NANOMET

Ultrafine grained materials

perspectives for transport, energy and bioengineering applications

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INNOVATIVE ECONOMY
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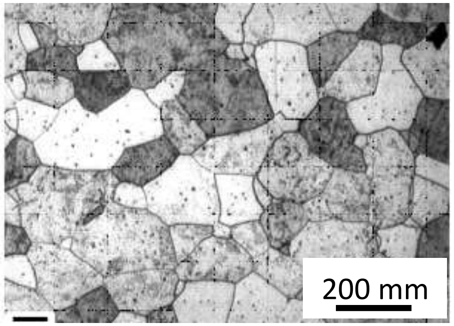
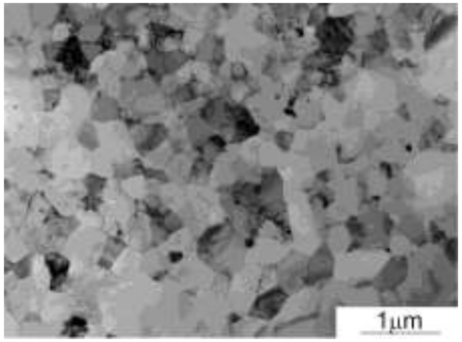
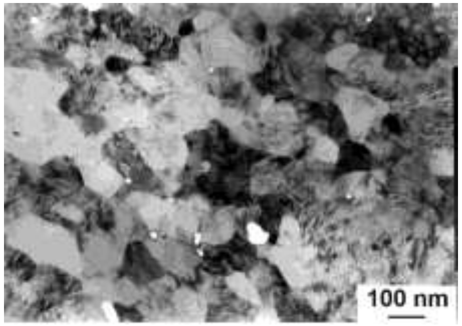
UFG materials



Micro
d > 1 μm

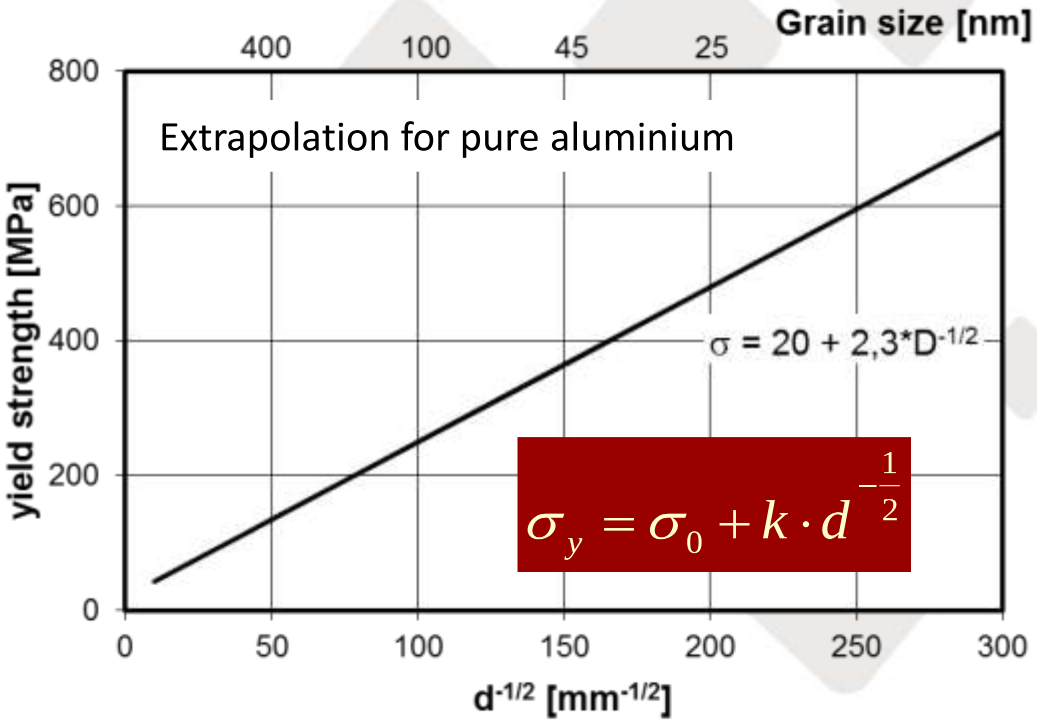


UFG
d < 1 μm



Nano
d < 100 nm

Halla-Petcha relationship



$$\sigma_y = \sigma_0 + k \cdot d^{-\frac{1}{2}}$$

- ☐ the potential of grain refinement is impressive
- ☐ technically pure Al may achieve 500 MPa yield strength if grain size is reduced to 25 nm

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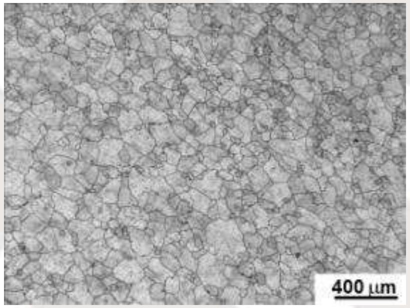
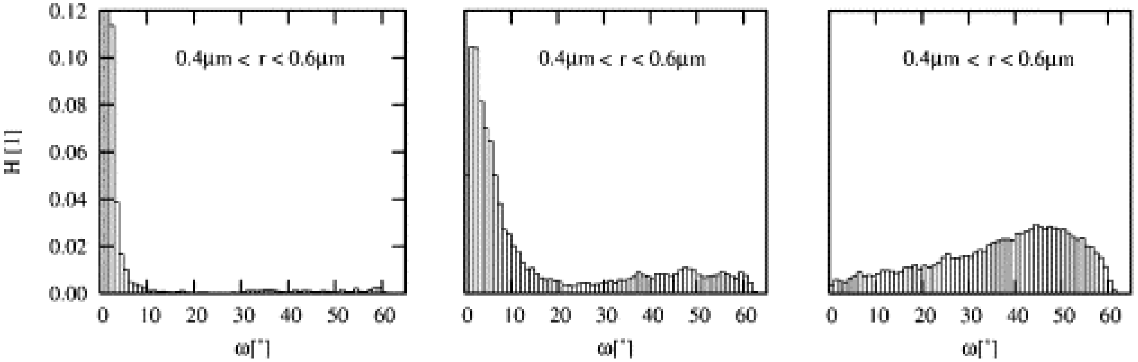
UFG materials

Characteristic features:

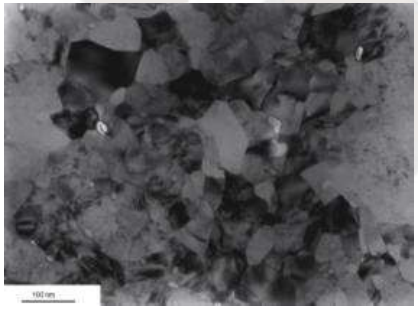
- Average grain size 50 – 500 nm
- High surface area of grain boundaries – by 2-3 orders of magnitude
- Various characteristics of grain boundaries



l = 70 μm
Sv = 28,6 **mm²**/mm³



R. Pippan et. al.; Acta Mater. 53 (2005) p. 393–402



l = 70 nm
Sv = 286 **cm²**/mm³

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How to obtain products in large quantities?

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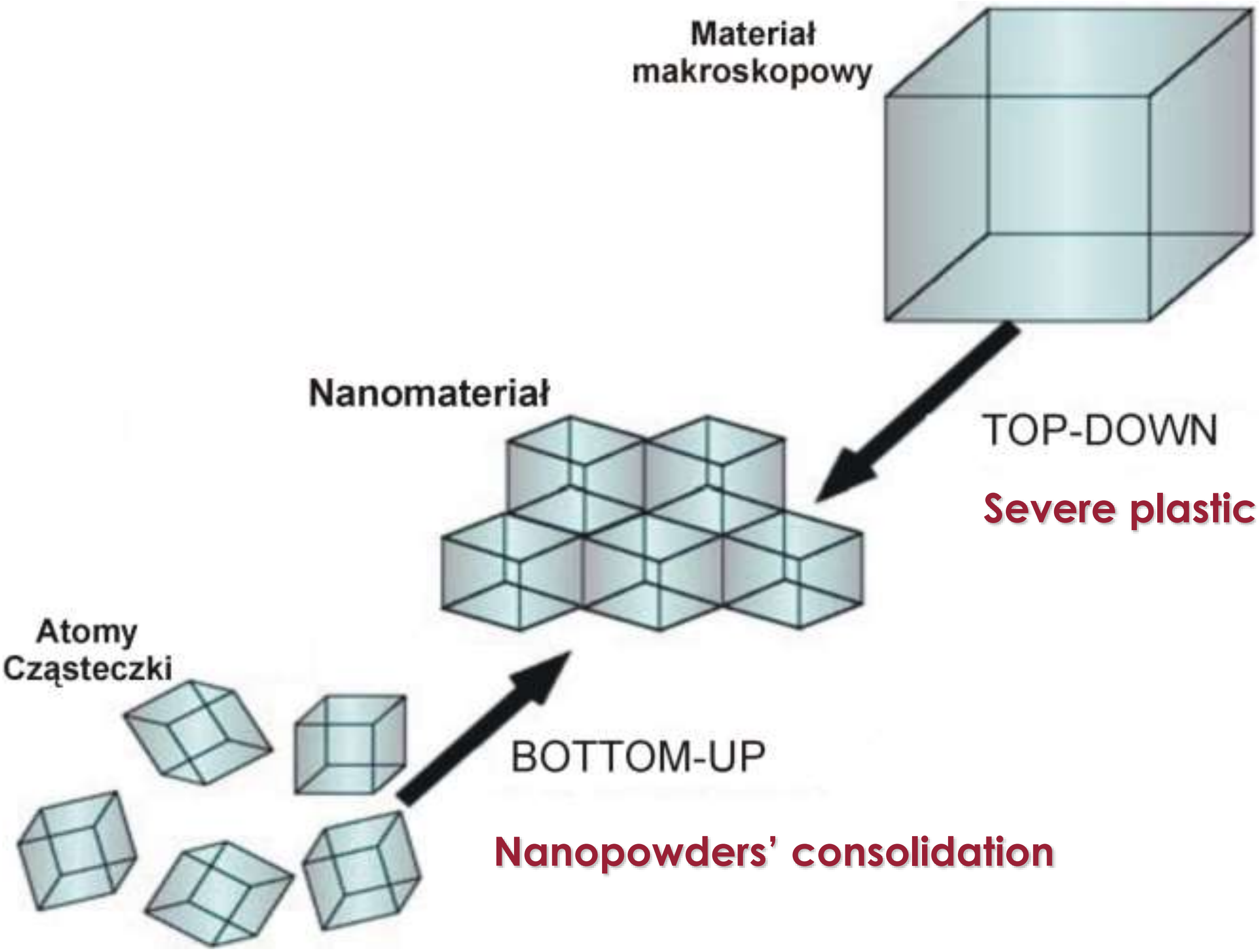
Processing techniques



Severe plastic deformation

Nanopowders' consolidation

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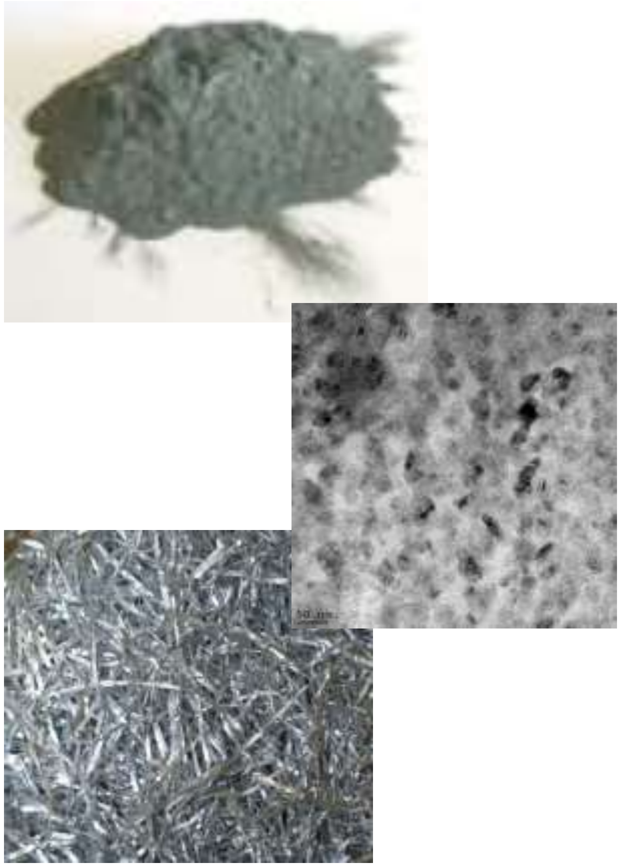
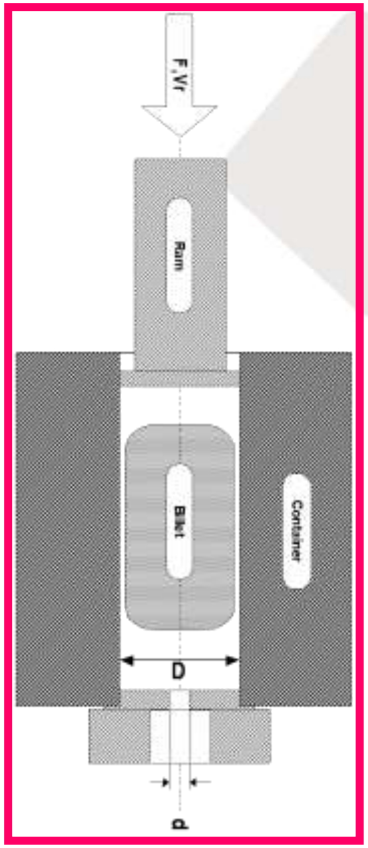
Processing techniques

Plastic consolidation of rapidly solidified powders





warm extrusion

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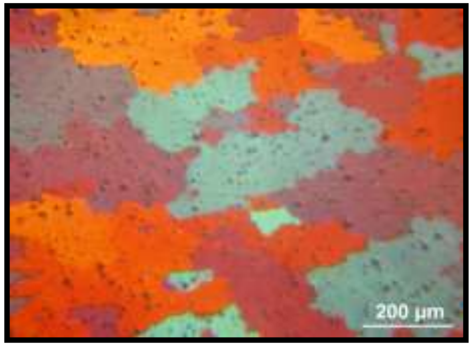
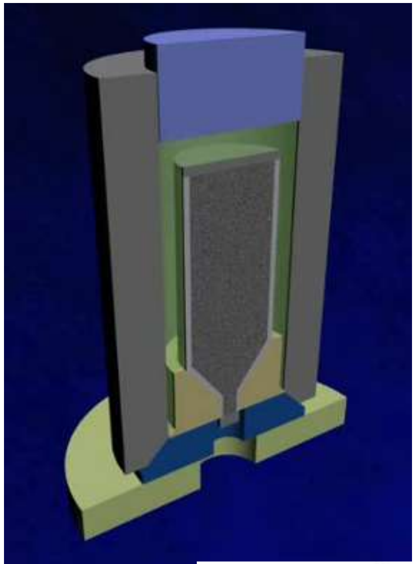
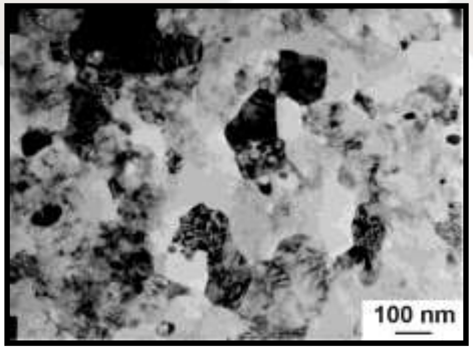
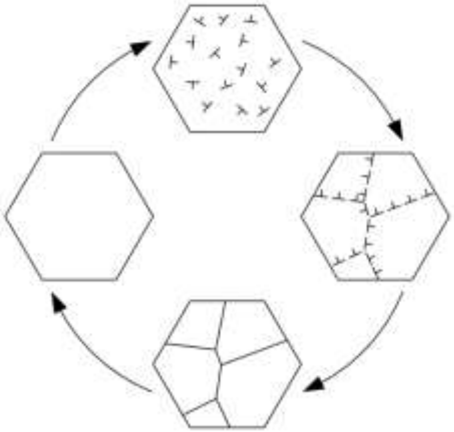
Processing techniques

Severe plastic deformation









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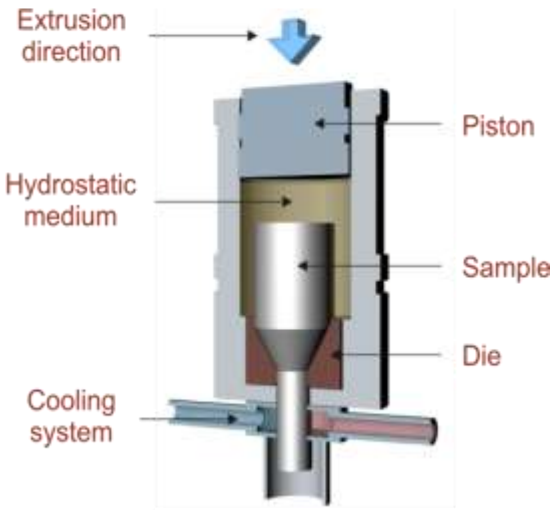
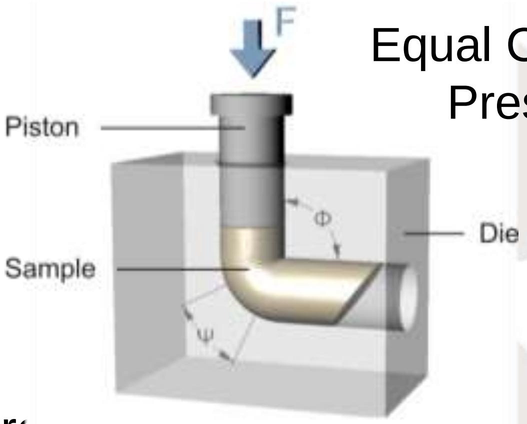
Processing techniques

Severe plastic deformation

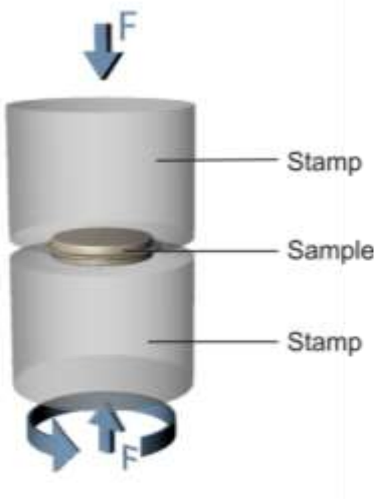
Hydrostatic extrusion HE



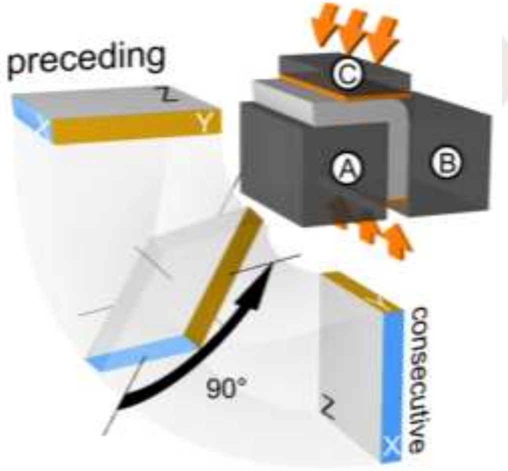
Equal Channel Angular Pressure ECAP



High Pressure Torsion HPT



Incremental ECAP



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Comparison of different fabrication routes

example of 5XXX aluminium alloys (Al-5Mg)

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Processing and properties

Al-5%Mg alloys

sample	yield strength [MPa]	ultimate tensile strength [MPa]	elongation to failure [%]
CR cold rolled (ε=0.7)	300	380	9.8
HE nano-refinement (ε=3.8)	450	545	13
PC nano-consolidation	410	465	15.5

- both nanostructured samples exhibit excellent mechanical properties, i.e. very high strength (above 400 MPa) and good ductility (elongation to failure above 10%)
- HE sample possesses higher strength whereas PC one better plasticity
- the properties of both HE and PC samples are better in terms of strength and ductility than the reference CR sample

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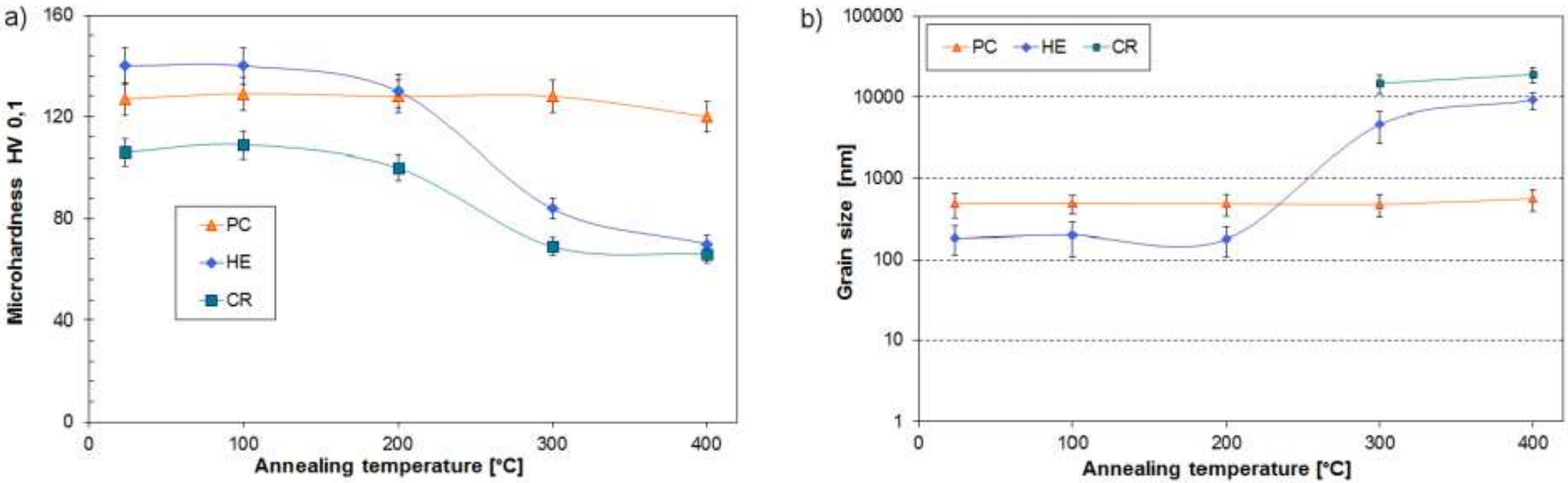
Processing and properties

Al-5%Mg alloys



- excellent thermal stability of PC sample (made of powders)
- the grain size does not change even upon annealing at 400°C for 1 hour

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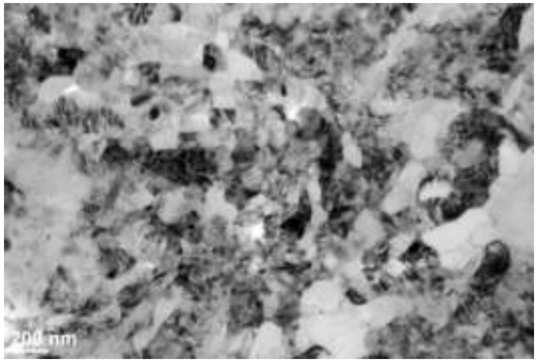
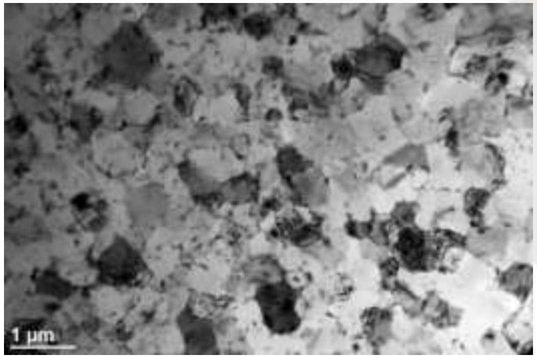
Nanoanalysis

Al-5%Mg alloys

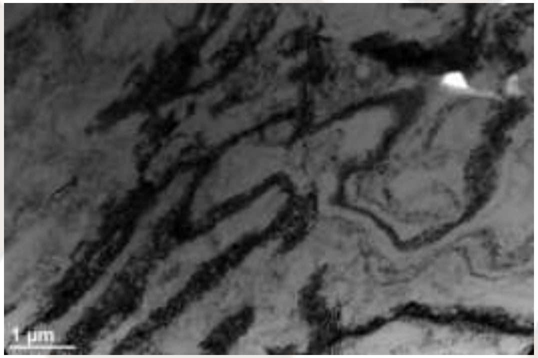
HE



PC



CR



- HE sample – smaller grain size (180 nm versus 480 for PC sample)
- HE sample – higher dislocation density

superposition of strengthening mechanisms:

$$\sigma_y = \Delta\sigma_p + \Delta\sigma_{SS} + \Delta\sigma_d + \Delta\sigma_{GB}$$

particles solid solution dislocations grain boundaries

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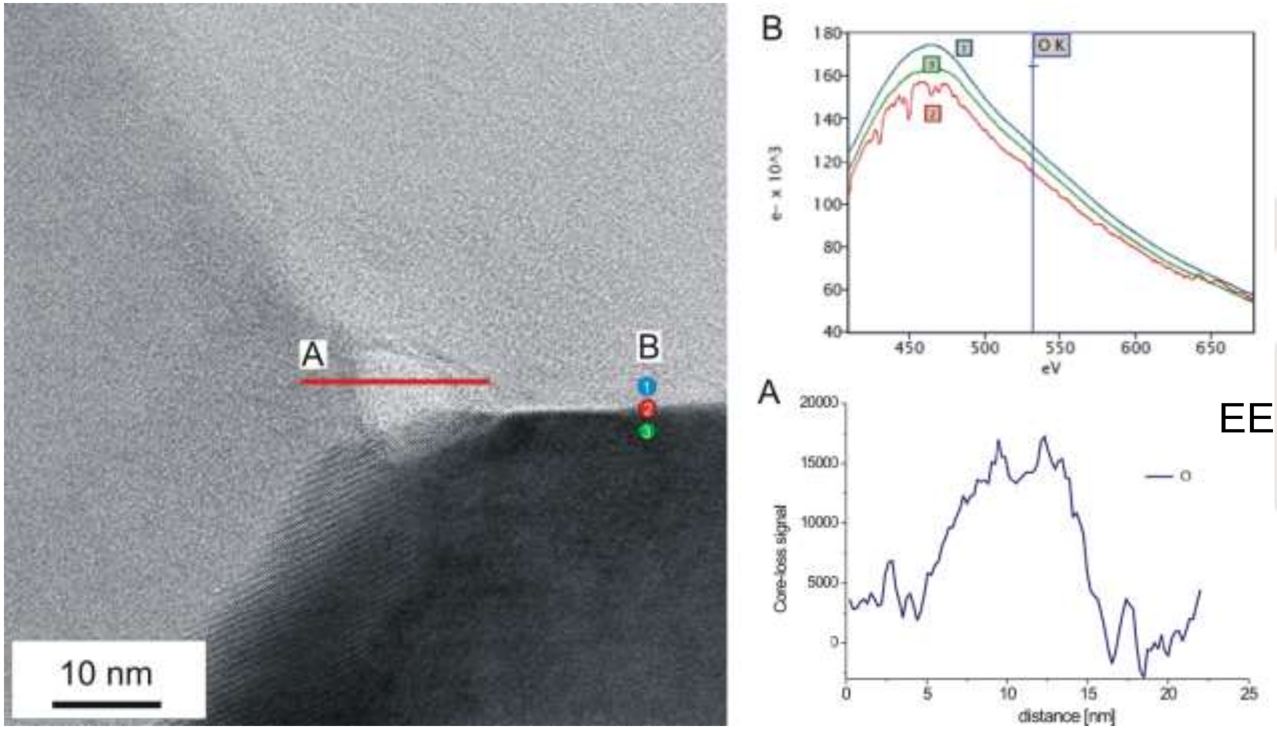
Nanoanalysis

Al-5%Mg alloys



EELS spectra

- ➢ no evidence of oxygen at grain boundaries
- ➢ small oxide particles at triple points

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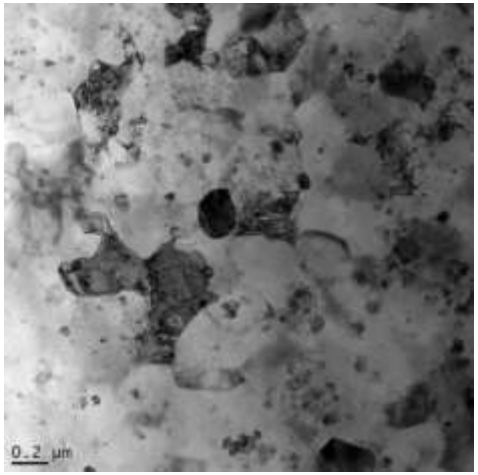
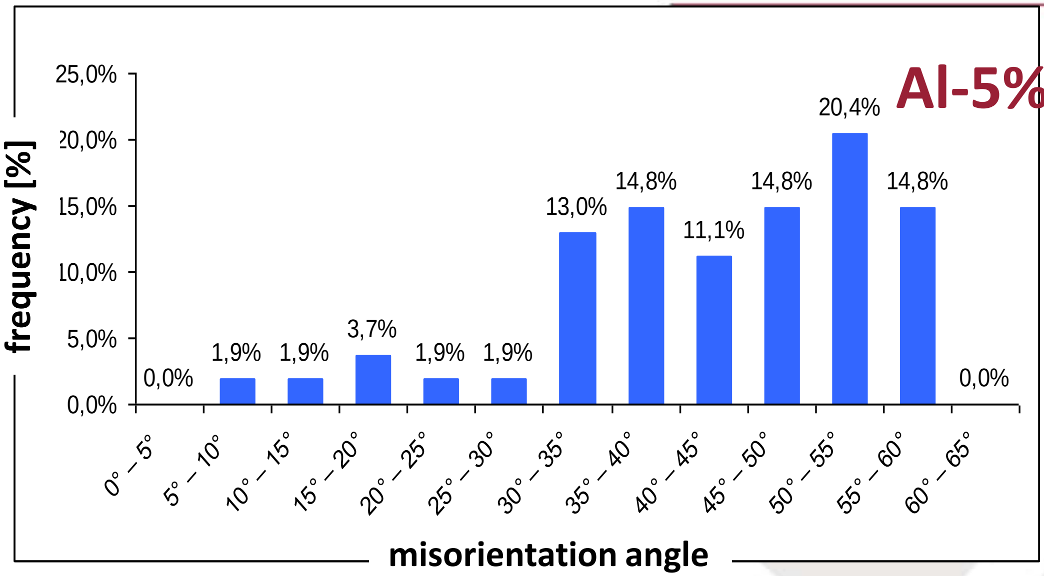
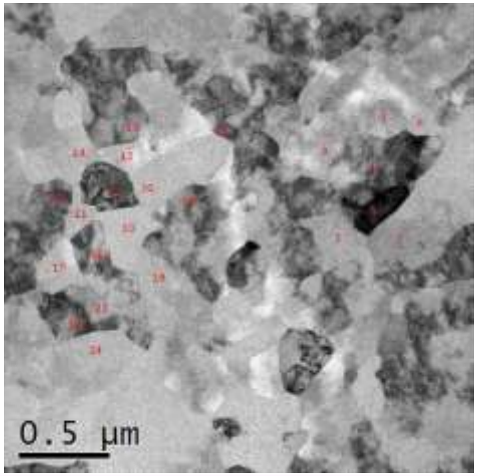
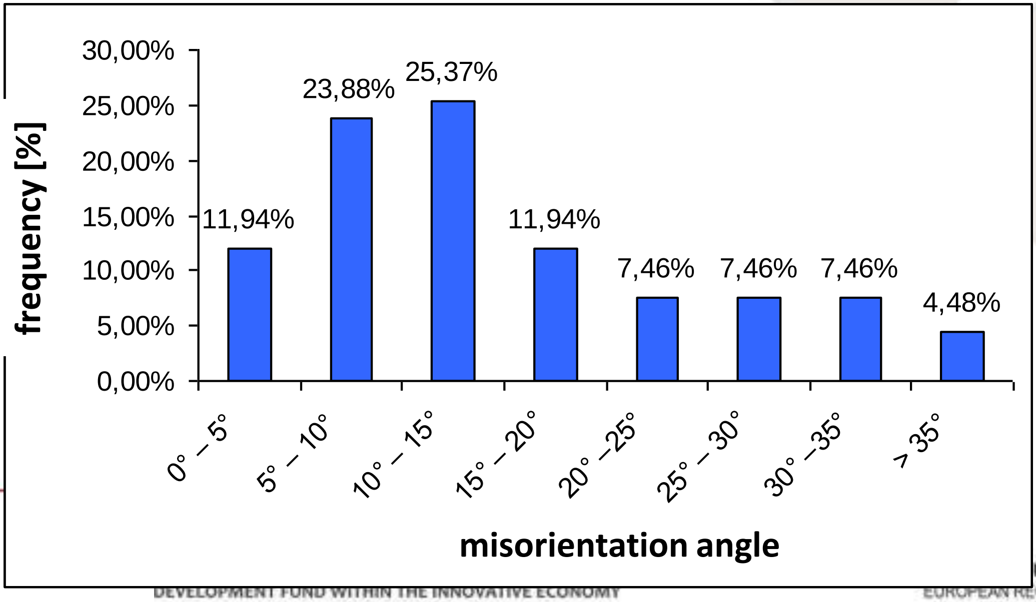
Nanoanalysis

Al-5%Mg alloys









Summary #1

Al-5%Mg alloys

1. Nano-engineering provides an unique opportunity to improve mechanical properties (both strength and ductility) of Al-Mg alloys.
2. Using described technologies, namely HE and PC, high performance materials can be obtained in relatively large quantities, which makes them useful for industrial applications.
3. Although PC route brings about a slightly higher grain size and in turn lower strength, it imparts superior thermal stability.
4. High thermal stability of PC sample can be attributed to the presence of nano-oxides and the dominating fraction of high angle grain boundaries.

Applications of nanometals

Transport – lightweight structures

Bioengineering – implant materials

Energy - electrical conductors

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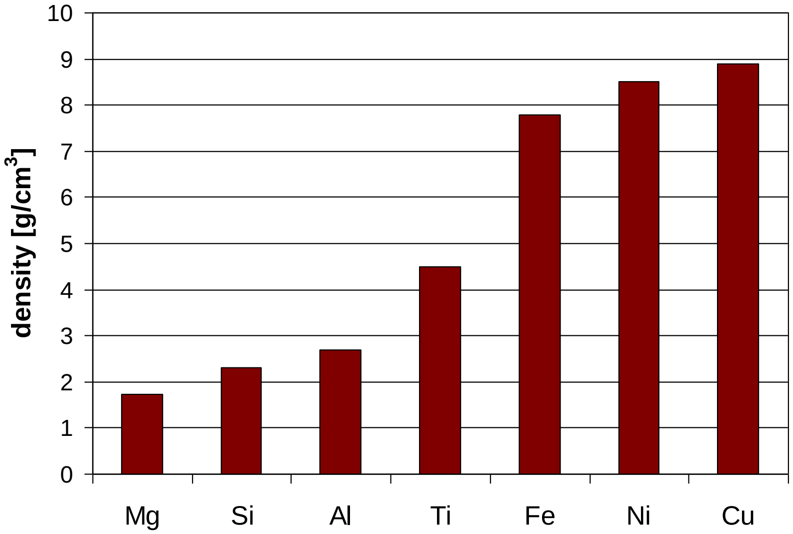
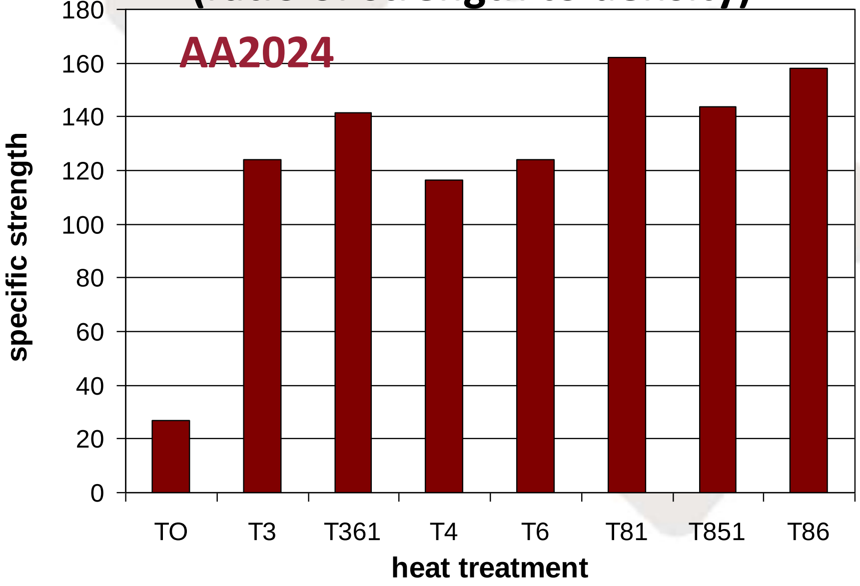
Lightweight structures

Lightweight is one of the most required features of engineering materials

Lightweight in absolute terms



Lightweight in relative terms (ratio of strength to density)



Improvement in strength makes the material lighter

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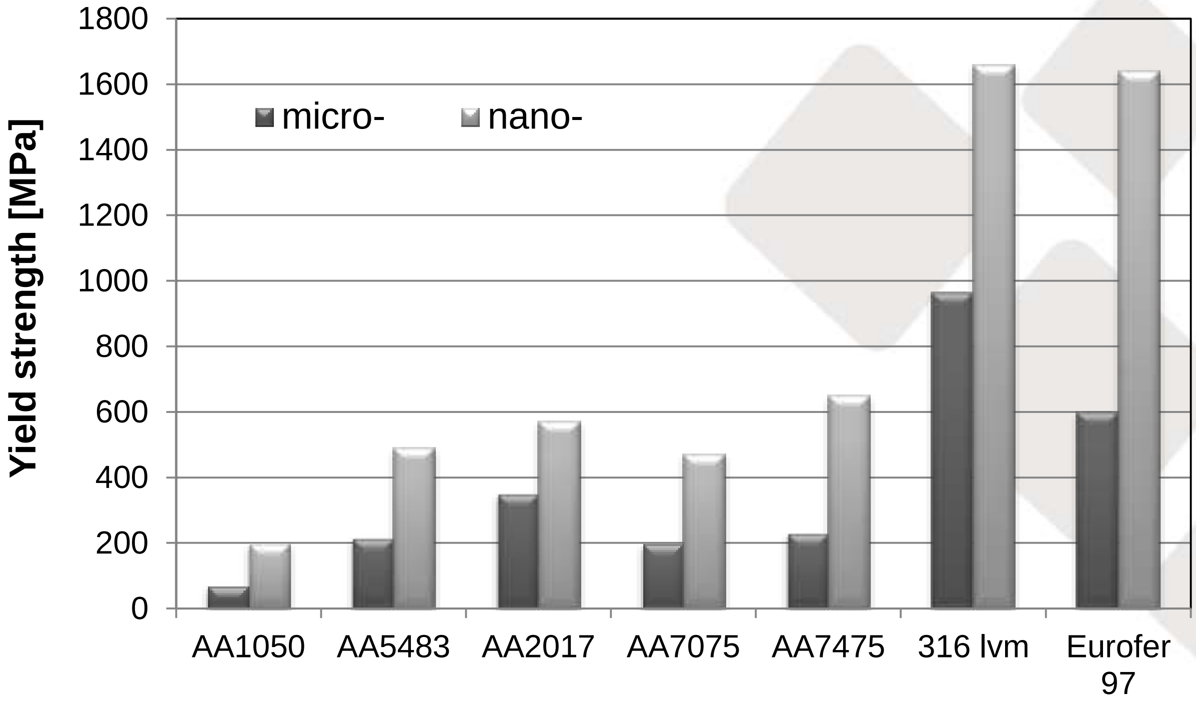
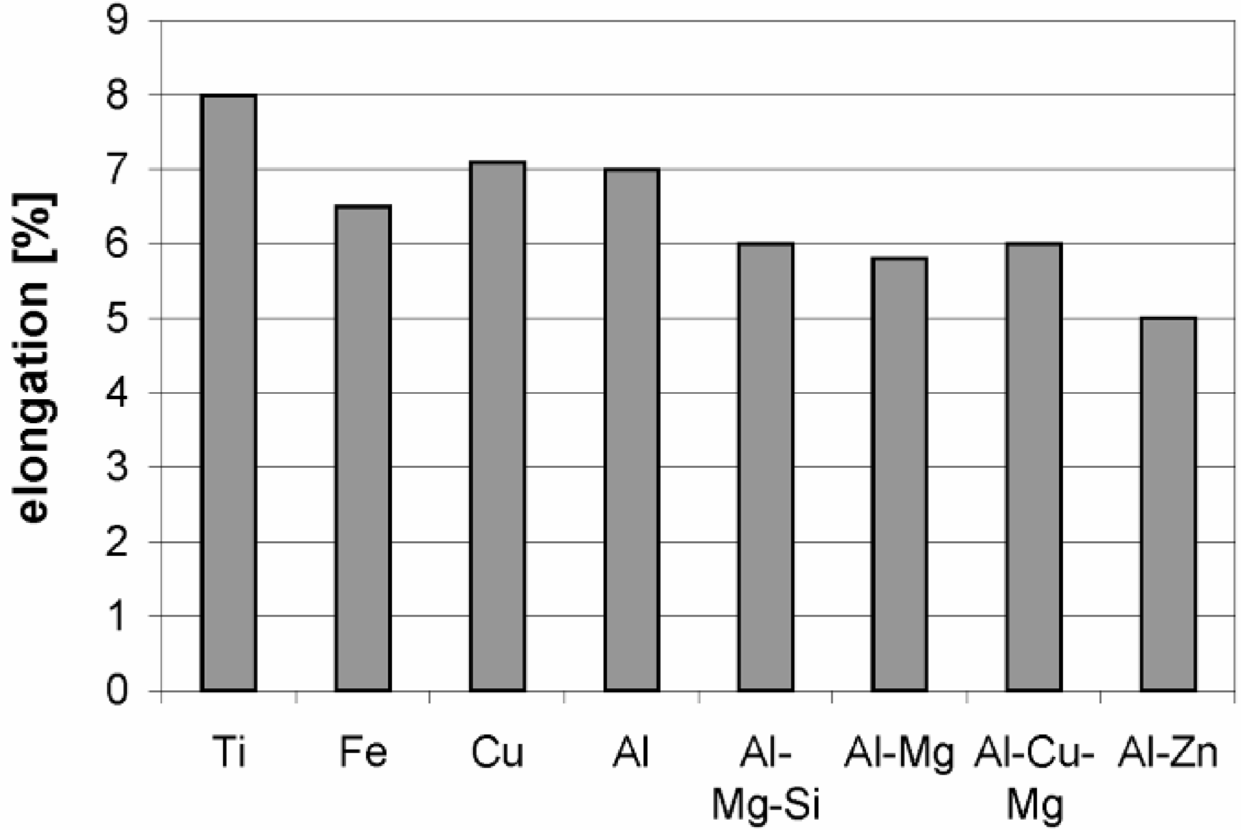
Mechanical strength



- ➢ strength of nanostructured metals is frequently higher by a factor of 2 or 3
- ➢ very high values for various materials

Plasticity



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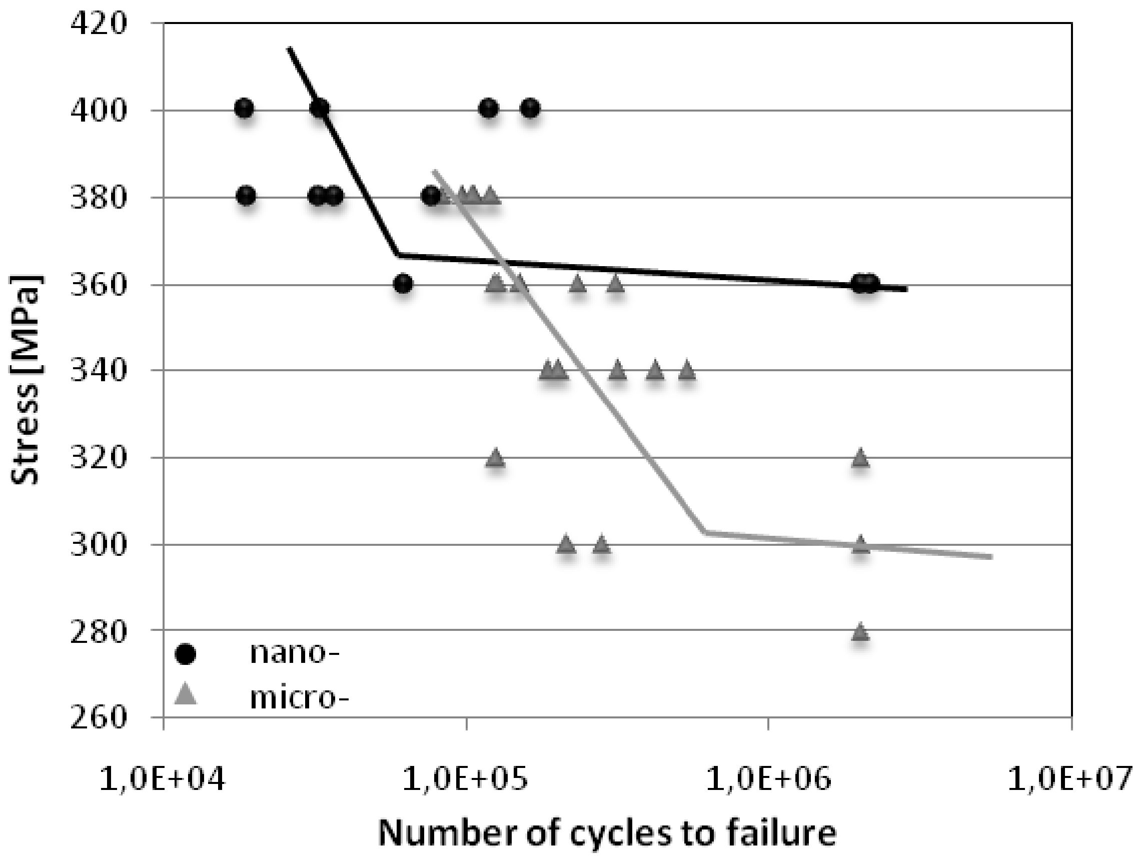
Fatigue



2017 aluminium alloy

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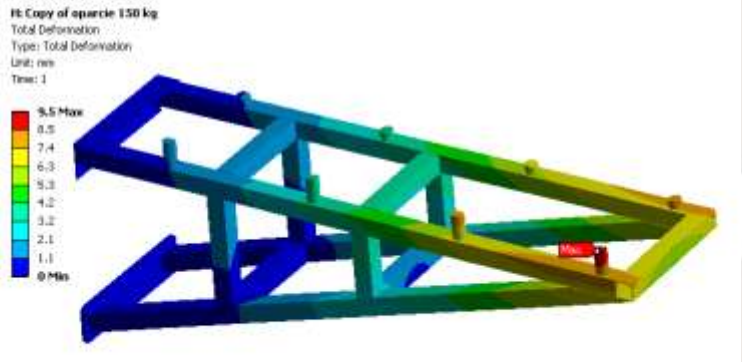
Lightweight structures



	max		
material	displacements [mm]	stress [%YS]	mass [kg]
6063 CG	4.3	0.96 YS	5.64
5083 UFG	9.5	0.99 YS	2.92

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Bio-engineering

Titanium based materials for medical implants

material	advantages	drawbacks	solution
Ti-6Al-4V The most commonly used	Good corrosion resistance High biocompatibility High strength and fatigue resistance	Release of Al and V	Pure Ti
CP titanium	Excellent corrosion resistance High biocompatibility	Insufficient strength	Grain size refinement

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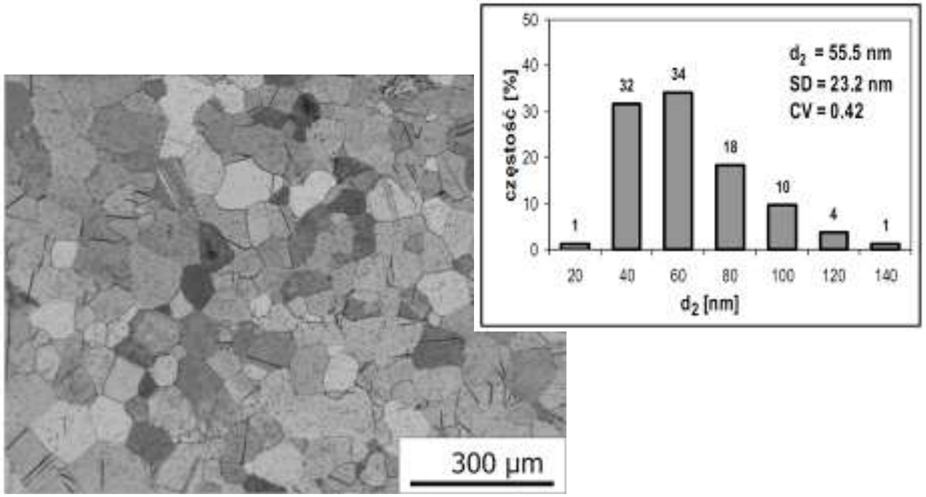

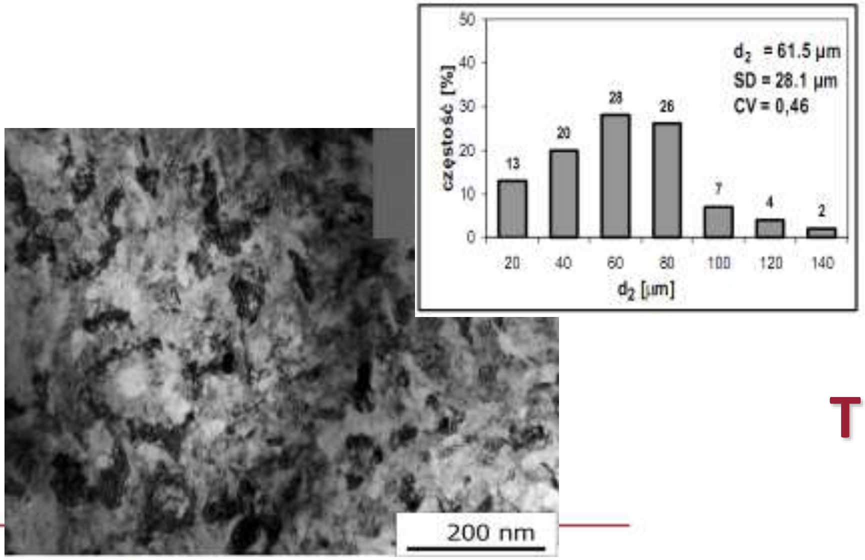

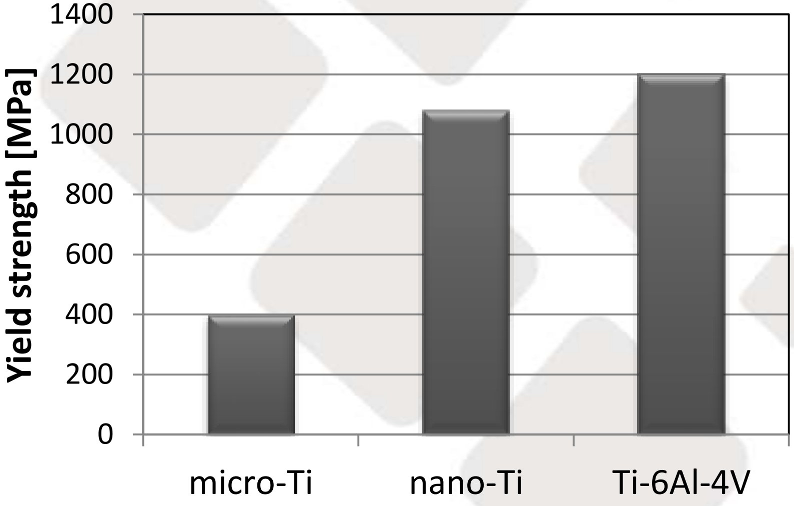

The yield strength of nano-titanium is similar to Ti-Al-V alloy

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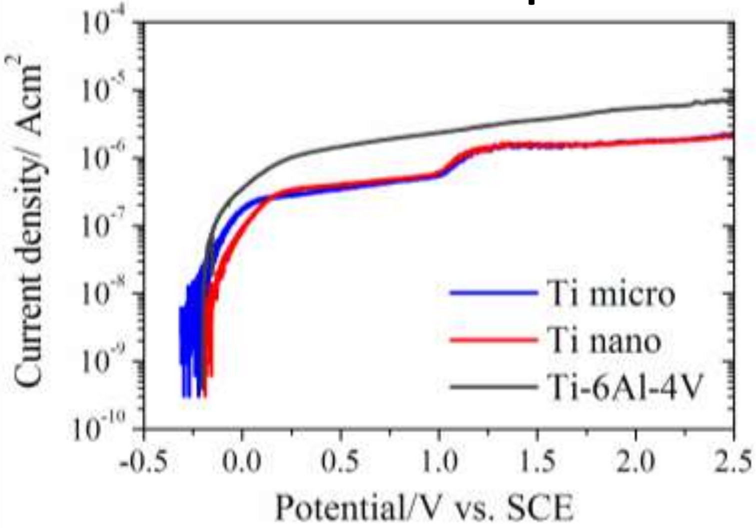
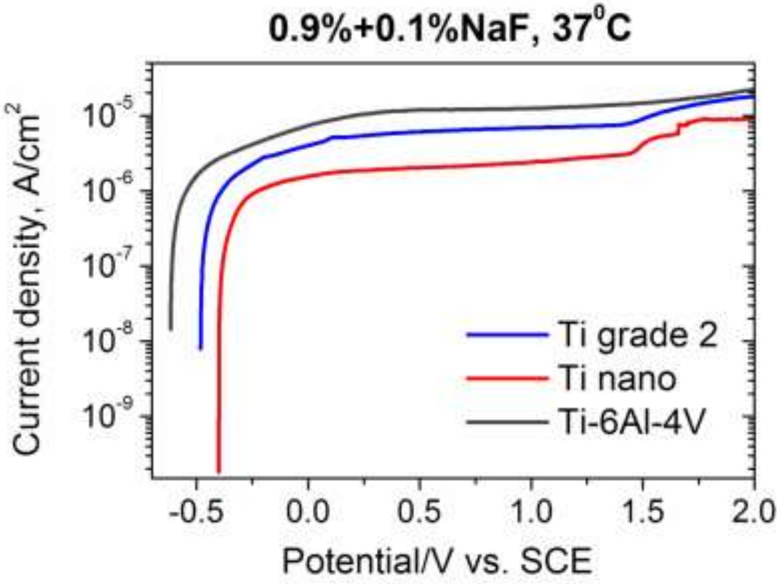
Bio-engineering


0.9% NaCl of pH 7.4


0.9%+0.1%NaF, 37°C

Corrosion resistance of nano-Ti better than microcystalline counterparts in a number of environments

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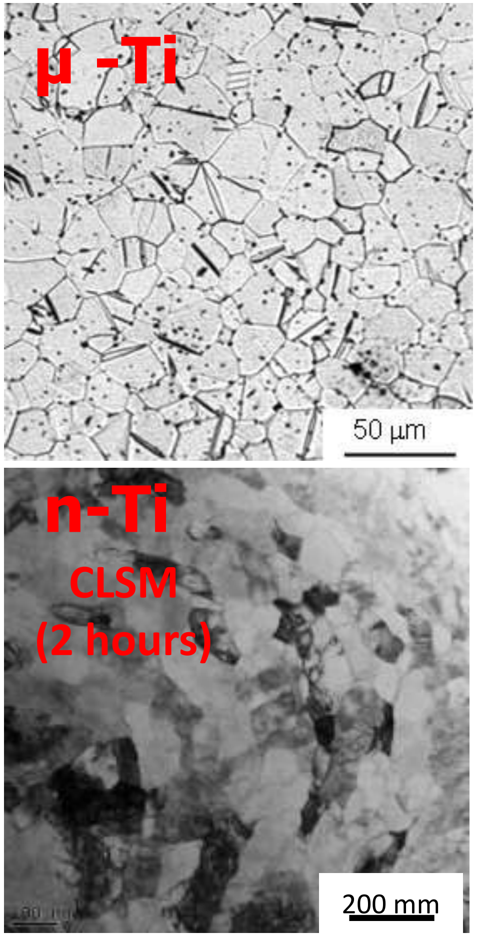

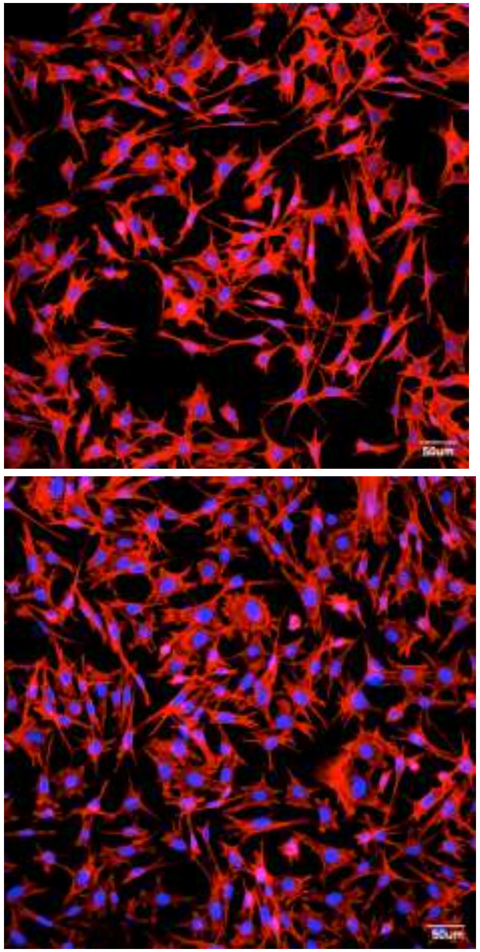

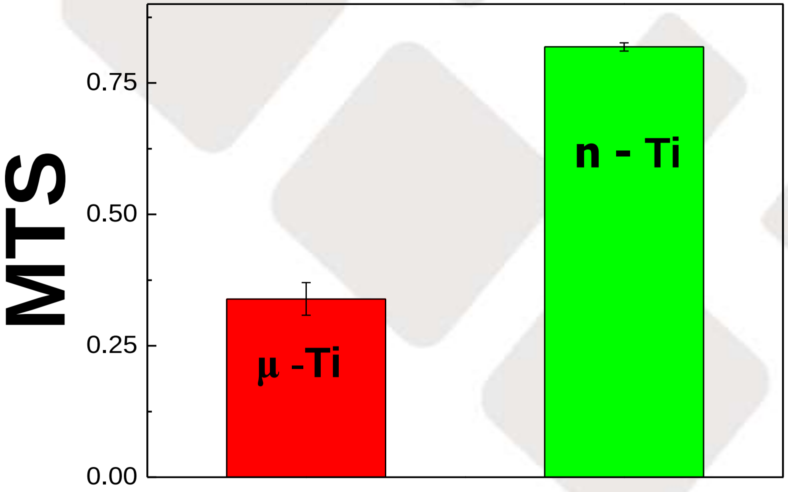

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CP titanium	Excellent corrosion resistance High biocompatibility	Insufficient strength	Grain size refinement
Nano-titanium	Excellent corrosion resistance High biocompatibility High strength	Too high elastic modulus - stress shielding effect	New generation of b-titanium alloys
β-titanium alloys	Excellent corrosion resistance High biocompatibility Low elastic modulus	Insufficient strength	Grain size refinement

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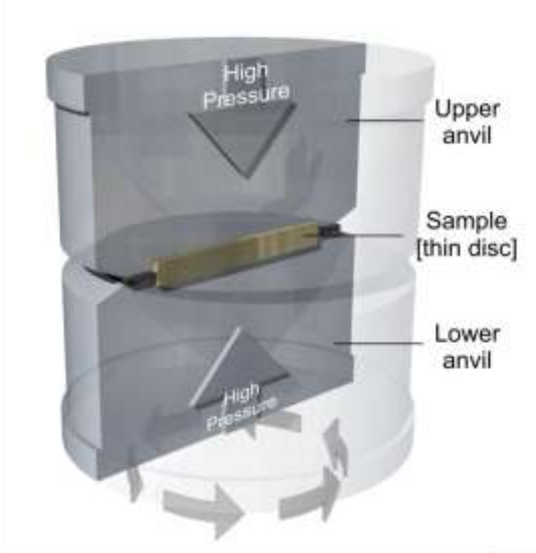
Bio-engineering

High pressure torsion



- Efficient way of grain size refinement - possibility to accumulate very high strain
- Although strain is non-homogenous at sample radius, fully homogenous samples can be obtained for high strain

Ti-24Nb-4Zr-8Sn

- Disk-shaped specimens (10 mm in diameter, 0.8 mm in height)
- Pressure 3.0 GPa
- 1, 5, 10, 20 and 50 turns
- Rotation speed 1 rpm

Sample processed by quasi-constrained high-pressure torsion

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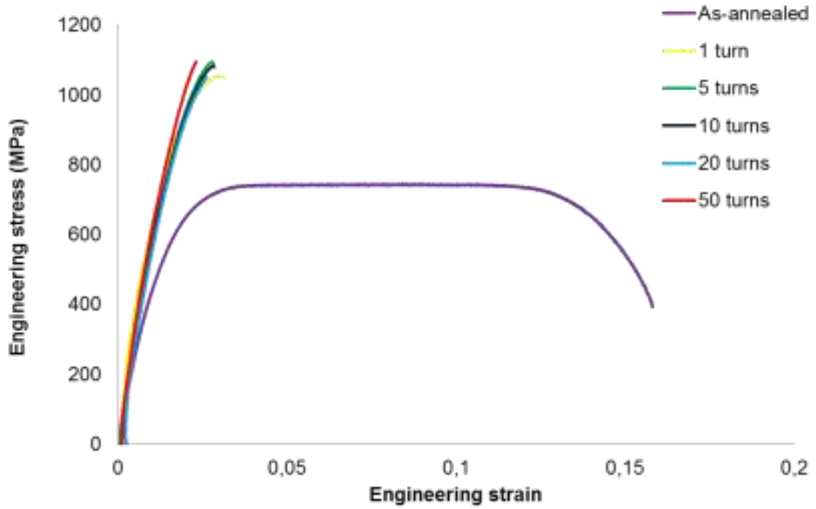
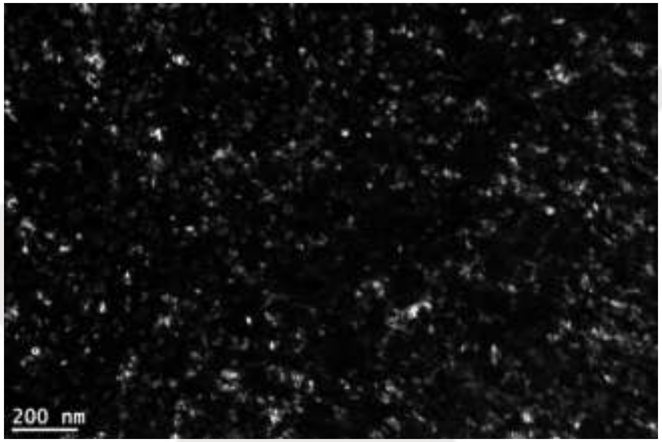
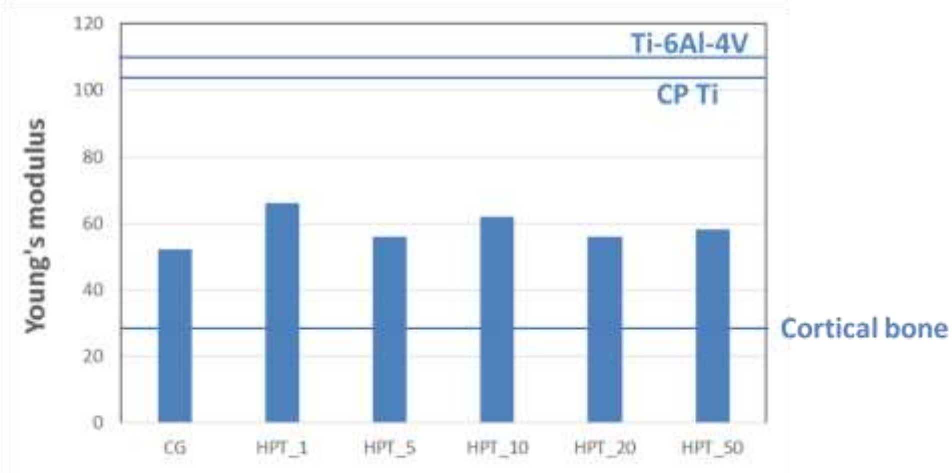
Bio-engineering







- Grain size refinement induces major changes in the mechanical properties.
- The tensile strength increases from about 700 MPa in the initial state to over 1000 MPa after processing while the Young's modulus remains at a relatively low level (less than 60 GPa).

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Electrical conductors

Aim:

to develop high strength aluminium alloys while maintaining high electrical conductivity

Challenge:

- high strength – high density of defects (grain boundaries, dislocations, precipitates, solute atoms)
- defects reduce electrical conductivity

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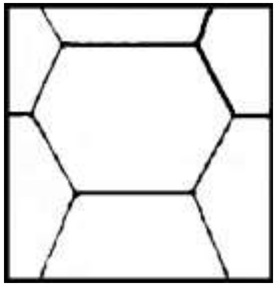
High strength

Superposition of grain boundary, dislocation and precipitation strengthening:

$$\sigma_y = \Delta\sigma_p + \Delta\sigma_d + \Delta\sigma_{GB}$$



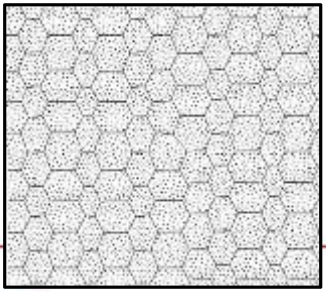
solution annealing at 520°C for 2 hours and water quenching

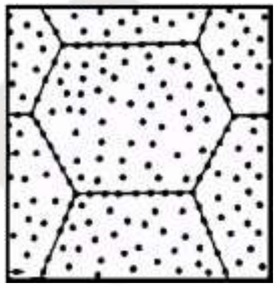
↓

grain size refinement

↓

Ageing at 100 and 160°C





Reference material: coarse grained T6

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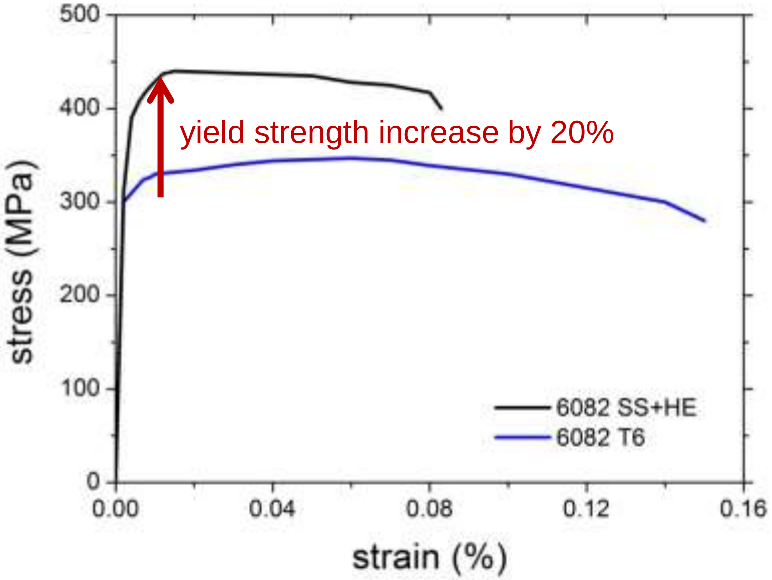
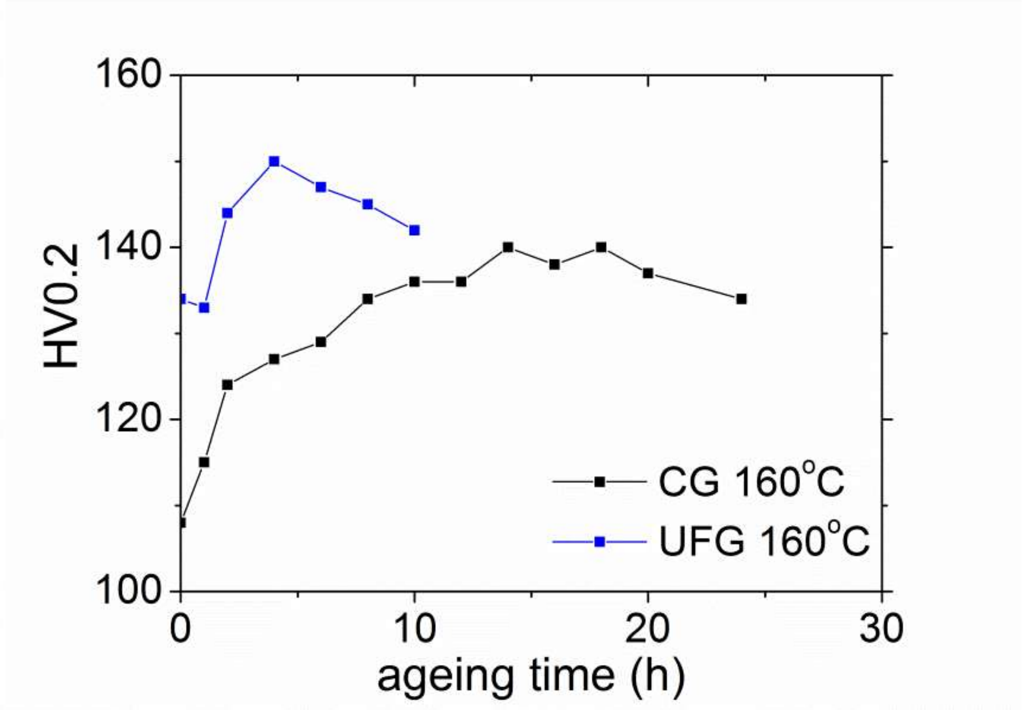
Effect of HE – mechanical properties



sample	YS [MPa]	UTS [MPa]	uniform elongation [%]	Total elongation [%]
CG T6	358	388	6	14
as-HE	436	440	1.5	8

Ageing behaviour



- both coarse grained (CG) and ultrafine grained (UFG) samples can be effectively strengthened by precipitates
- precipitation strengthening effect in UFG sample is somewhat lower than for CG one

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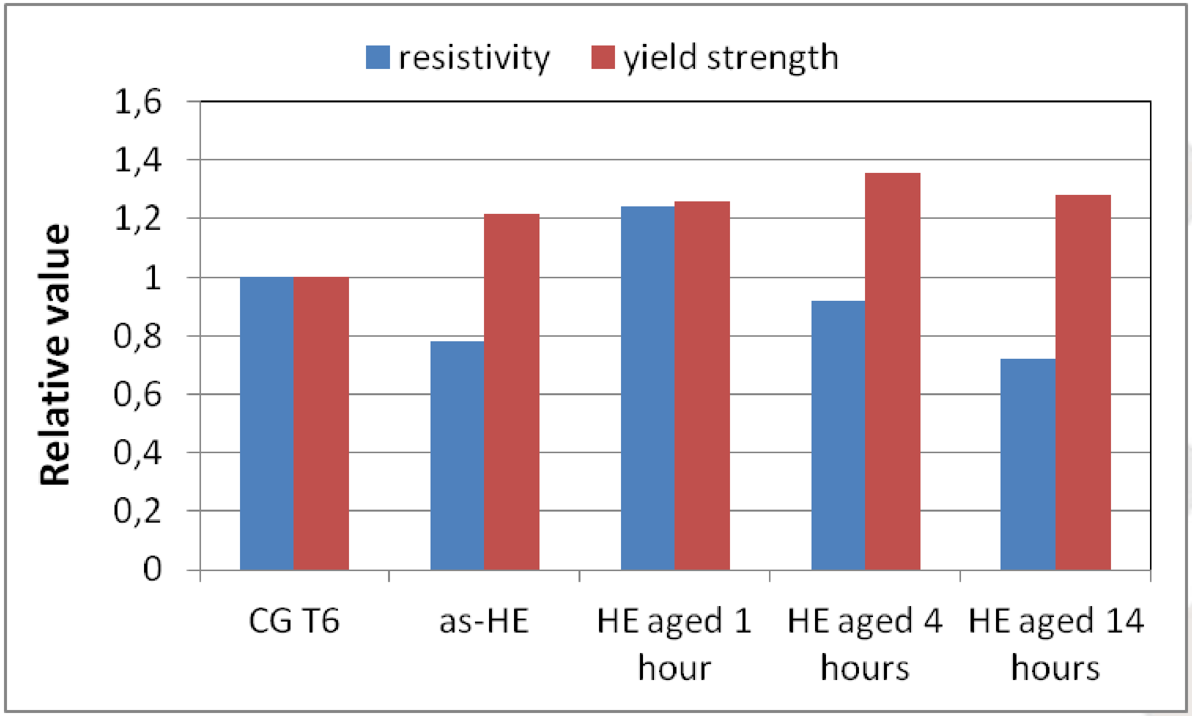
Electrical vs. mechanical properties



CG T6	S-HE	HE aged 1 hour	HE aged 4 hours	HE aged 14 hours
Grain size: 70 mm Prec.: high density Disl.: low density	Grain size: 130 nm Prec.: no Disl.: high density	Grain size: 120 nm Prec.: high density Disl.: high density	Grain size: 180 nm Prec.: high density Disl.: medium density	Grain size: 260 nm Prec.: medium density Disl.: low density

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Summary

1. UFG materials have already passed their first tests for industrial maturity – currently available technologies allow to obtain them in relatively large quantities (in the form of plates, rods and wires)
2. The main advantage of grain refinement down to UFG regime is a significant increase in mechanical strength – UFG materials exhibit a very high strength not possible to obtain by other strengthening mechanisms
3. Also a profound improvement in many others mechanical and physical properties has been found as a result of grain size refinement.
4. This opens up the prospects for their broader application in innovative industries such as transport, energy and bioengineering.

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