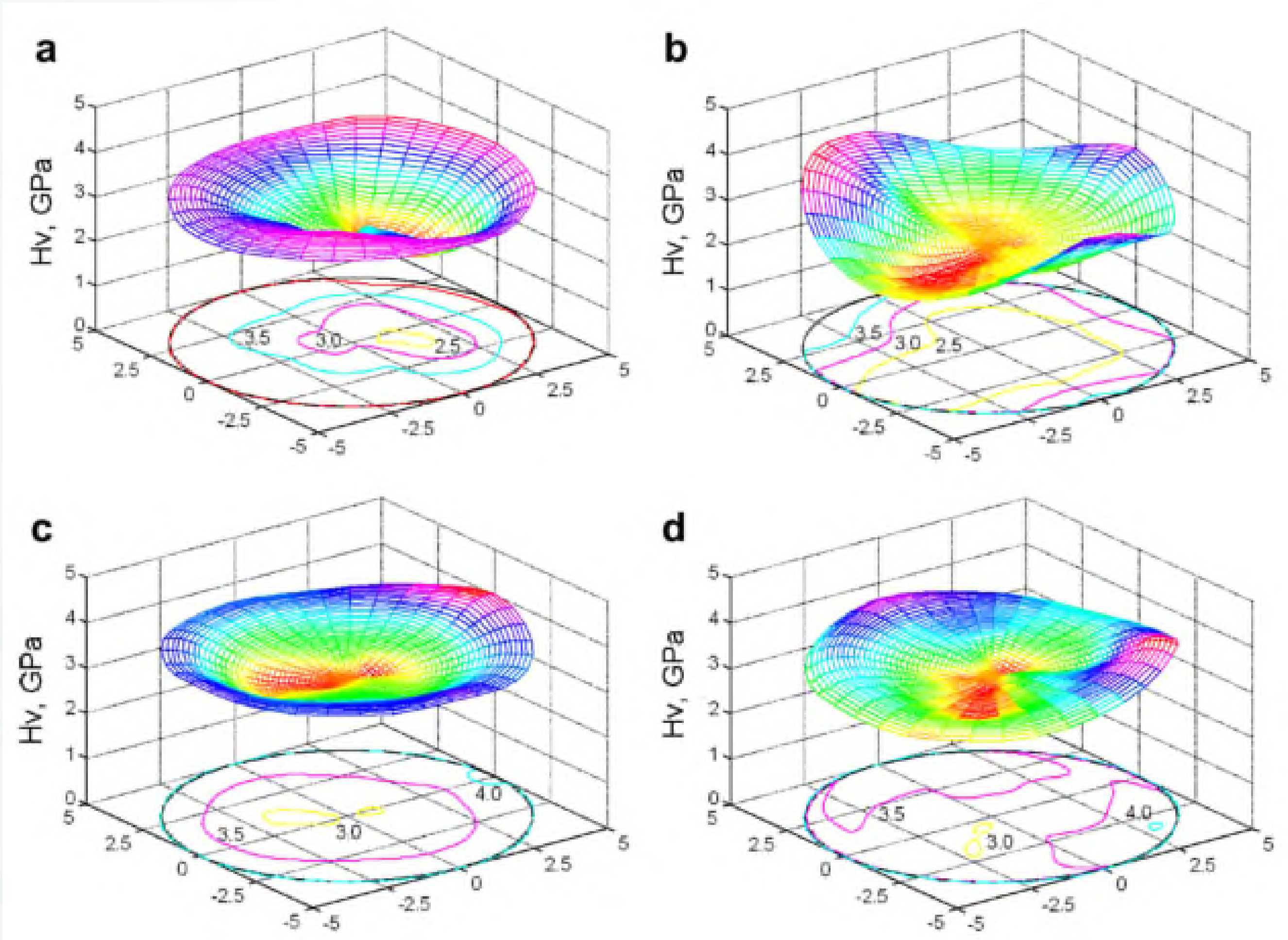
HPT

P = 1 GPa (a);

P = 3 GPa (b);

P = 6 GPa (c);

P = 9 GPa (d)



High-Pressure Torsion (HPT)

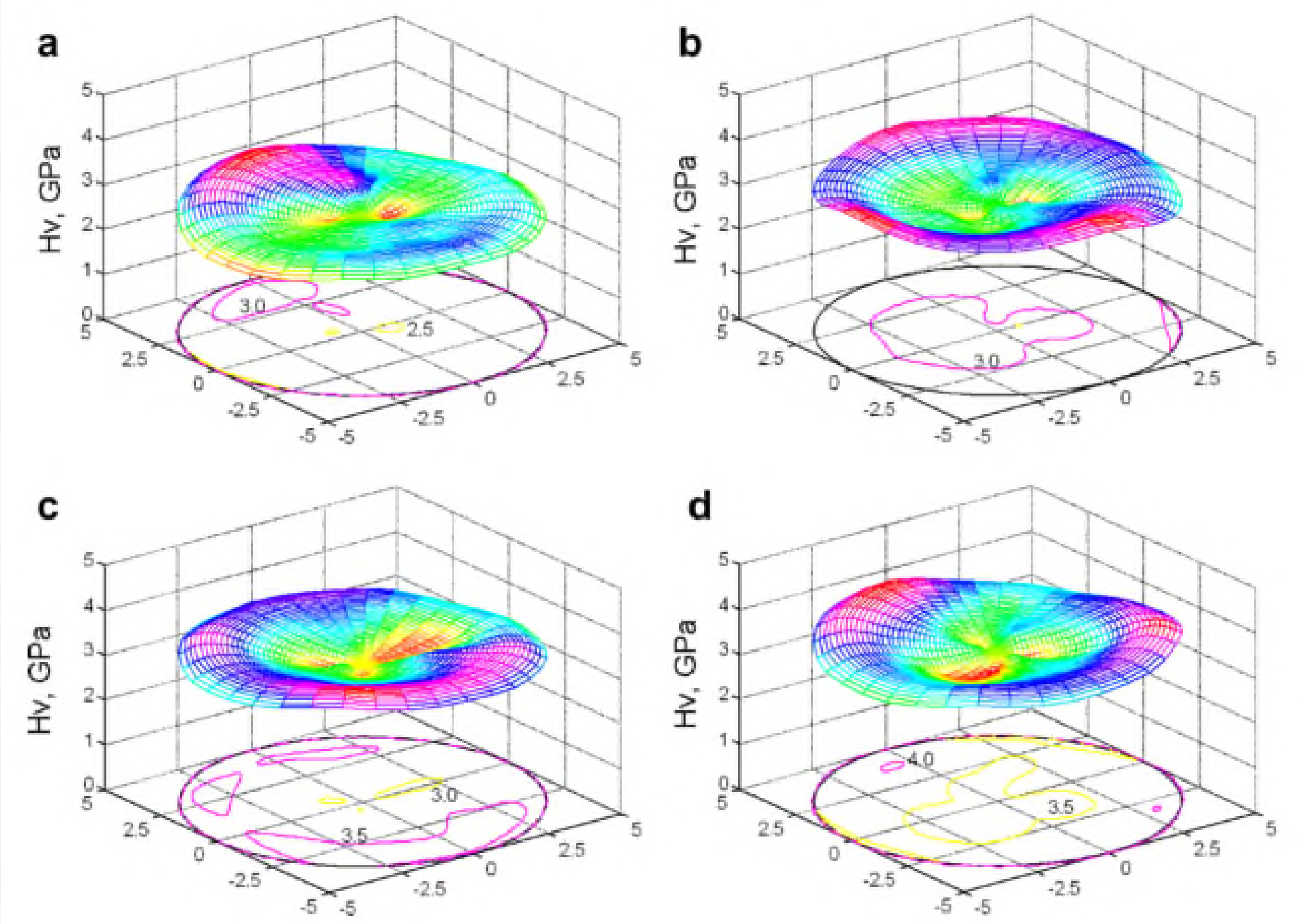
HPT @ P=6GPa

Turns = 0.5 (a);

Turns = 1 (b);

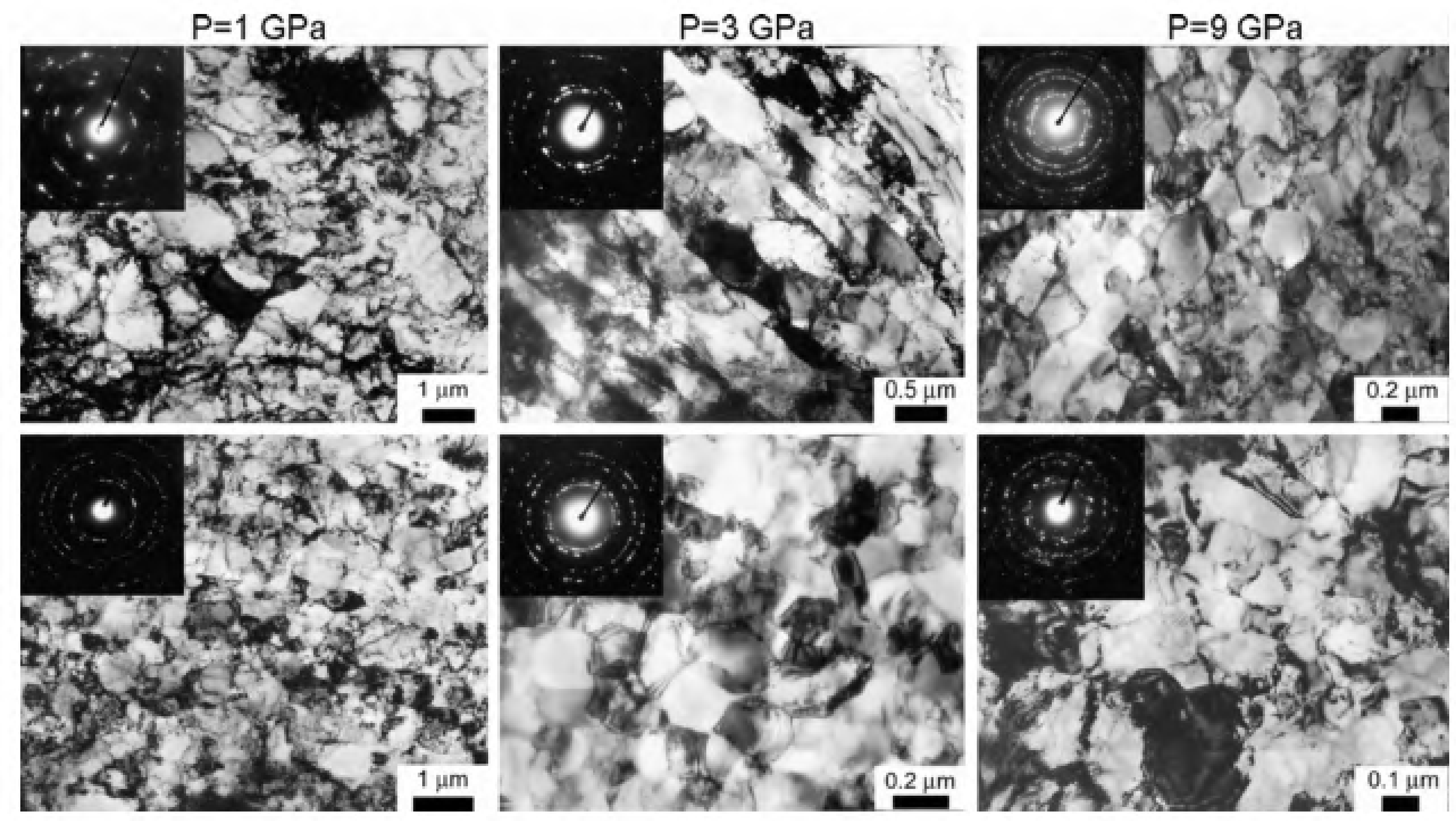
Turns = 3 (c);

Turns = 7 (d)



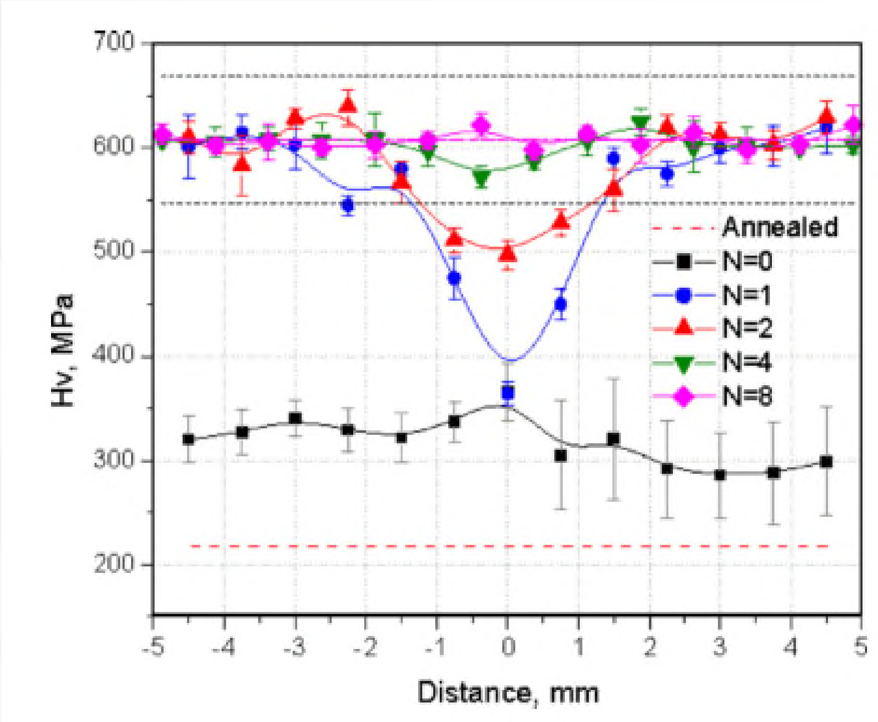
High-Pressure Torsion (HPT)

Grain size evolution

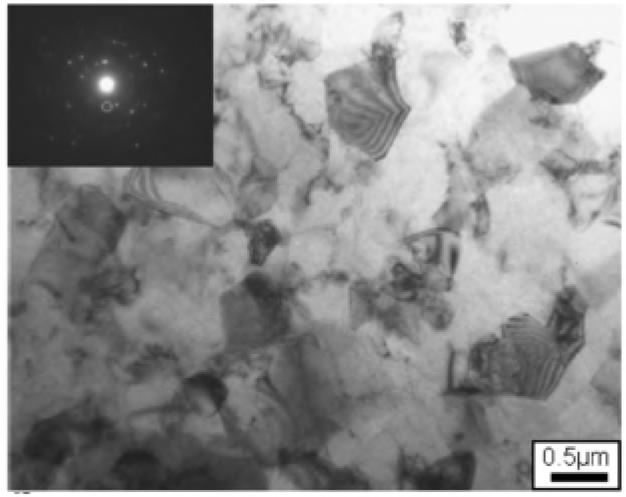


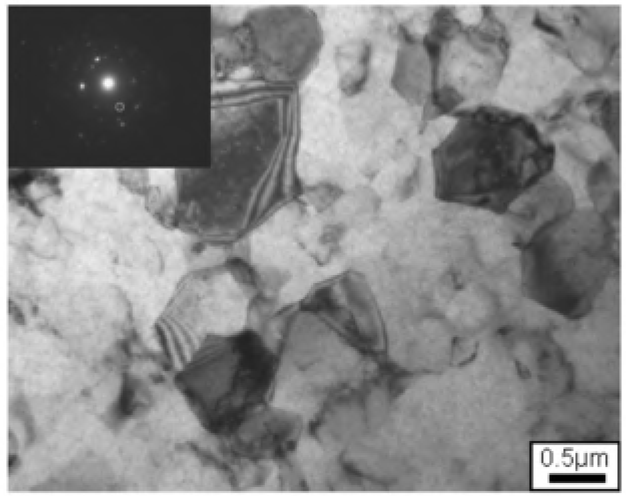
High-Pressure Torsion (HPT)

Microstructure homogeneization with HPT straining



central region

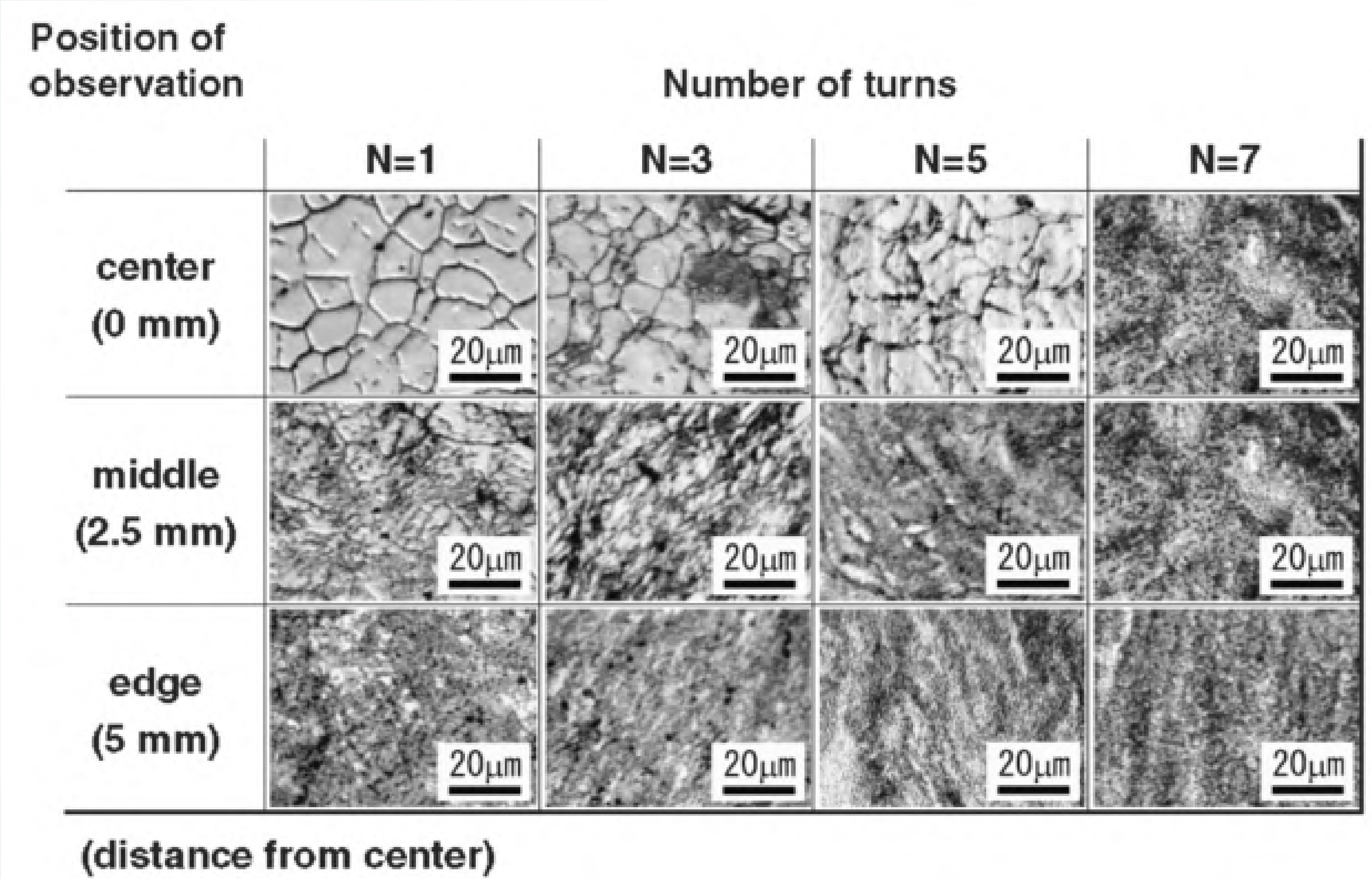




near periphery

High-Pressure Torsion (HPT)

Grain size evolution

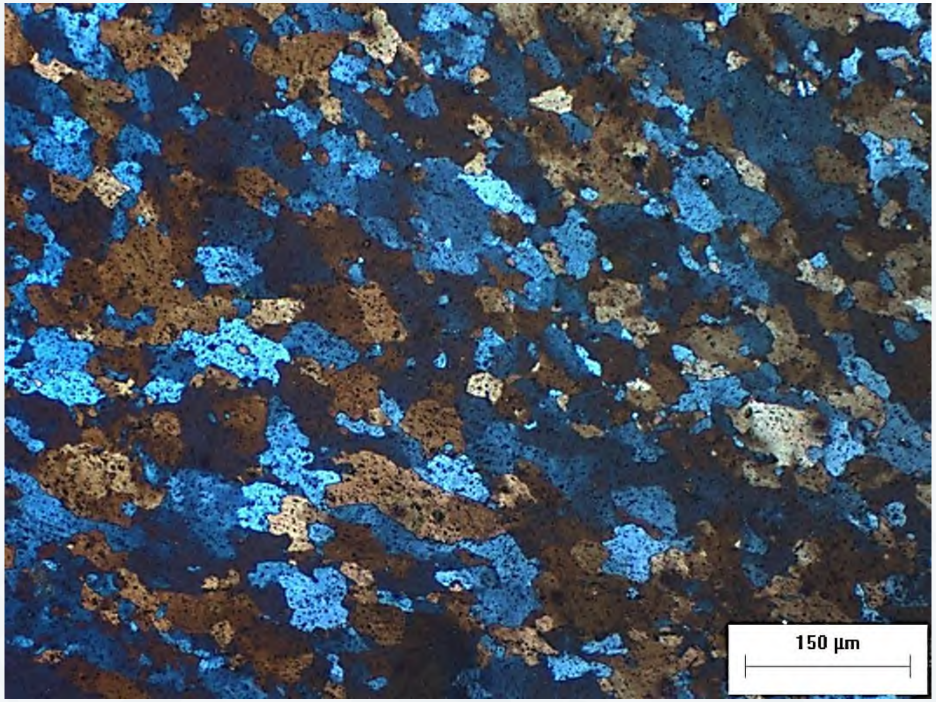


Combined effect of ECAP and HPT

Combined effect of ECAP + HPT

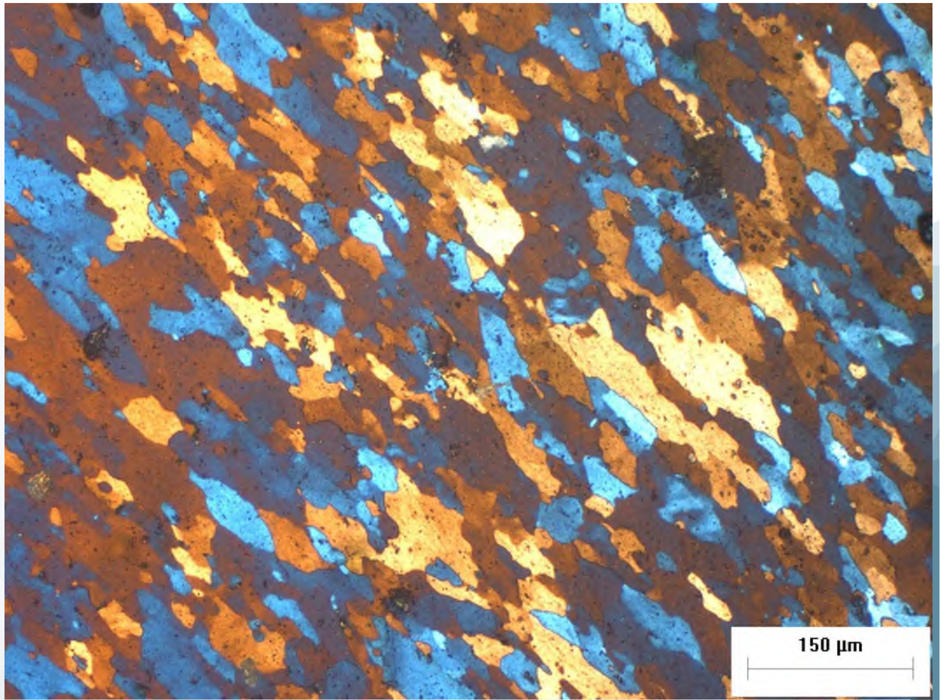
ECAP-4 / HPT

P=9GPa – opposite rotation direction with respect previous ECAP shearing



ECAP-4 / HPT

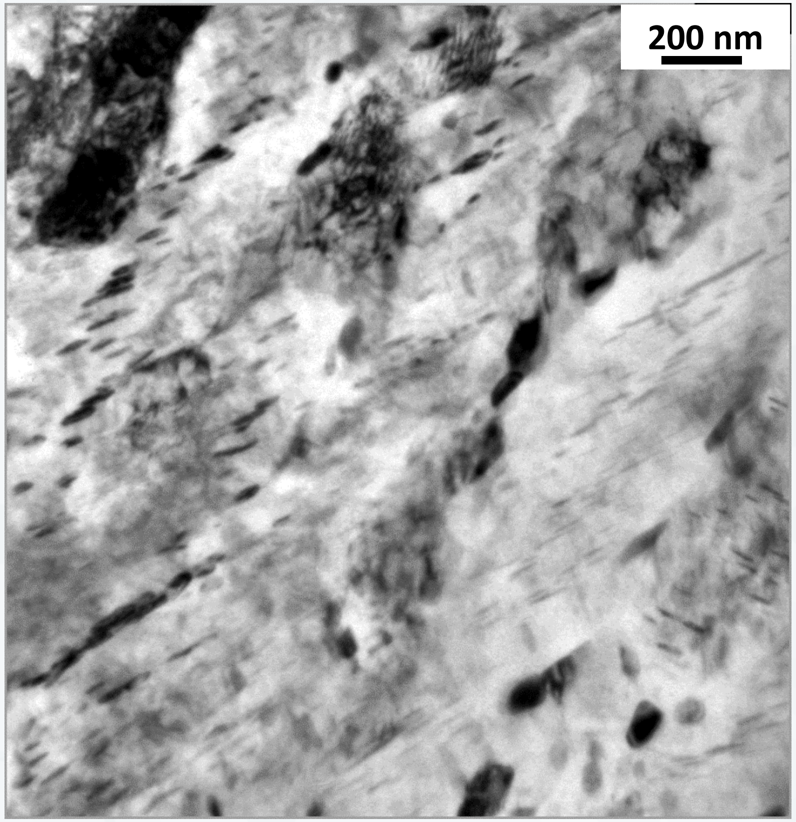
P=9GPa – concurrent rotation direction with respect previous ECAP shearing



Combined effect of ECAP + HPT

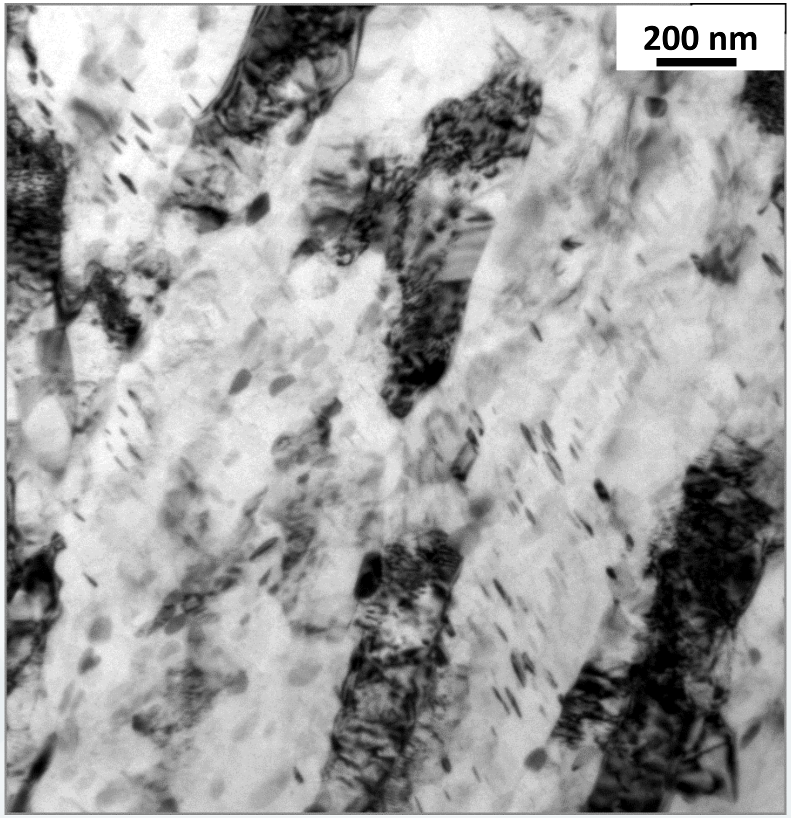
ECAP-4 / HPT

P=9GPa – opposite rotation direction with respect previous ECAP shearing



ECAP-4 / HPT

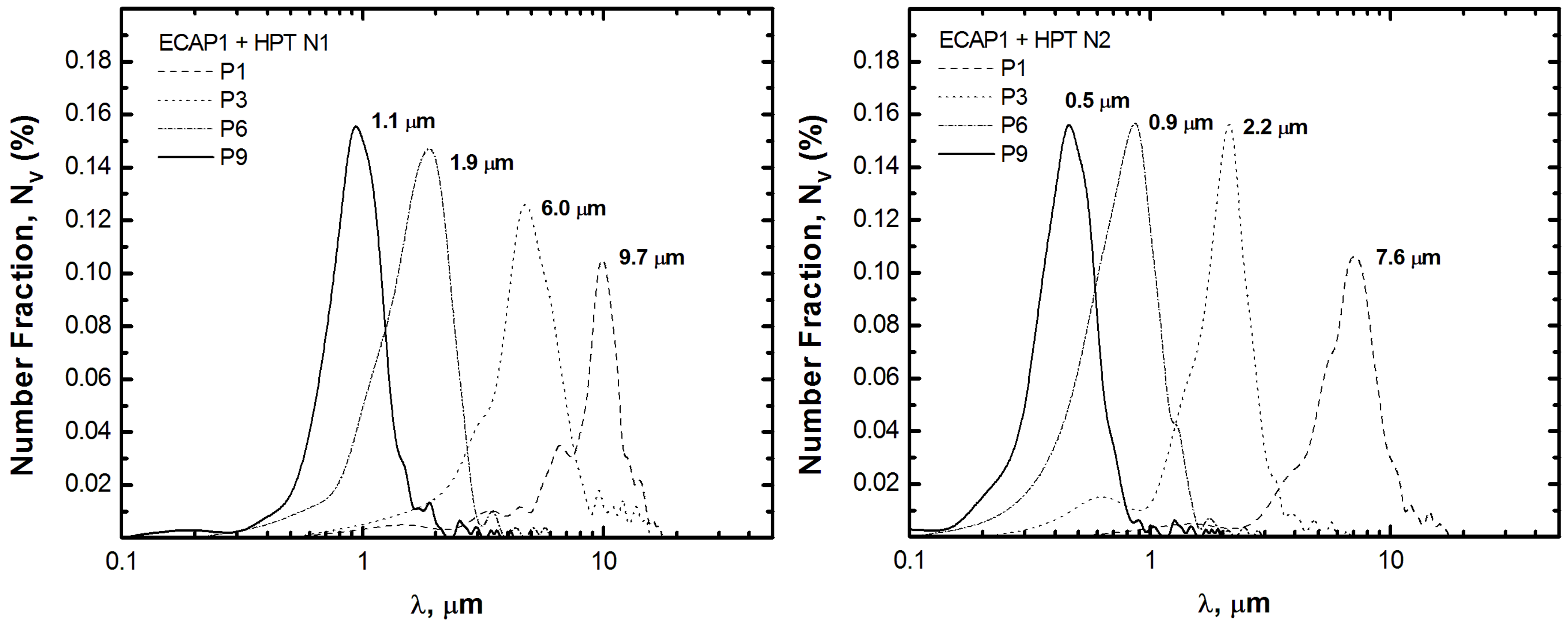
P=9GPa – concurrent rotation direction with respect previous ECAP shearing



Combined effect of ECAP + HPT

Grain size evolution

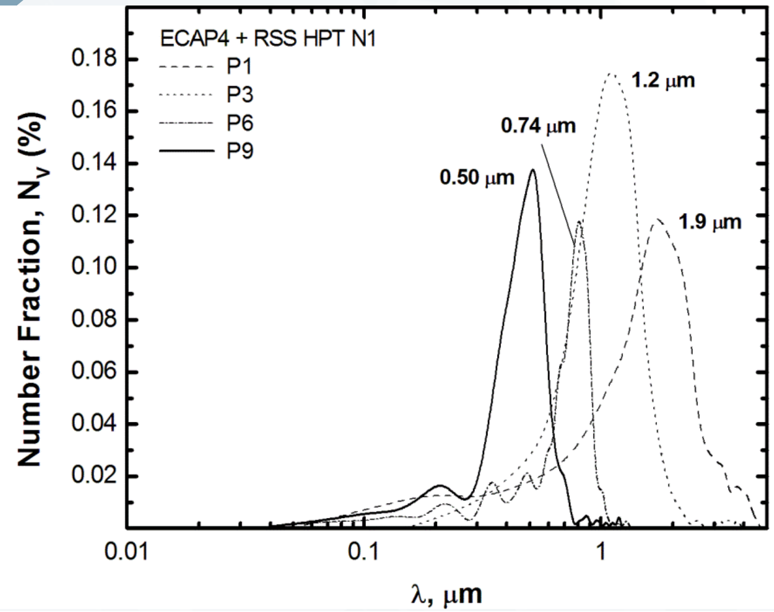
ECAP-1 / HPT

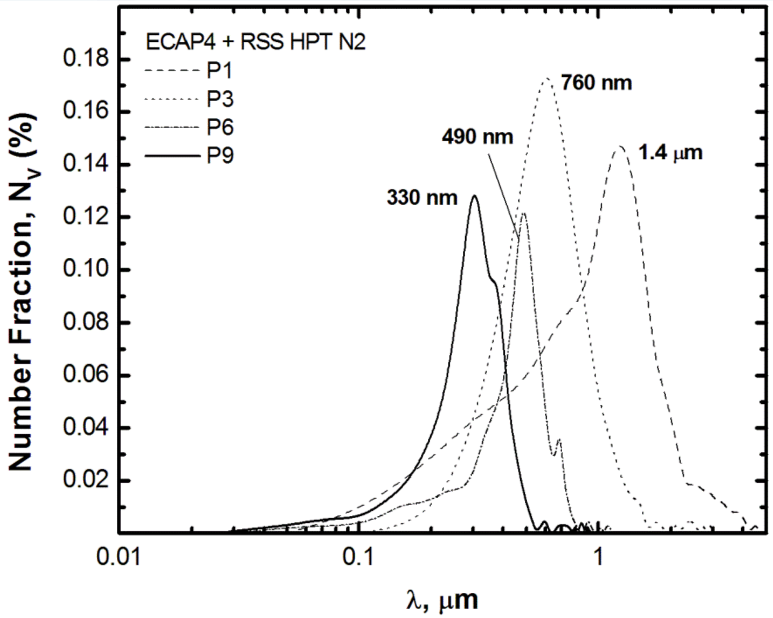


Combined effect of ECAP + HPT

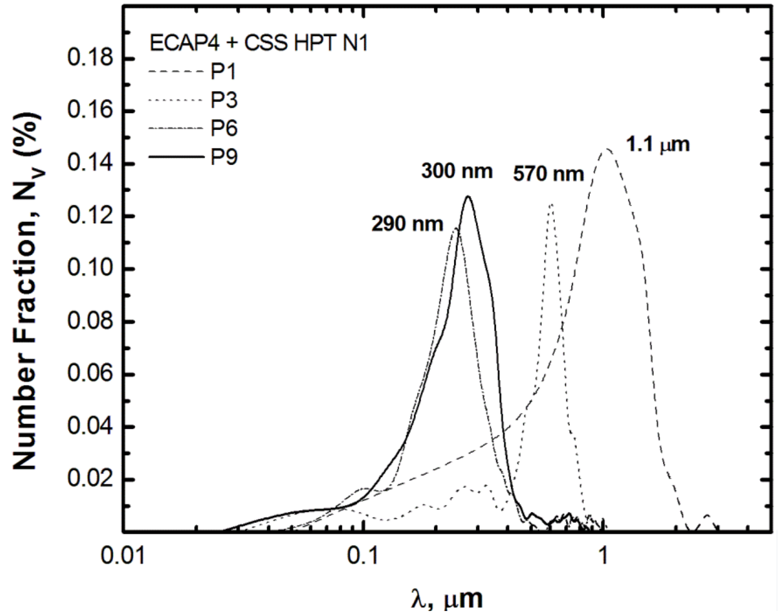
Grain size evolution

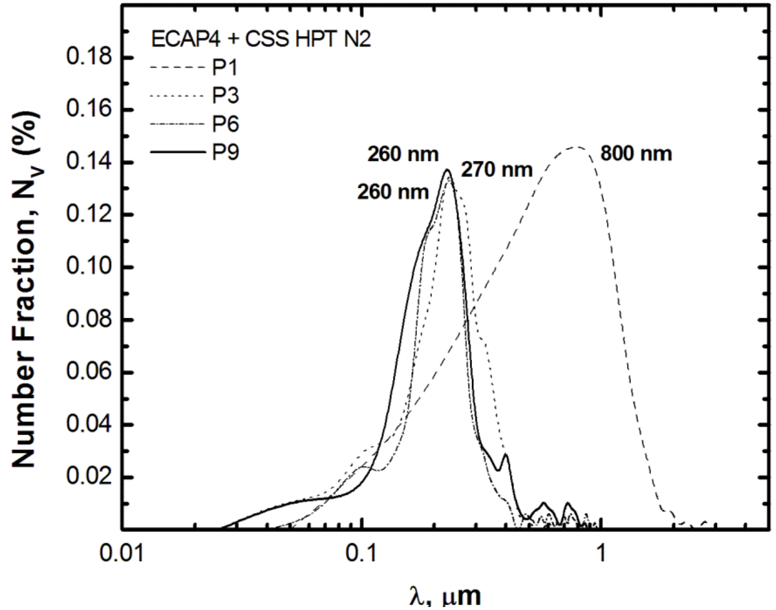
HPT opposite to ECAP



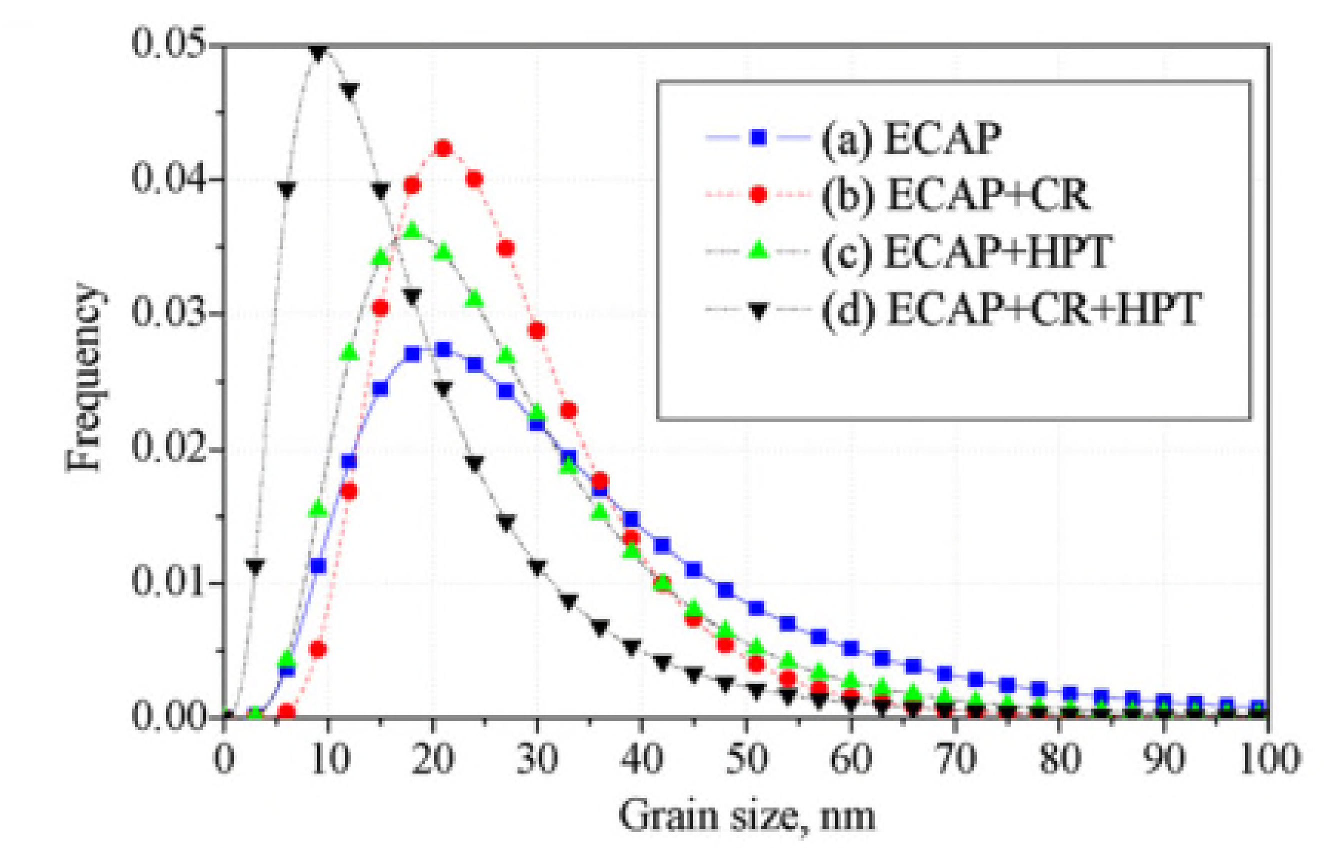


HPT same direction as ECAP





Combined effect of ECAP + HPT



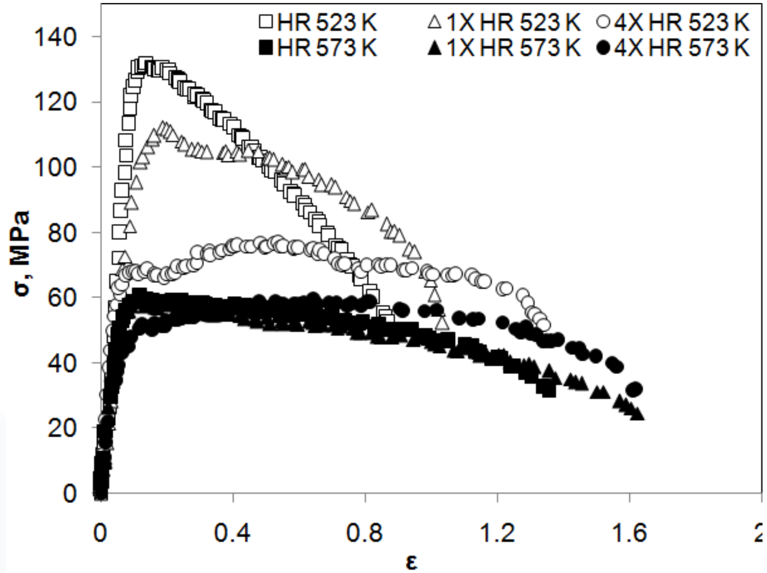
Severe Plastic Deformation techniques potentials

SPD potentials

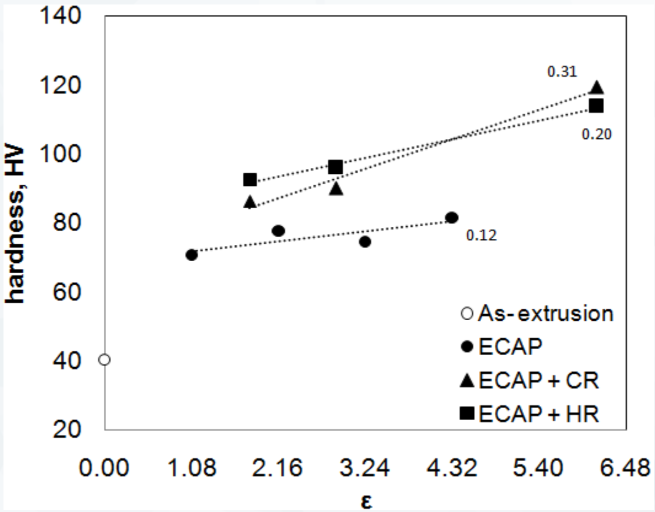
ECAP for Ductility improvement

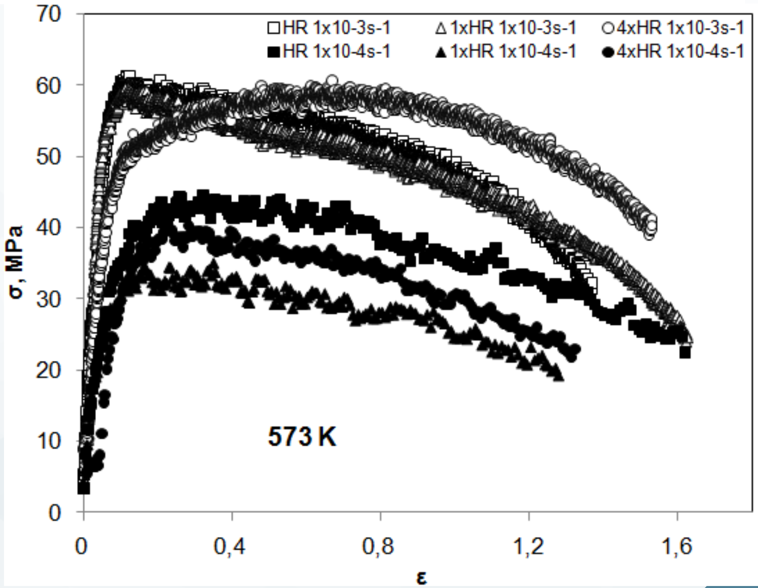
Tensile stress-strain curves at ἑ=1x10-3 s-1 of the AA3004 alloy (523 and 573K) (up)

at 573K for decreasing strain rate (ἑ=1x10-3 s-1, ἑ=1x10-4 s-1) (523 and 573K) (down)



Hardness vs. accumulative strain for ECAP (1X-to-4X), ECAP+CR and ECAP+HR

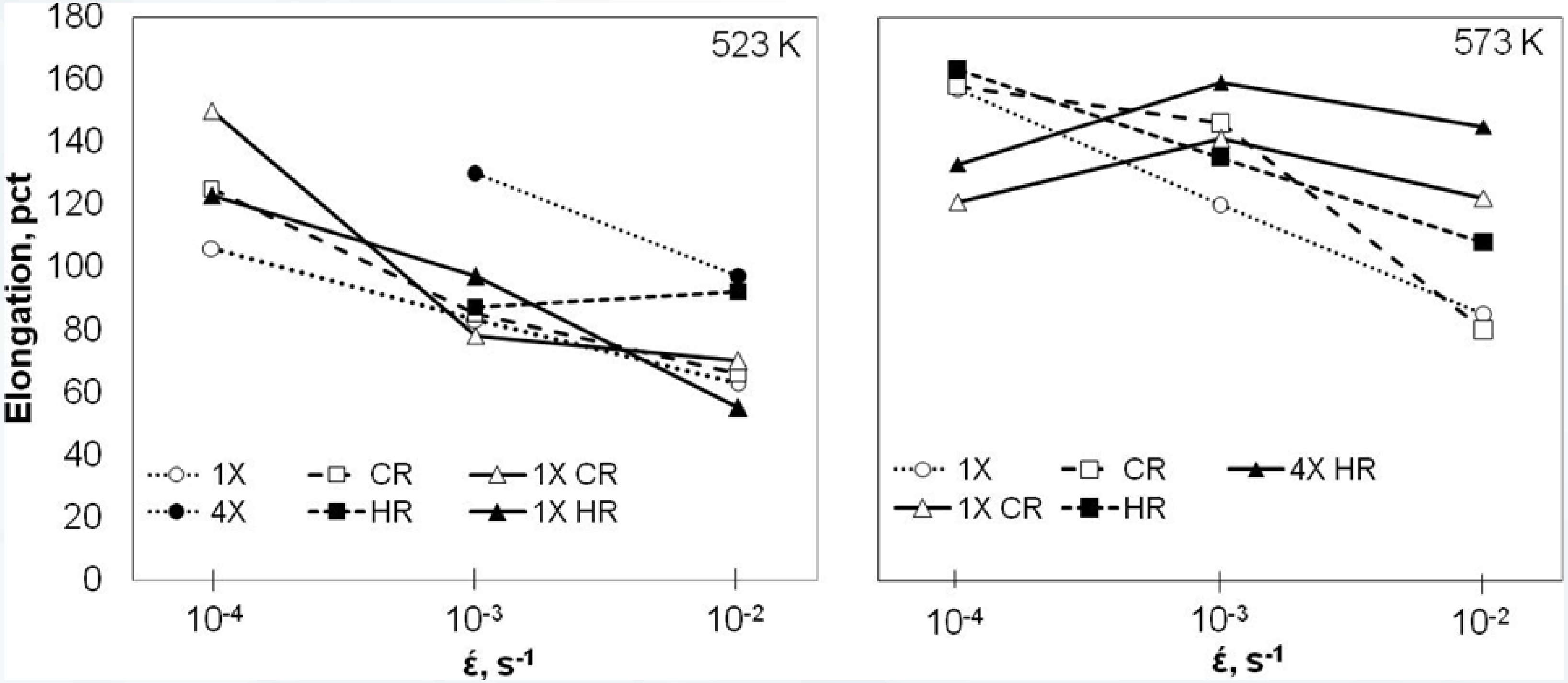




SPD potentials

ECAP for Ductility improvement

A better sheet formability of AA3000 series / ECAP-route A

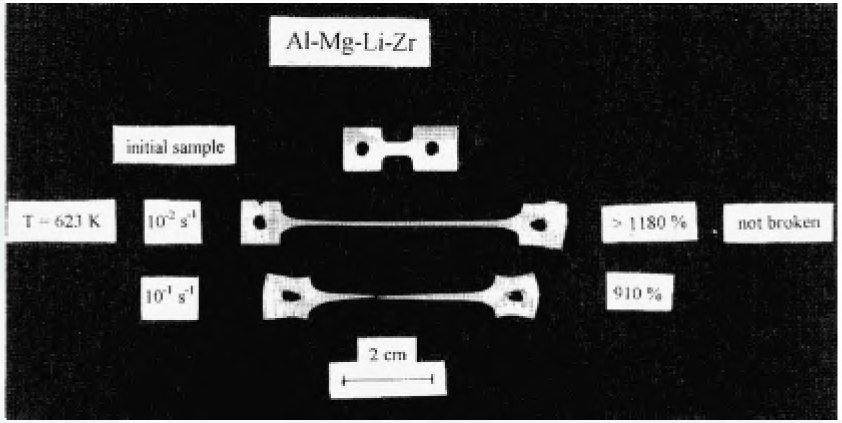


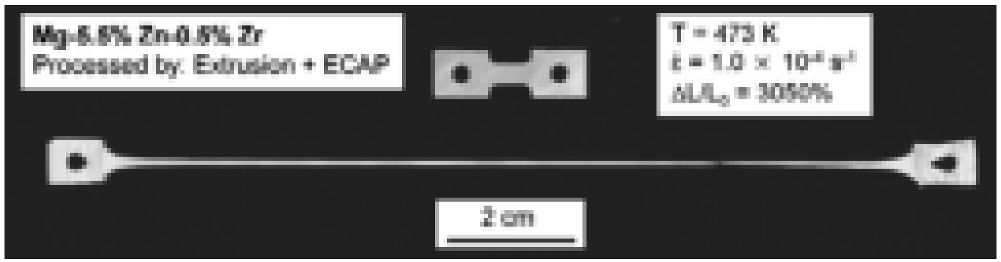
best elongation to failure response: ECAP+HR and ECAP+CR at 573K

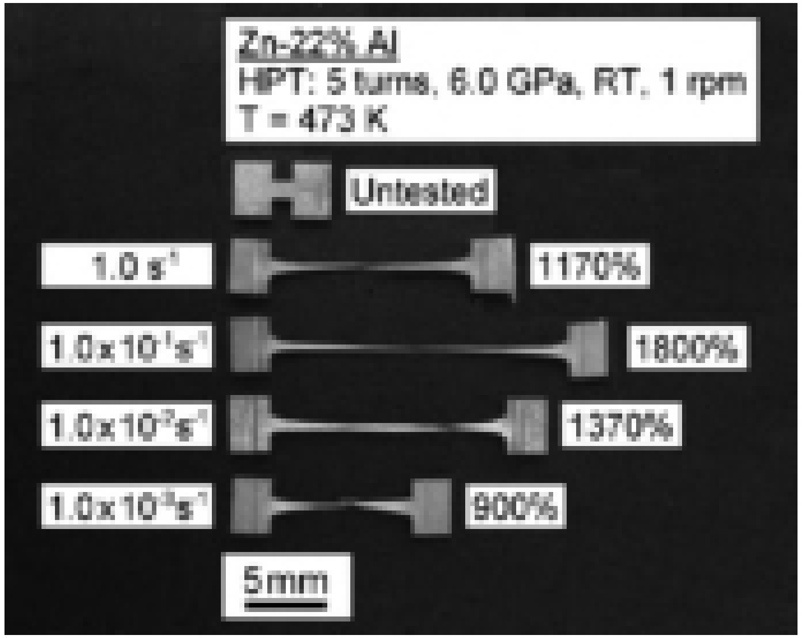
with no significant ductility deterioration with strain rate

SPD potentials

Superplasticity behavior



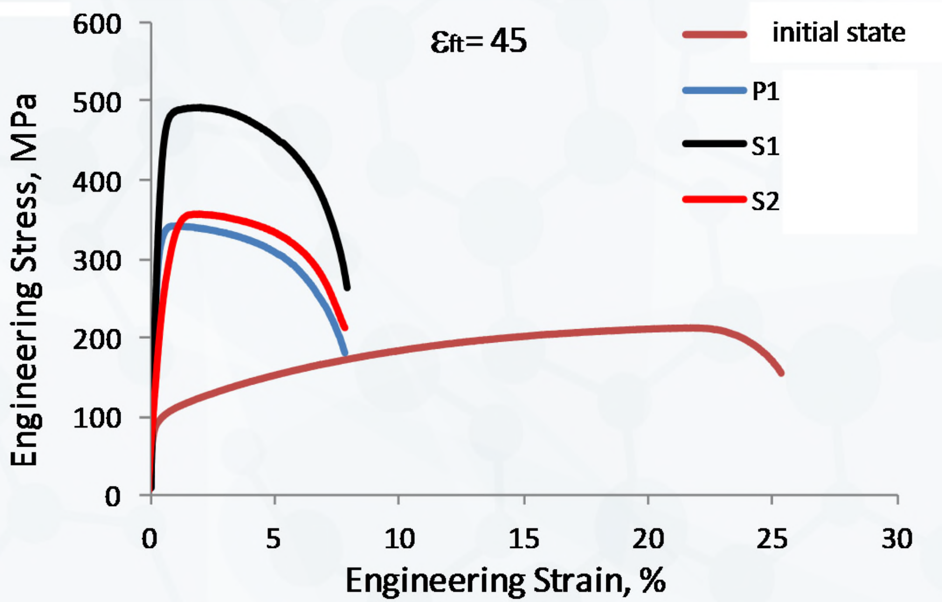


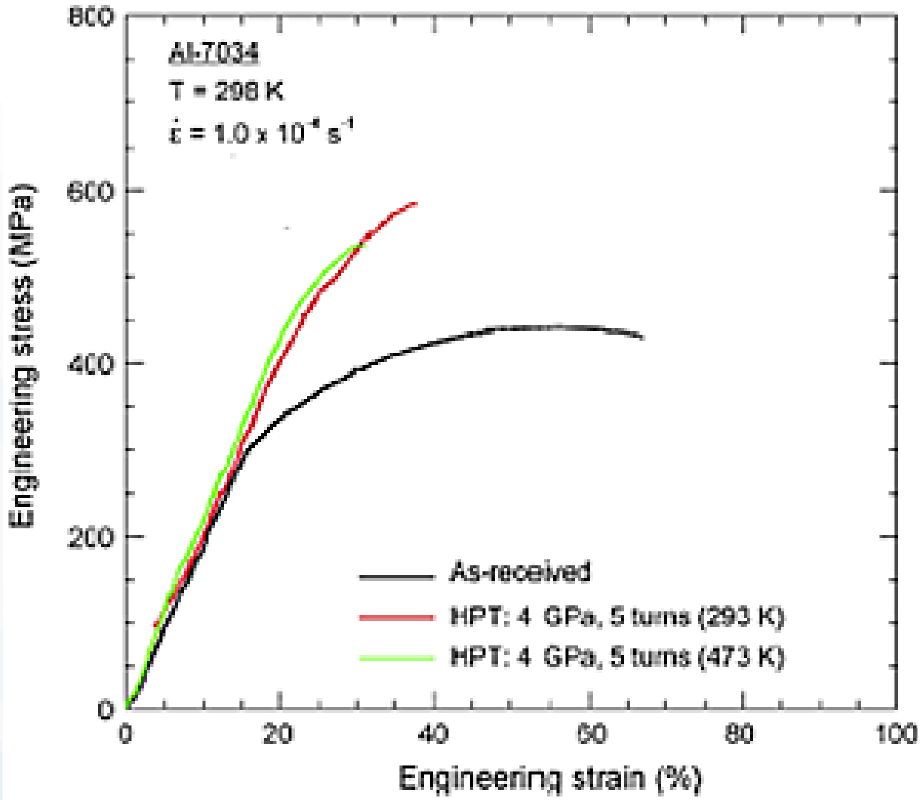


After T.C. Langdon

T.G. LANGDON, Acta Mater., 61, (2013) p.7033.

Superplasticity behavior





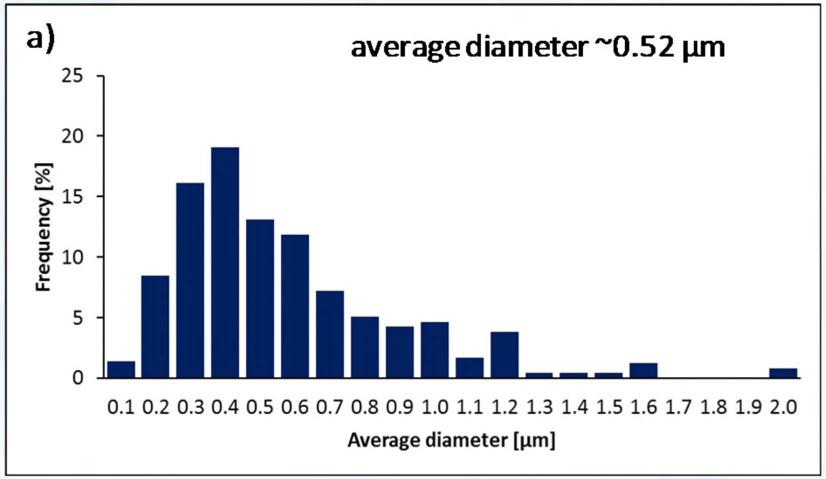
After T.C. Langdon

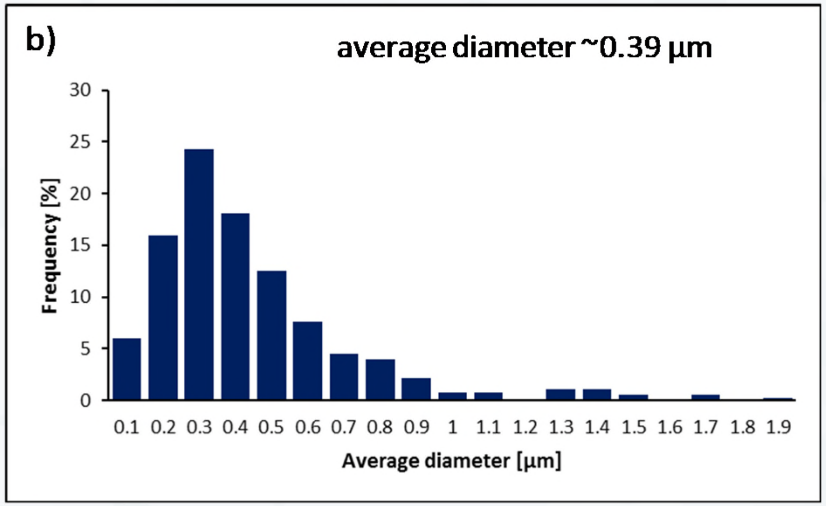
T.G. LANGDON, Acta Mater., 61, (2013) p.7033.

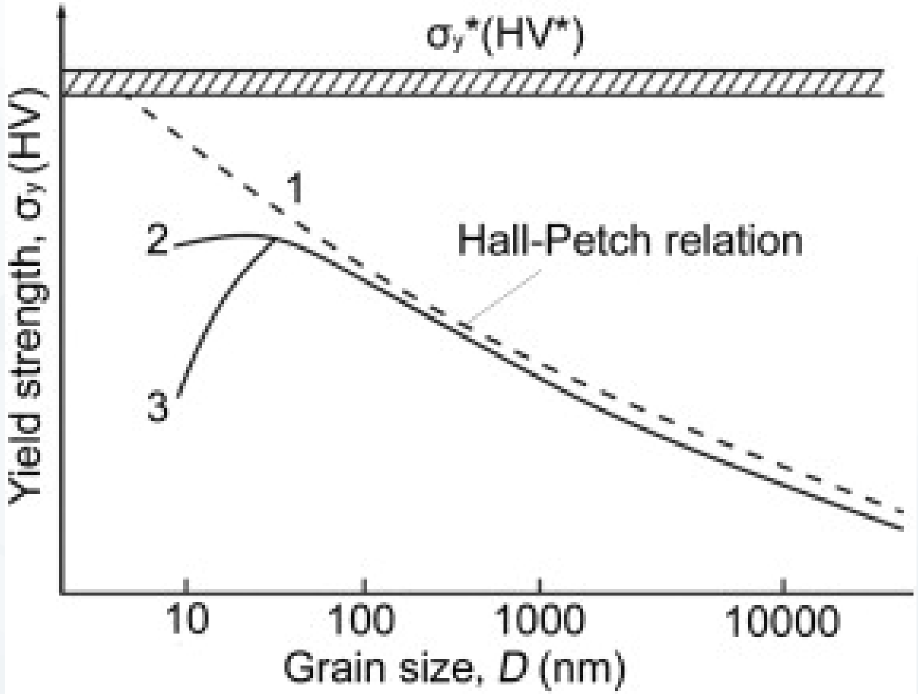
Limits of ECAP and HPT

Limits of ECAP and HPT

grain size reduction physical limit



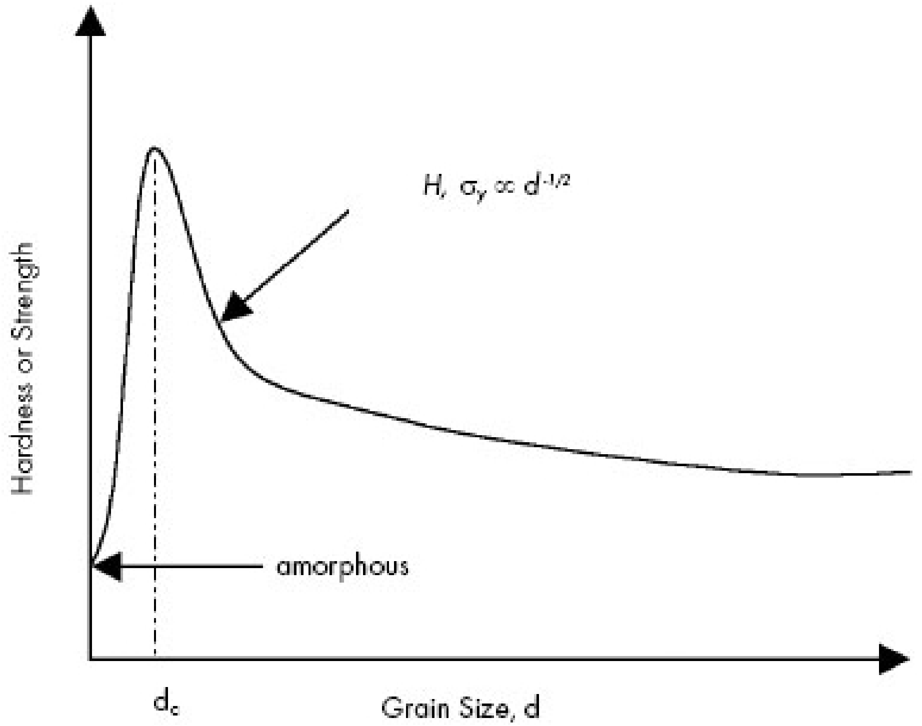




Limits of ECAP and HPT

grain size reduction physical limit:

deviation from the Hall-Petch relationship



Hall-Petch Equations

$\sigma_y = \sigma_o + Kd^{-1/2}$ $\quad$ $H = H_o + Kd^{-1/2}$

σ_y: yield strength

σ_o: lattice yield stress (minimum stress required to move a dislocation)

H : hardness

H_o: single crystal hardness

K: constant

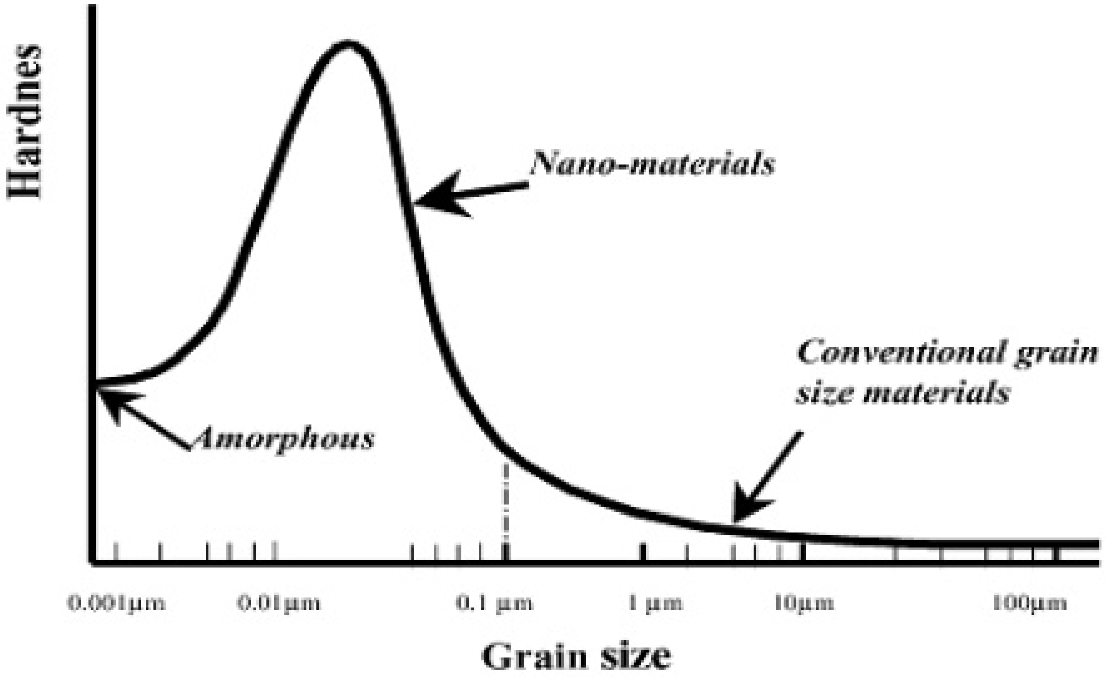
d: average grain size

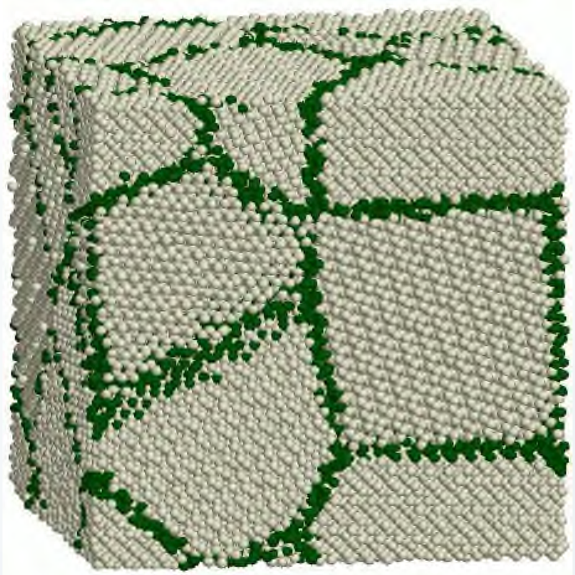
Limits of ECAP and HPT

grain size reduction physical limit:

deviation from the Hall-Petch relationship

(grain boundary region role)



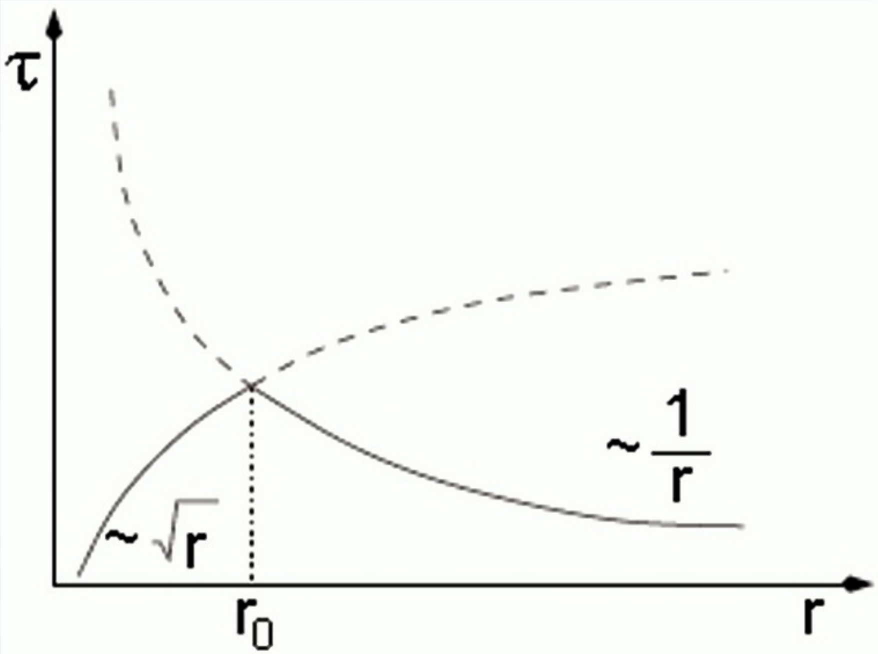


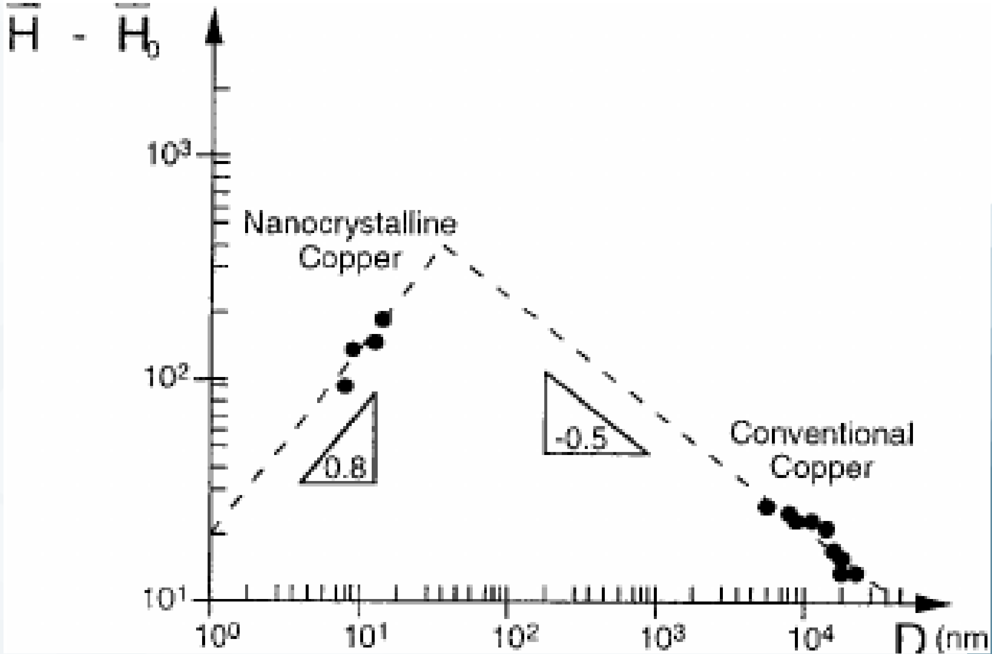
Limits of ECAP and HPT

grain size reduction physical limit:

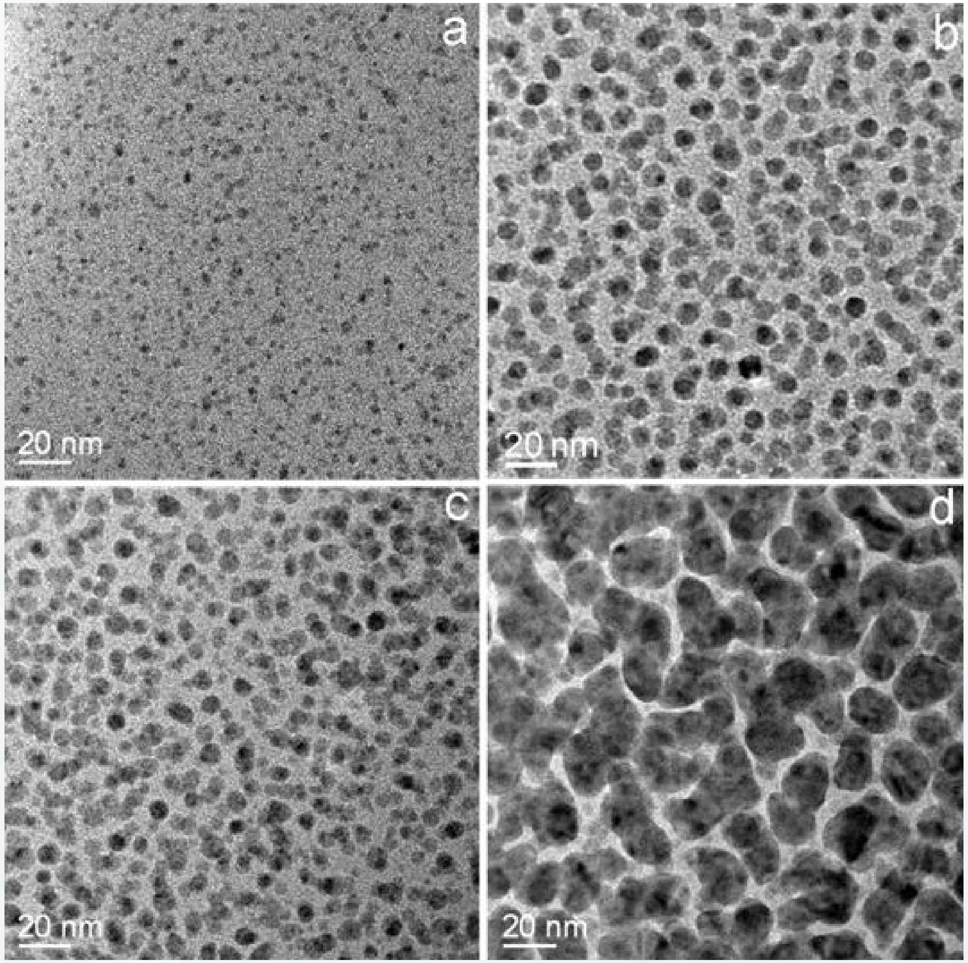
deviation from the Hall-Petch relationship

(grain boundary region role)





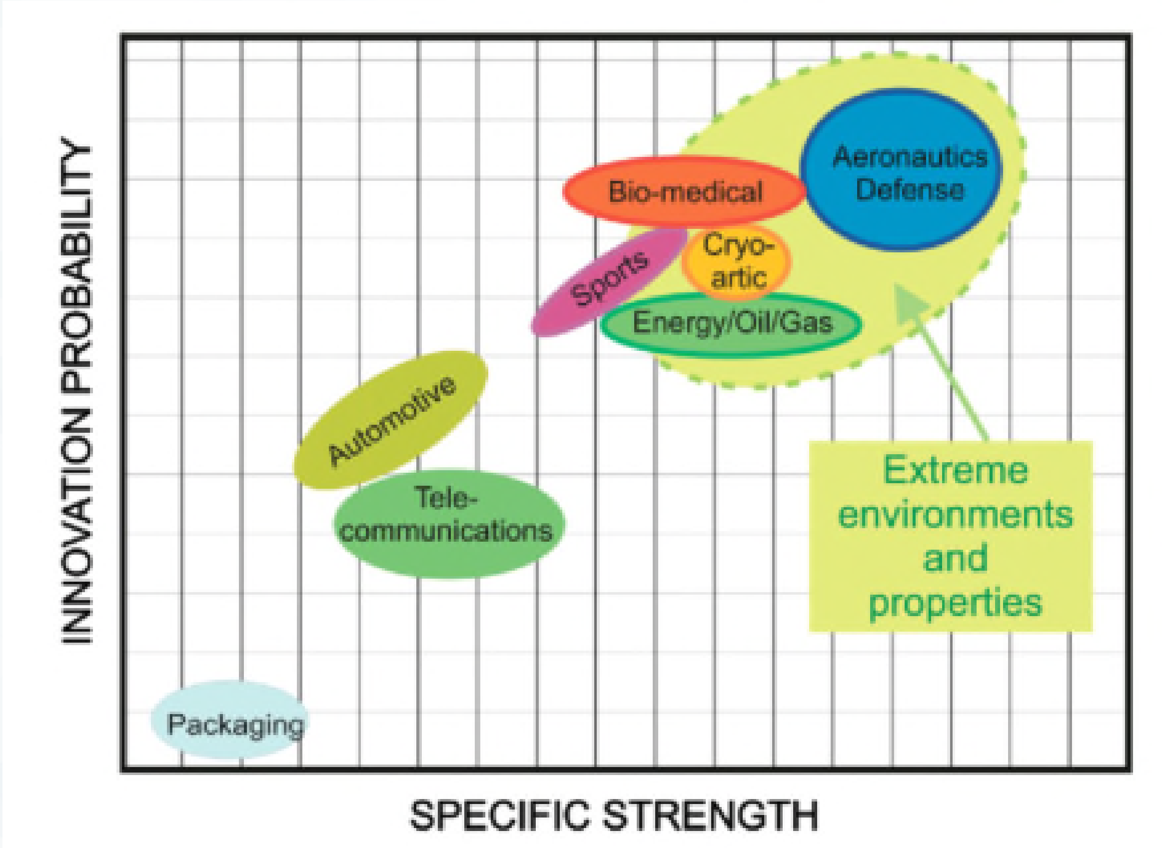
From the «Top-Down» approach to the «Bottom-Up»



OUTLOOK

OUTLOOK

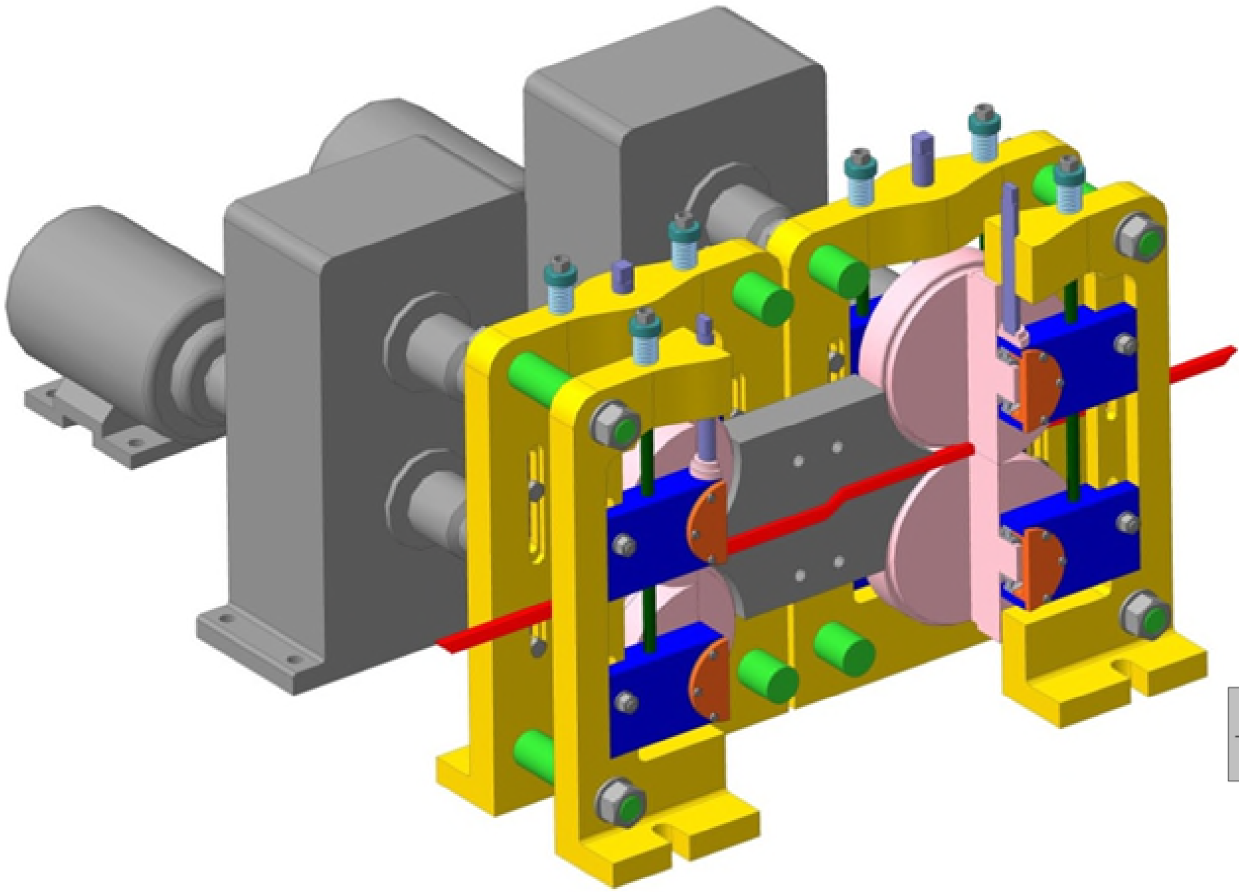
ICARUS SUPERMAT

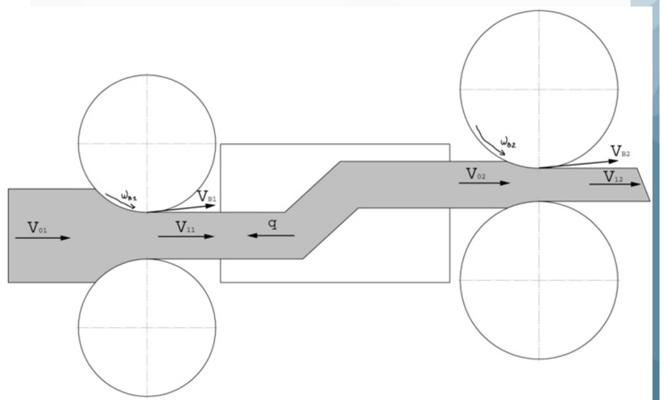


Innovation probability in various sectors versus the specific strength:
the highest potential is anticipated in applications and products under extreme environments and/or requiring extreme specific strength

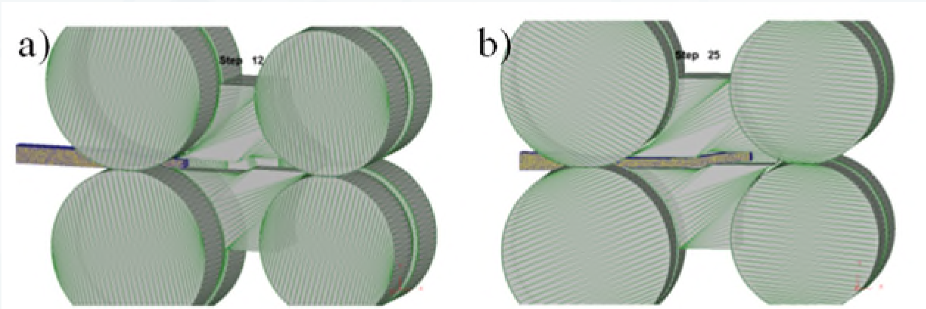
R.Z. Valiev , M.J. Zehetbauer, Y. Estrin, H.W. Höppel, Y. Ivanisenko, H. Hahn, et al. Adv Eng Mater, 9 (2007), 527

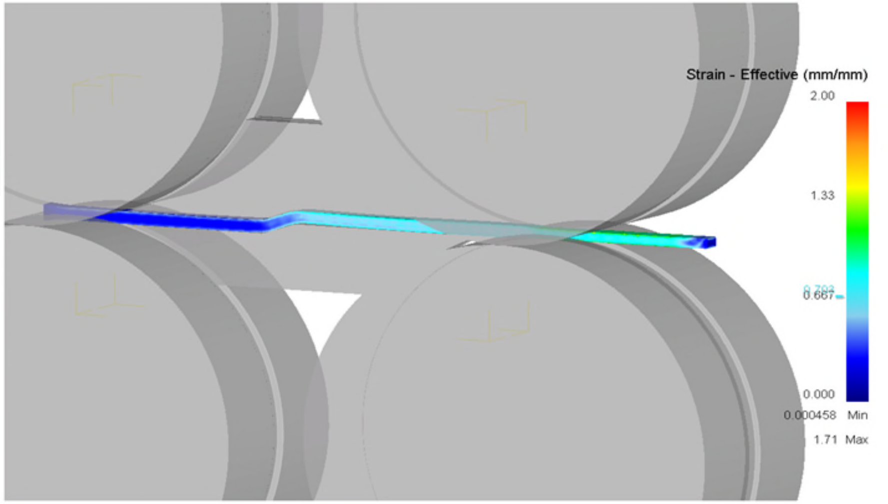
Industrial scaling up

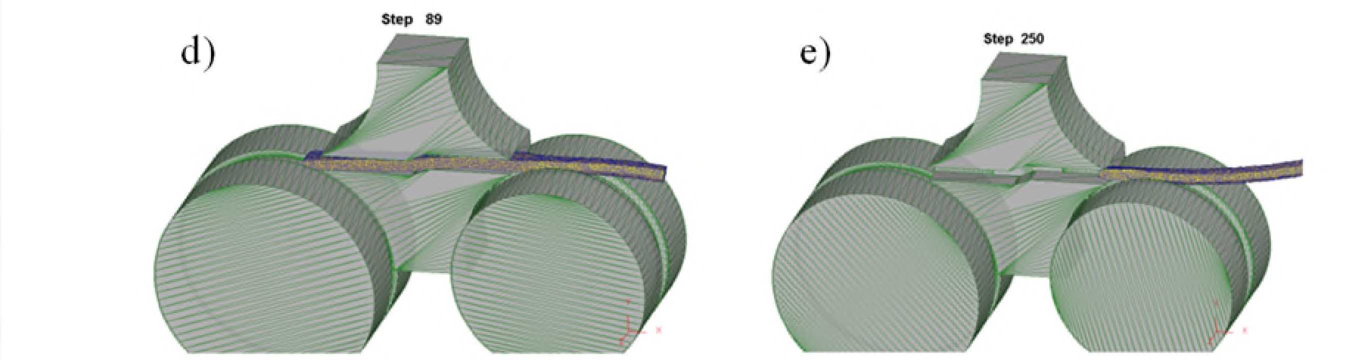




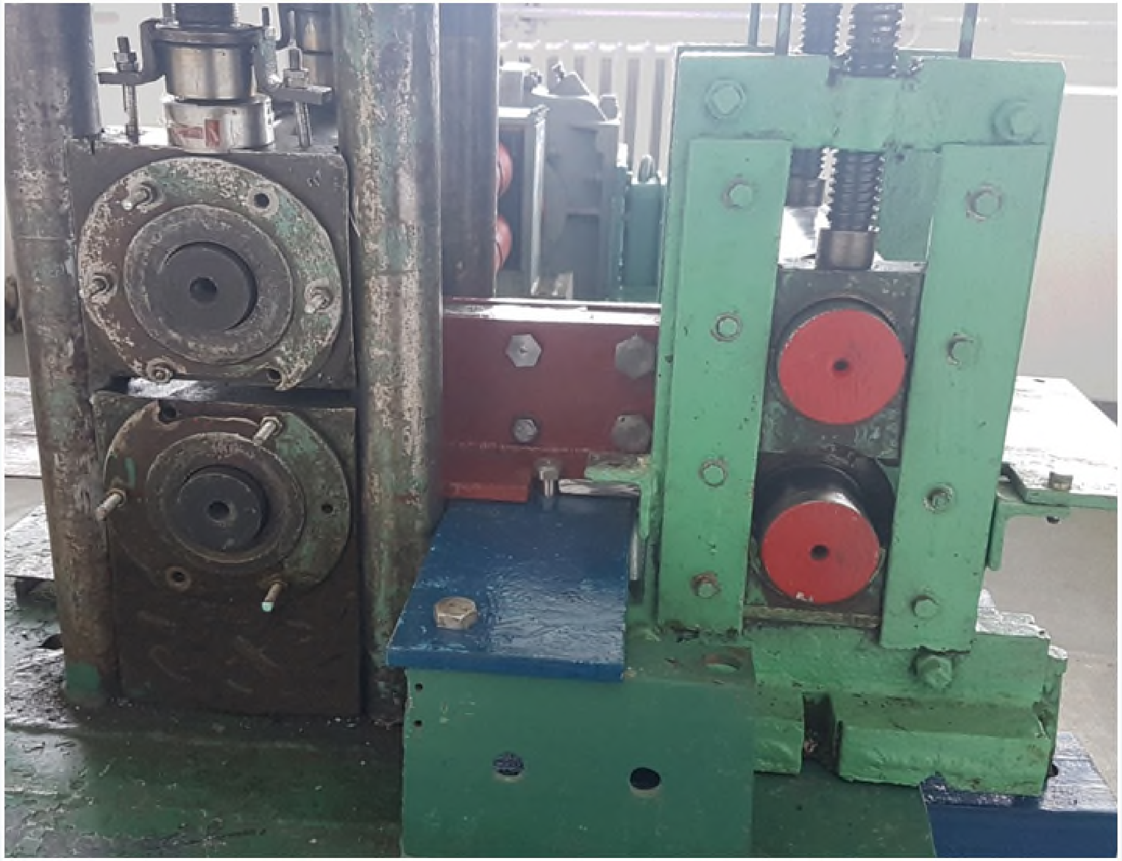
Industrial scaling up





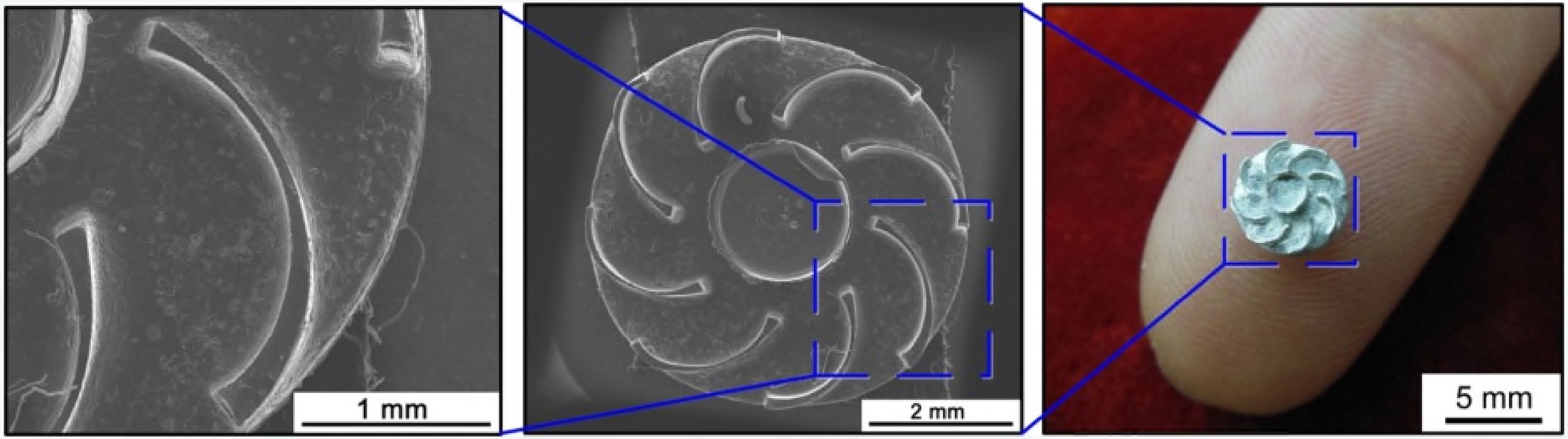


Industrial scaling up: the prototype



OUTLOOK

Micro-turbine of UFG pure aluminum formed at room- temperature



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