Магниевые сплавы: назначение, свойства и управление ими

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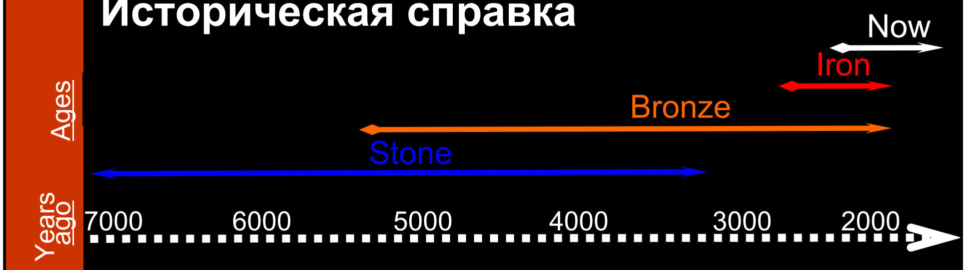
Содержание доклада

- Магний и его сплавы: сопоставление с другими материалами и потенциальные применения;
- Проблемы при разработке технологий получения изделий из магниевых сплавов;
- Ключевые элементы управления свойствами магниевых сплавов:
  - Кристаллическая решетка магния, механизмы и типичные текстуры деформации;
  - Текстуры металлических материалов (*справка*)
    - Потребность в введении такого параметра;
    - Основные понятия и методы анализа;
    - Отображение и использование информации;
  - Легирование, фазы и морфология интерметаллидов;
- Управление свойствами в магниевых сплавах на примере ЗК60;
- Новый проект

Магний и его сплавы

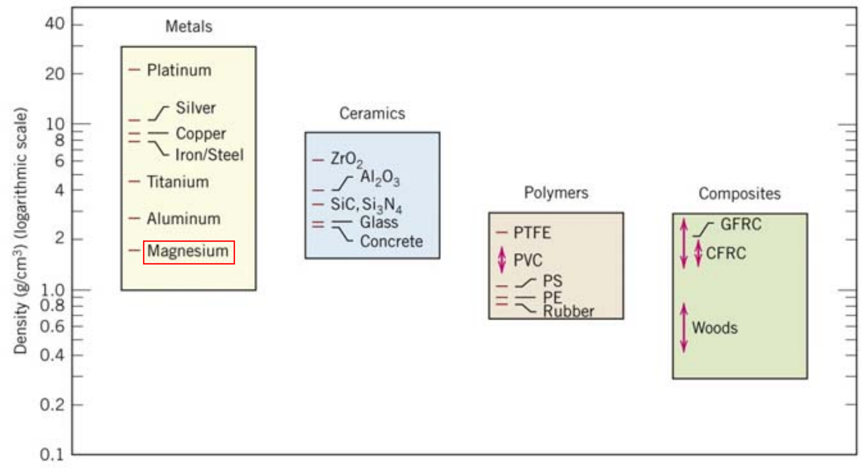
сопоставление с другими материалами

Историческая справка

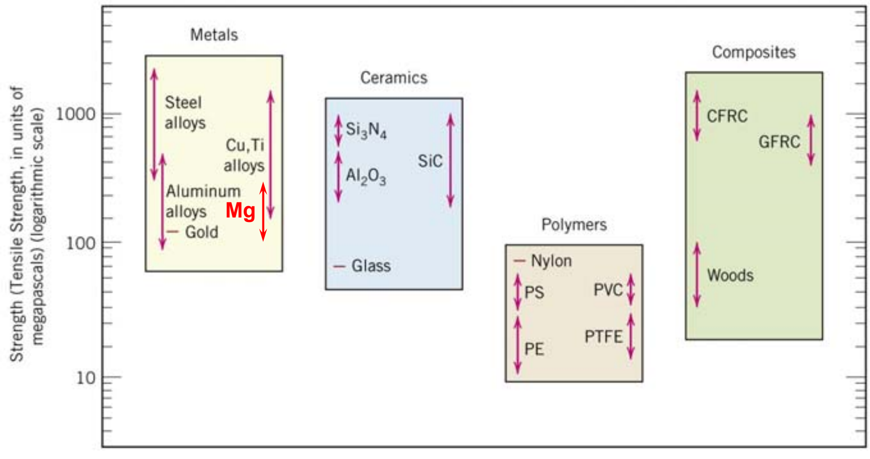


- **Materials drive our society**
  - **Stone Age**
  - **Bronze Age**
  - **Iron Age**
  - **Now?**
    - **Magnesium Age?**
    - **Polymer Age?**
    - **Silicon Age?**

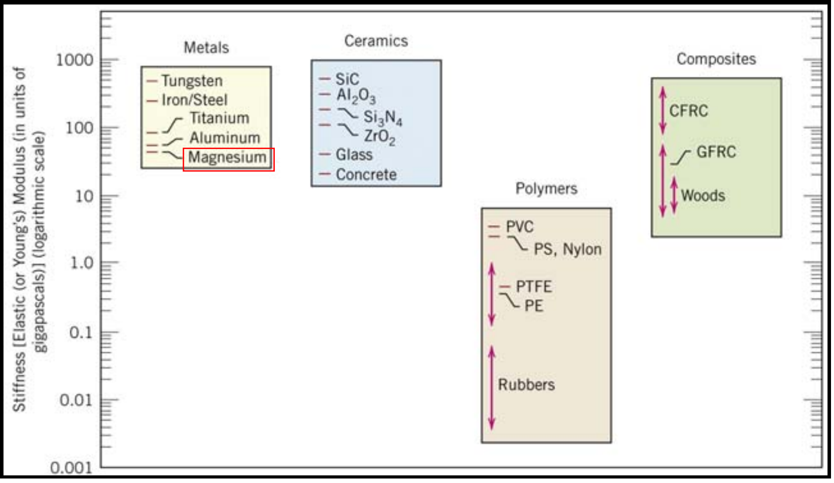
Плотность



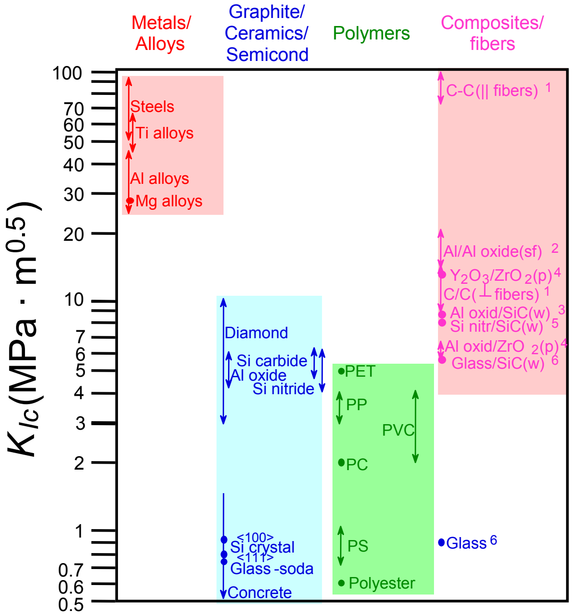
Прочность



Жесткость



Fracture Toughness

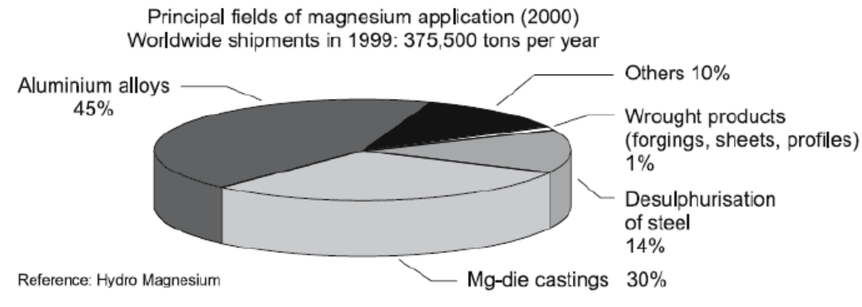


Based on data in Table B.5, *Callister & Rethwisch 8e.*

Composite reinforcement geometry is: f = fibers; sf = short fibers; w = whiskers; p = particles. Addition data as noted (vol. fraction of reinforcement):

1. (55vol%) *ASM Handbook*, Vol. 21, ASM Int., Materials Park, OH (2001) p. 606.
2. (55 vol%) Courtesy J. Cornie, MMC, Inc., Waltham, MA.
3. (30 vol%) P.F. Becher et al., *Fracture Mechanics of Ceramics*, Vol. 7, Plenum Press (1986). pp. 61-73.
4. Courtesy CoorsTek, Golden, CO.
5. (30 vol%) S.T. Buljan et al., "Development of Ceramic Matrix Composites for Application in Technology for Advanced Engines Program", ORNL/Sub/85-22011/2, ORNL, 1992.
6. (20vol%) F.D. Gace et al., *Ceram. Eng. Sci. Proc.*, Vol. 7 (1986) pp. 978-82.

Использование


Principal fields of magnesium application (2000)
Worldwide shipments in 1999: 375,500 tons per year

Reference: Hydro Magnesium

Магний и его сплавы

потенциальные применения

Make our society more sustainable through...

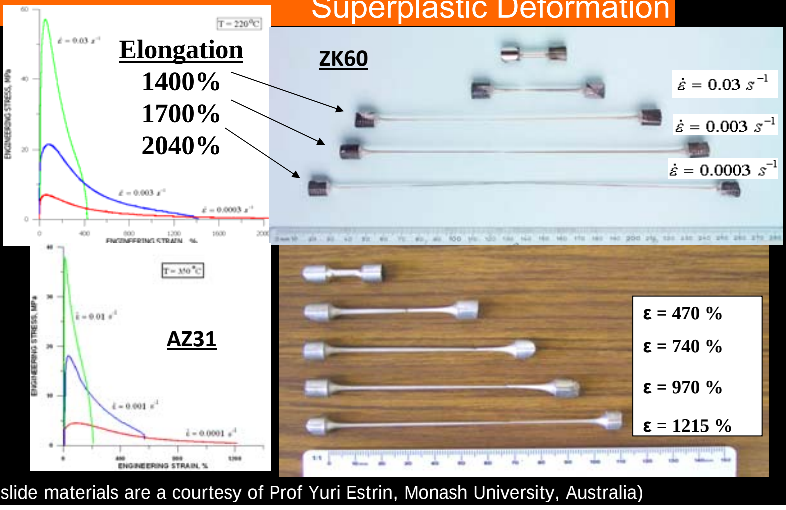
- Higher structural efficiency:
  - LIGHTER VEHICLES ➔
    - ➔ less material to construct;
    - ➔ less fuel to move;
    - ➔ improved energy absorption in collisions (safety)

Make our society more sustainable through...

- Improved functional properties:
  - NEW HORIZONS FOR DEVICES AND APPLICATIONS ➔
    - ➔ Metals for hydrogen storage;
    - ➔ ‘Clean’ and bio-resorbable implants;
    - ➔ Up to your imagination…

Ultra-fine grained Mg for…

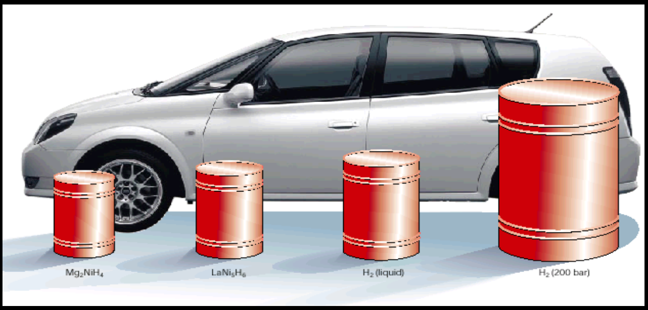
Superplastic Deformation



(The slide materials are a courtesy of Prof Yuri Estrin, Monash University, Australia)

Mg can be a material for…

Hydrogen Storage

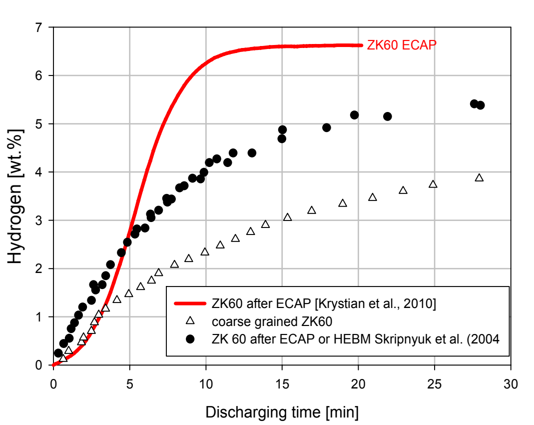


The automotive industry demands:
-at least 6-7 wt.% of H_2 in hydride;
-H_2 should be released below 200 C;
-Fast desorption kinetics

(The slide materials are a courtesy of Prof Yuri Estrin, Monash University, Australia)

Example

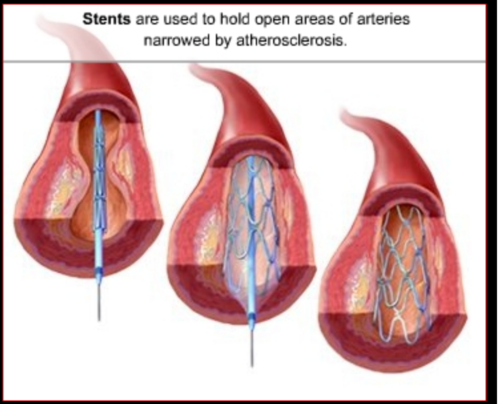
In Mg alloy ZK60



(The slide materials are a courtesy of Prof Yuri Estrin, Monash University, Australia)

Mg can be a material for…

Vascular stents



Stents are used to hold open areas of arteries narrowed by atherosclerosis.

Requirements:

-Strength $\propto 1/\sqrt{GRAIN\ SIZE}$

-Reproducibility of properties

→ ***Ultrafine granularity***

(The slide materials are a courtesy of Prof Yuri Estrin, Monash University, Australia)

Изделия из магниевых сплавов

- Проблемы при разработке технологий получения:
  - Низкая технологическая пластичность

- Возможный путь решения:
  - Литье конечных изделий;
  - Создание процессов деформационной обработки с преобладанием всестороннего сжатия в схеме нагружения;
  - Управление текстурой

Изделия из магниевых сплавов

- Проблемы при разработке технологий получения:
  - Низкая прочность

- Возможный путь решения:
  - Легирование;
  - Измельчение структуры;
  - Управление текстурой

Изделия из магниевых сплавов

- Проблемы при разработке технологий получения:
  - Низкая коррозионная стойкость

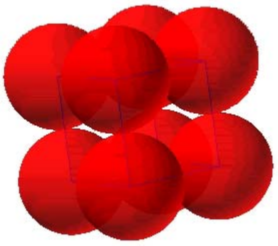
- Возможный путь решения:
  - Нанесение защитных покрытий;
  - Легирование для улучшения коррозионной стойкости по всему объему;
  - Использование эффекта

Магний и его сплавы

кристаллография и механизмы деформации

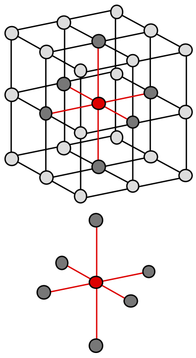
Simple Cubic Structure (SC)

- Rare due to low packing density (only Po has this structure)
- Close-packed directions are cube edges.



(Courtesy P.M. Anderson)

- Coordination # = 6
(# nearest neighbors)

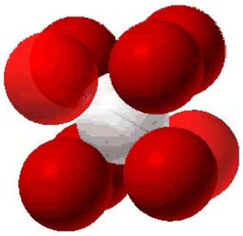


Body Centered Cubic Structure (BCC)

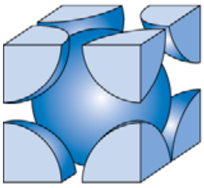
- Atoms touch each other along cube diagonals.
--Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.

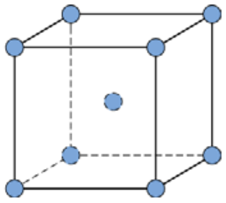
ex: Cr, W, Fe (α), Tantalum, Molybdenum

- Coordination # = 8



(Courtesy P.M. Anderson)





Adapted from Fig. 3.2, *Callister & Rethwisch 8e.*

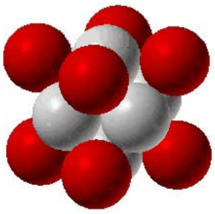
2 atoms/unit cell: 1 center + 8 corners x 1/8

Face Centered Cubic Structure (FCC)

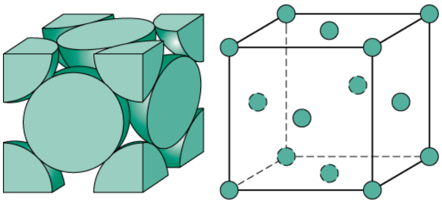
- Atoms touch each other along face diagonals.
  --Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

ex: Al, Cu, Au, Pb, Ni, Pt, Ag

- Coordination # = 12



(Courtesy P.M. Anderson)

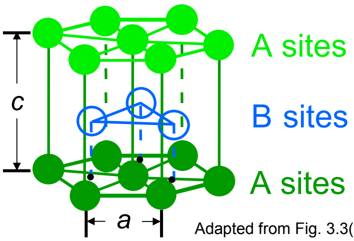


Adapted from Fig. 3.1, *Callister & Rethwisch 8e.*

4 atoms/unit cell: 6 face x 1/2 + 8 corners x 1/8

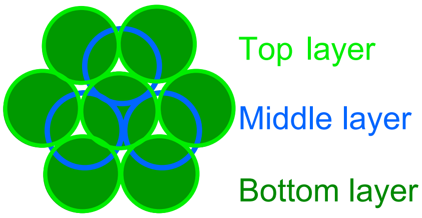
Hexagonal Close-Packed Structure (HCP)

- 3D Projection



Adapted from Fig. 3.3(a), *Callister & Rethwisch 8e.*

- 2D Projection



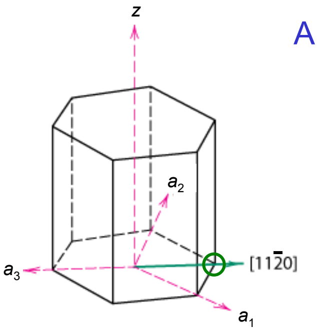
- Coordination # = 12

6 atoms/unit cell

ex: Cd, Mg, Ti, Zn

- *c*/*a* = 1.633

HCP Crystallographic Directions



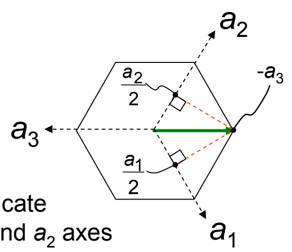
Adapted from Fig. 3.8(a), *Callister & Rethwisch 8e.*

Algorithm

1. Vector repositioned (if necessary) to pass through origin.
2. Read off projections in terms of unit cell dimensions a_1, a_2, a_3, or c
3. Adjust to smallest integer values
4. Enclose in square brackets, no commas

[*uvtw*]

ex: ½, ½, -1, 0 => [11$\bar{2}$0]



dashed red lines indicate projections onto a_1 and a_2 axes

HCP Crystallographic Directions

- Hexagonal Crystals
  - 4 parameter Miller-Bravais lattice coordinates are related to the direction indices (i.e., *u'v'w'*) as follows.

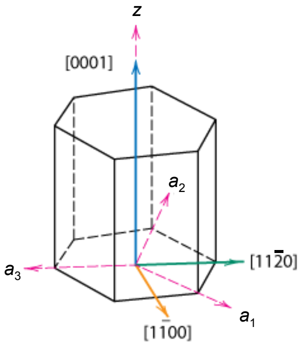


Fig. 3.8(a), *Callister & Rethwisch 8e.*

$$[u'v'w'] \rightarrow [uvtw]$$

$$u = \frac{1}{3}(2u' - v')$$

$$v = \frac{1}{3}(2v' - u')$$

$$t = -(u + v)$$

$$w = w'$$

Crystallographic Planes

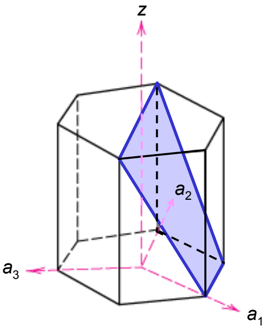
- Miller Indices: Reciprocals of the (three) axial intercepts for a plane, cleared of fractions & common multiples. All parallel planes have same Miller indices.

- Algorithm
  1. Read off intercepts of plane with axes in terms of *a*, *b*, *c*
  2. Take reciprocals of intercepts
  3. Reduce to smallest integer values
  4. Enclose in parentheses, no commas i.e., (*hkl*)

Crystallographic Planes (HCP)

example	a_1	a_2	a_3	c
1. Intercepts	1	∞	-1	1
2. Reciprocals	1	$1/\infty$	-1	1
	1	0	-1	1
3. Reduction	1	0	-1	1

4. Miller-Bravais Indices $(10\bar{1}1)$

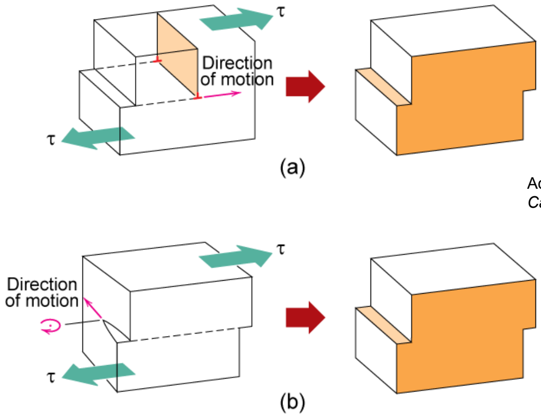


Adapted from Fig. 3.8(b), *Callister & Rethwisch 8e.*

Possible Deformation Mechanisms

Dislocation slip:

- A dislocation moves along a slip plane in a slip direction perpendicular to the dislocation line
- The slip direction is the same as the Burgers vector direction

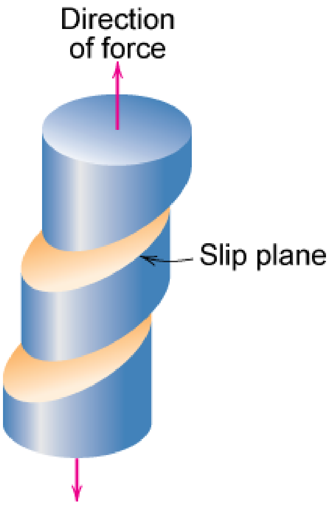


Edge dislocation

Adapted from Fig. 7.2, *Callister & Rethwisch 8e.*

Screw dislocation

Single Crystal Slip



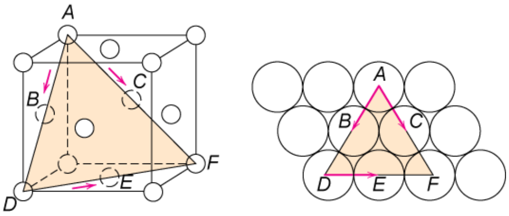
Adapted from Fig. 7.8, *Callister & Rethwisch 8e.*

Adapted from Fig. 7.9, *Callister & Rethwisch 8e.*

Deformation Mechanisms

Slip System

- Slip plane - plane on which easiest slippage occurs
  - Highest planar densities (and large interplanar spacings)
- Slip directions - directions of movement
  - Highest linear densities



(a) (b)

Adapted from Fig. 7.6, *Callister & Rethwisch 8e.*

- FCC Slip occurs on {111} planes (close-packed) in <110> directions (close-packed)

  => total of 12 slip systems in FCC
- For BCC & HCP there are other slip systems.

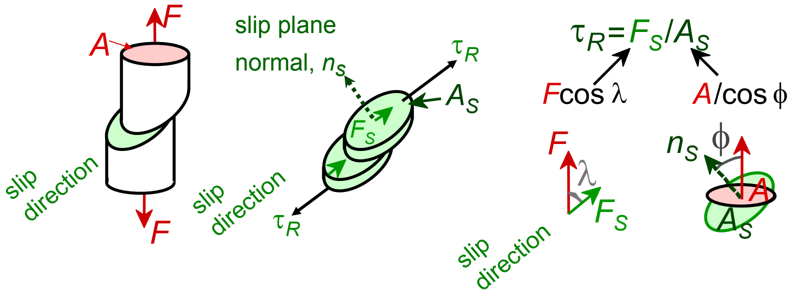
Stress and Dislocation Motion

- Resolved shear stress, τ_R
  - results from applied tensile stresses

Applied tensile stress: $\sigma = F/A$

Resolved shear stress: $\tau_R = F_S/A_S$

Relation between σ and τ_R



$$\tau_R = \sigma \cos\lambda \cos\phi$$

Critical Resolved Shear Stress

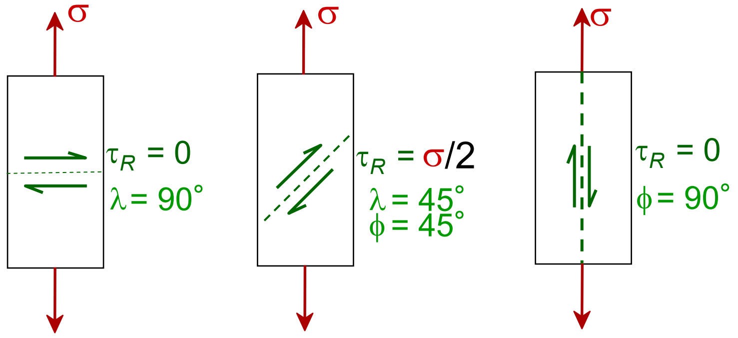
- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

typically

10^{-4} GPa to 10^{-2} GPa

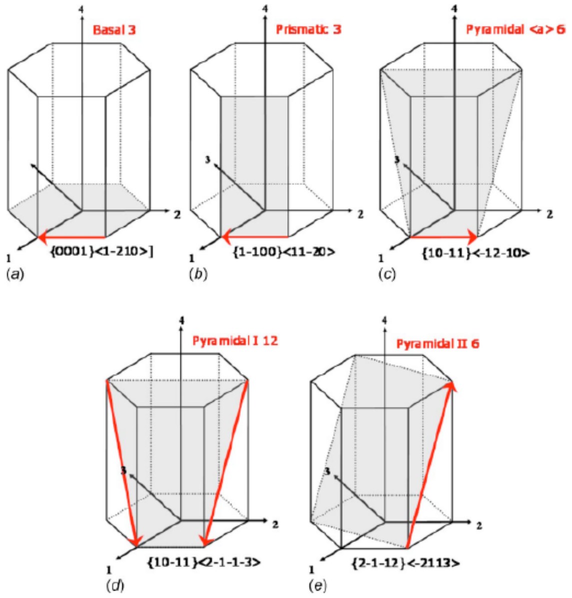
- Ease of dislocation motion depends on crystallographic orientation

$\tau_R = \sigma \cos\lambda \cos\phi$



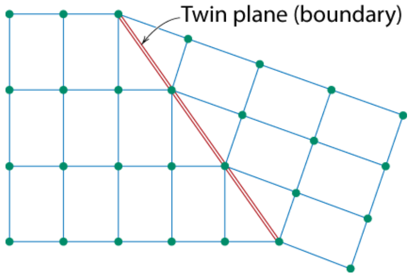
τ maximum at $\lambda = \phi = 45°$

Dislocation slip systems in Mg



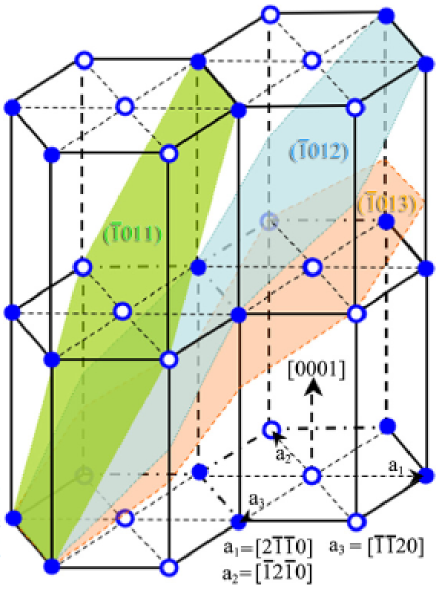
Possible Deformation Mechanisms

- TWINNING
- Twin boundary (plane)
  - Essentially a reflection of atom positions across the twin plane.



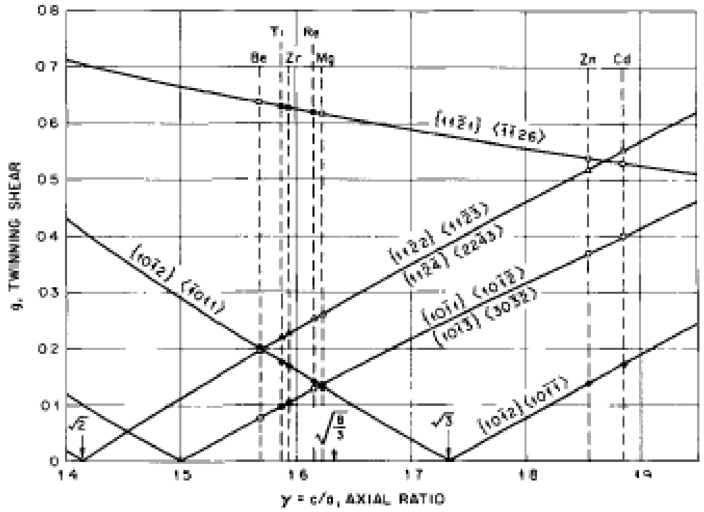
Adapted from Fig. 4.9, *Callister & Rethwisch 8e.*

Twinning in Mg



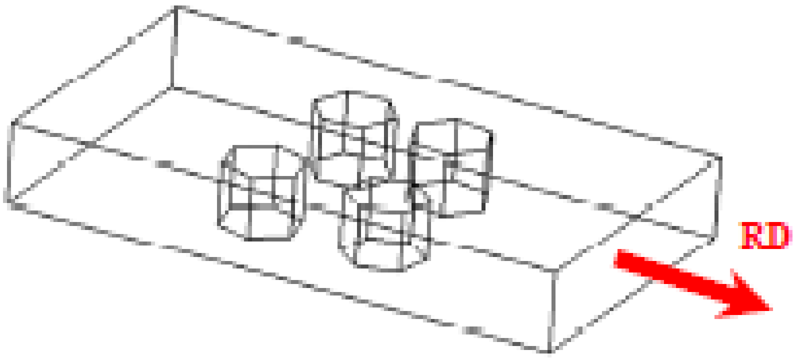
An hcp crystal lattice showing three twinning planes, $(\bar{1}011)$, (1012) and $(\bar{1}013)$, which share the common zonal axis parallel to $[\bar{1}2\bar{1}0]$. Atoms are represented with solid circles in A-type $(\bar{1}2\bar{1}0)$ plane and empty circles in B-type $(\bar{1}2\bar{1}0)$ plane. The spacing between adjacent A-type and B-type $(\bar{1}2\bar{1}0)$ planes is equal to $a/2$, where a is the lattice constant. The intermediate basis layers of the hcp crystal are omitted for clarity.

Direction of twinning in HCP metals



Variation of twinning shear with the axial ratio. For t hexagonal metals, a filled symbol indicates that the twin mod active mode.

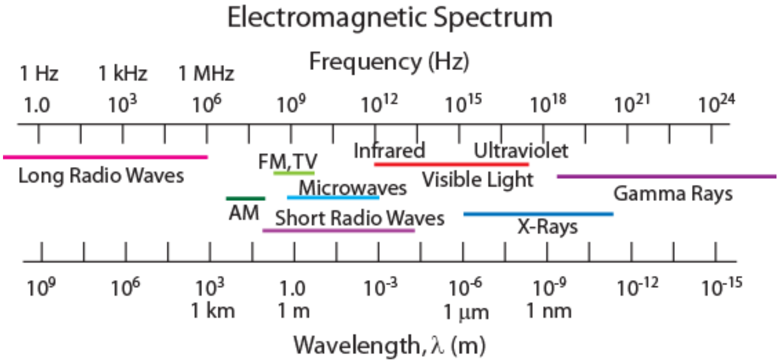
Typical rolling texture of Mg



справка

текстуры металлических материалов

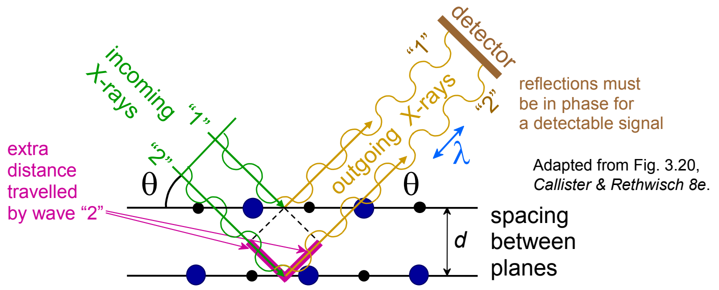
X-Ray Diffraction



- Diffraction gratings must have spacings comparable to the wavelength of diffracted radiation.
- Can’t resolve spacings < λ
- Spacing is the distance between parallel planes of atoms.

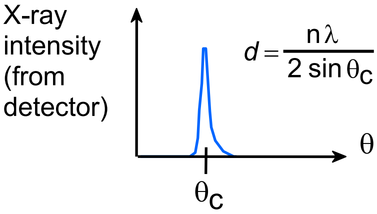
X-Rays to Determine Crystal Structure

- Incoming X-rays diffract from crystal planes.



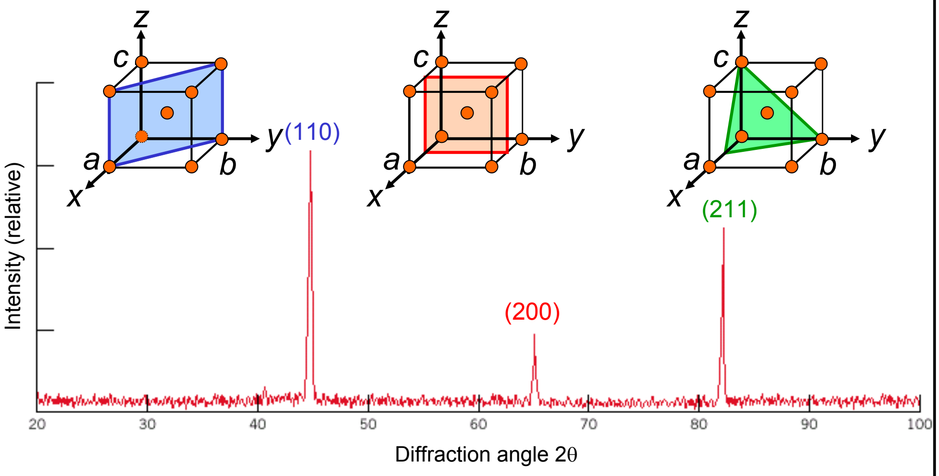
Adapted from Fig. 3.20, *Callister & Rethwisch 8e*.

Measurement of critical angle, θ_c, allows computation of planar spacing, *d*.



$$d = \frac{n\lambda}{2\sin\theta_c}$$

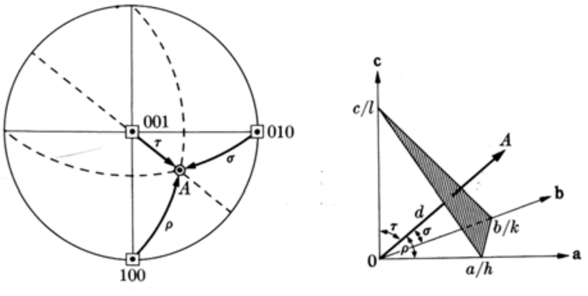
X-Ray Diffraction Pattern



Diffraction pattern for polycrystalline α-iron (BCC)

Miller indices of a pole

Miller indices are a convenient way to represent a **direction** or a **plane normal** in a crystal, based on **integer multiples** of the **repeat distance** parallel to each axis of the **unit cell** of the **crystal lattice**. This is simple to understand for cubic systems with equiaxed Cartesian coordinate systems but is more complicated for systems with lower crystal symmetry. **Directions** are simply defined by the set of multiples of lattice repeats in each direction. **Plane normals** are defined in terms of **reciprocal** intercepts on each axis of the unit cell.



(a) (b)

When a plane is written with parentheses, (hkl), this indicates a particular plane normal: by contrast when it is written with curly braces, {hkl}, this denotes a the family of planes related by the crystal symmetry. Similarly a direction written as [uvw] with square brackets indicates a particular direction whereas writing within angle brackets , <uvw> indicates the family of directions related by the crystal symmetry.

Fig. 2–39 Determination of the Miller indices of a pole.

The Stereographic Projection

- Uses the inclination of the normal to the crystallographic plane: the points are the intersection of each crystal direction with a (unit radius) sphere

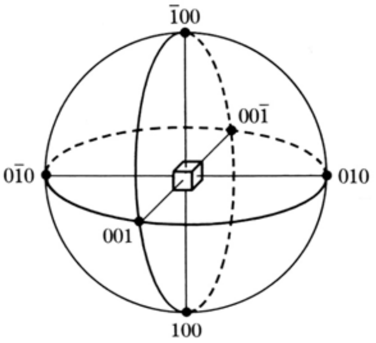


Fig. 2–25 {100} poles of a cubic crystal.

Projection from Sphere to Plane

- Projection of spherical informatior onto a flat surface
  - Equal area projectior (Schmid projection)
  - Equiangular projectic (Wulff projection, more common in crystallography)

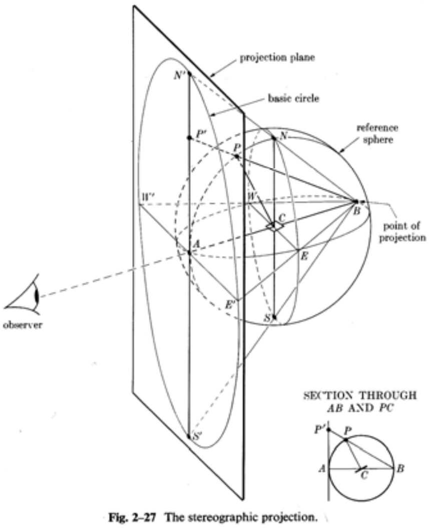
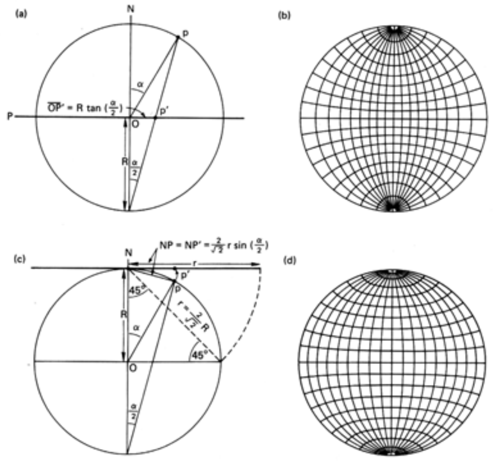


Fig. 2–27 The stereographic projection.

Stereographic, Equal Area Projections

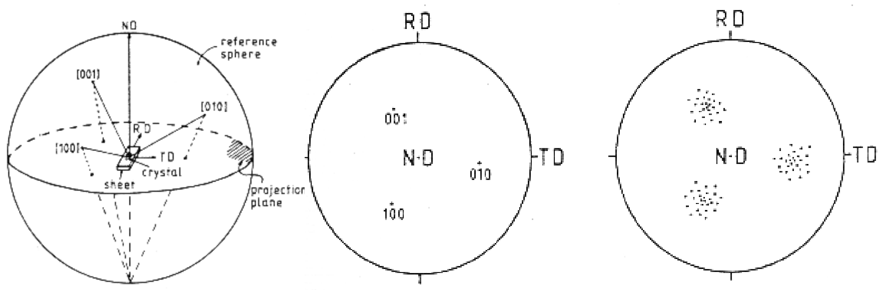
Stereographic (Wulff) Projection*: *OP'*=*R*tan(θ/2)

Equal Area (Schmid) Projection: *OP'*=*R*sin(θ/2)



Pole Figure Example

- If the goniometer is set for {100} reflections, then all directions in the sample that are parallel to <100> directions will exhibit diffraction. The example shows a crystal oriented to put all 3 <100> directions approximately equally spaced from the ND.

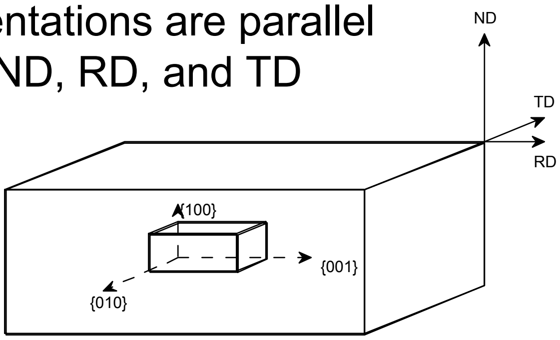


Miller Index Definition of a Crystal Orientation

- We use a set of three orthogonal directions as the reference frame. Mathematicians set up a set of **unit vectors** called e_1 e_2 *and* e_3.
- In many cases we use the names Rolling Direction (RD) // e_1, Transverse Direction (TD) // e_2, and Normal Direction (ND) // e_3.
- We then identify a crystal (or plane normal) parallel to 3rd axis (ND) and a crystal direction parallel to the 1st axis (RD), written as (hkl)[uvw].

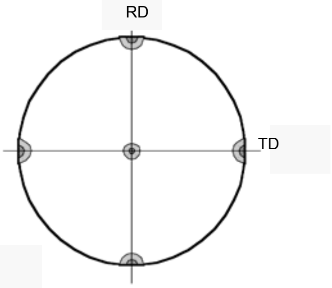
Cube Texture (100)[001]: cube-on-face

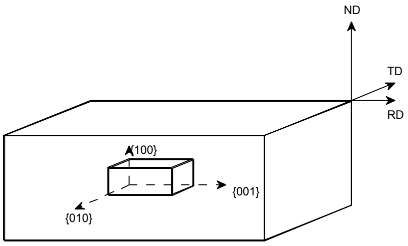
- Observed in recrystallization of *fcc* metals
- The 001 orientations are parallel to the three ND, RD, and TD directions.



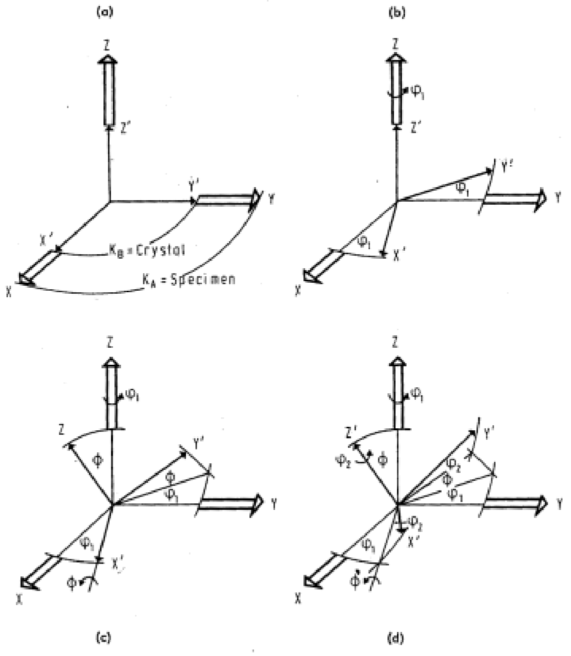
Sharp Texture (Recrystallization)

- Look at the (001) pole figures for this type of texture: maxima correspond to {100} poles in the standard stereographic projection.



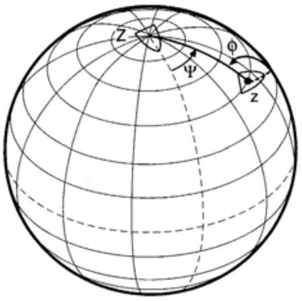


(Bunge) Euler Angle Definition



Euler Angles, Ship Analogy

- Analogy: position and the heading of a boat with respect to the globe. *Latitude (Θ)* and *longitude (ψ)* describe the position of the boat; third angle describes the *heading (ϕ)* of the boat relative to the line of longitude that connects the boat to the North Pole.

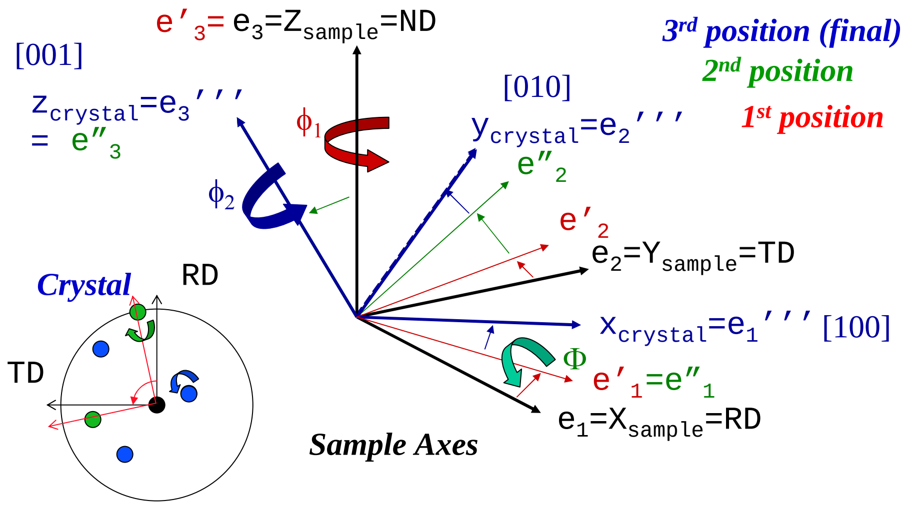


Kocks vs. Bunge angles:
to be explained later!

Meaning of Euler angles

- The first two angles, ϕ_1 and Φ, tell you the position of the [001] crystal direction relative to the specimen axes.
- Think of rotating the crystal about the ND (1st angle, ϕ_1); then rotate the crystal out of the plane (about the [100] axis, Φ);
- Finally, the 3rd angle (ϕ_2) tells you how much to rotate the crystal about [001].

Euler Angles, Animated



Complete orientations in the Pole

(ϕ_1,Φ,ϕ_2) ~ (30°,70°,40°).

Note the loss of information in a diffraction experiment if each set of poles from a single component cannot be related to one another.

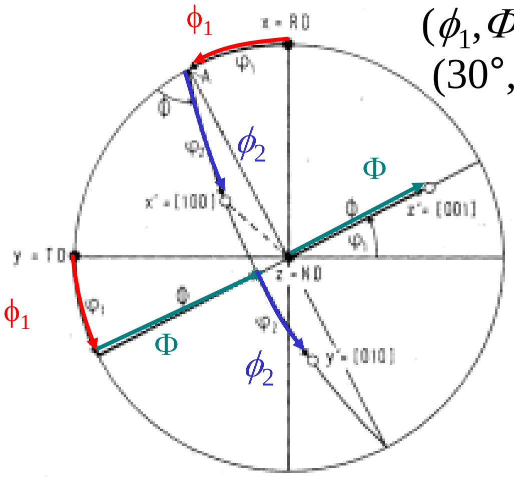
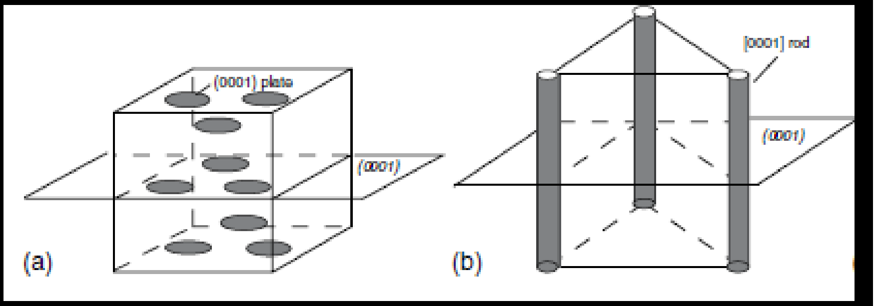


Figure 2.22 The orientation of the crystal directions X' = [100], Y' = [010] Z' = [001] in the stereographic projection in the sample coordinate system (pole figure) expressed by the EULER *angles* $\varphi_1\Phi\varphi_2$

Магний и его сплавы

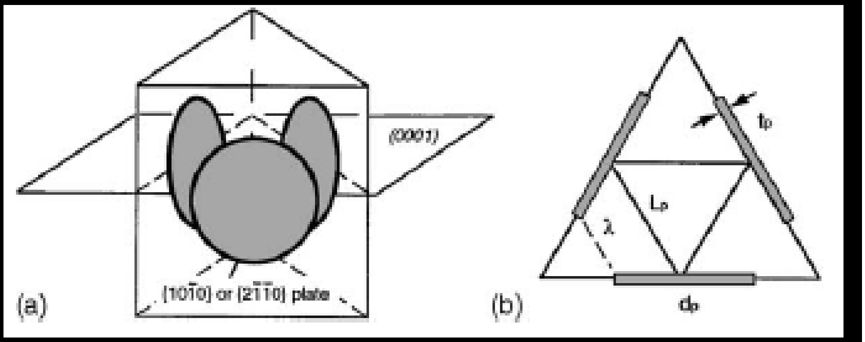
Морфология интерметаллидов

Possible precipitate shapes in Mg alloys



[Nie, Scr.Mat. (2003)]

Possible precipitate shapes in Mg alloys

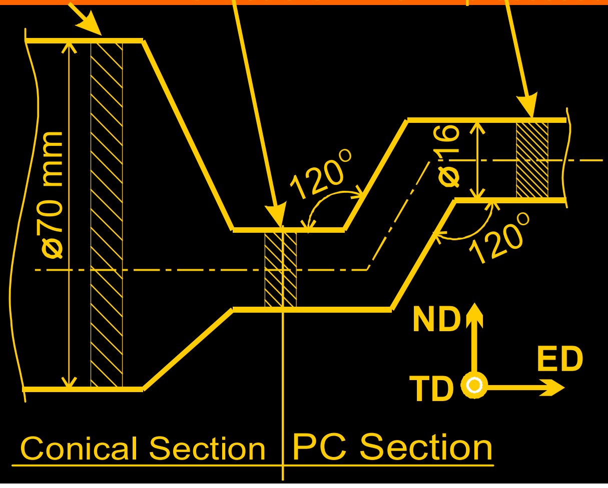


[Nie, Scr.Mat. (2003)]

Integrated extrusion and ECAP

to improve performance
of magnesium alloy
ZK60

Scheme of Integrated Extrusion and ECAP

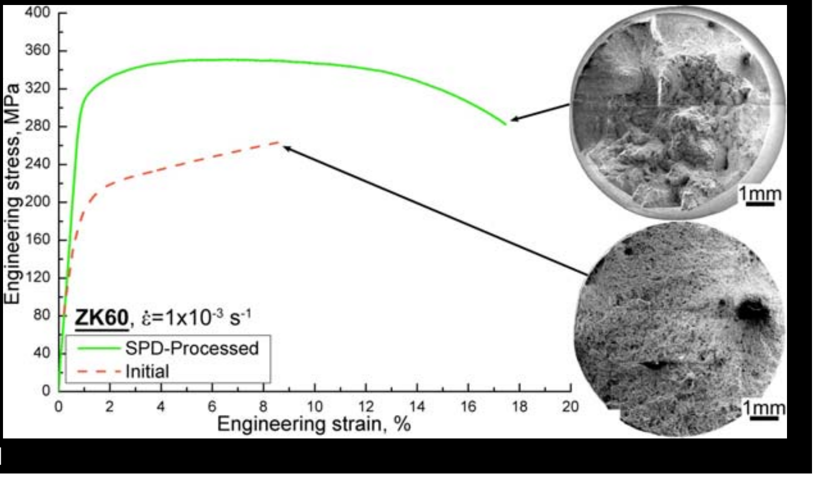


Initial Intermediate SPD-processed

Conical Section | PC Section

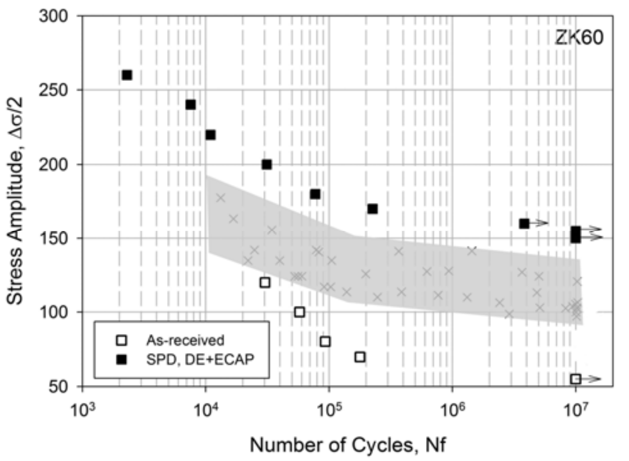
[Orlov et al,
Acta.Mat. (2011)]

Mg ZK60, Tensile Property Performance



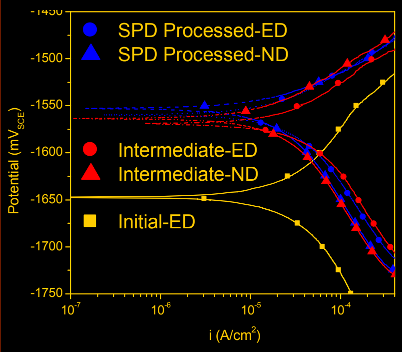
[Orlov et al,
Acta.Mat. (2011)]

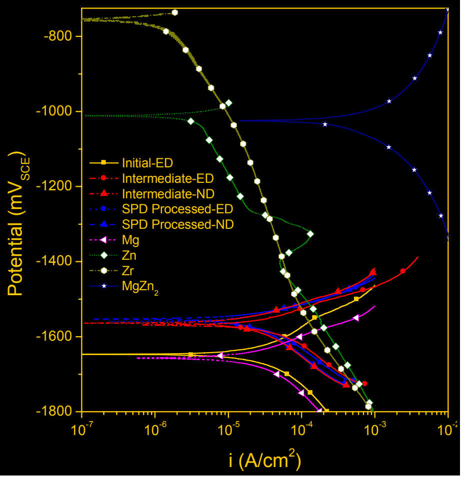
Mg ZK60, Fatigue Performance



[Vinogradov et al,
Scr.Mat. (2012)]

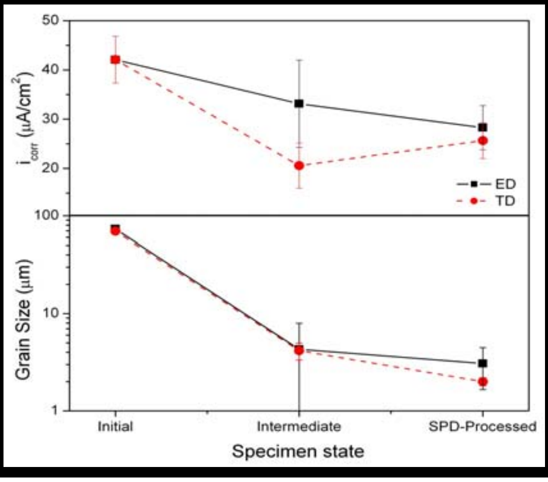
Mg ZK60, Corrosion Performance



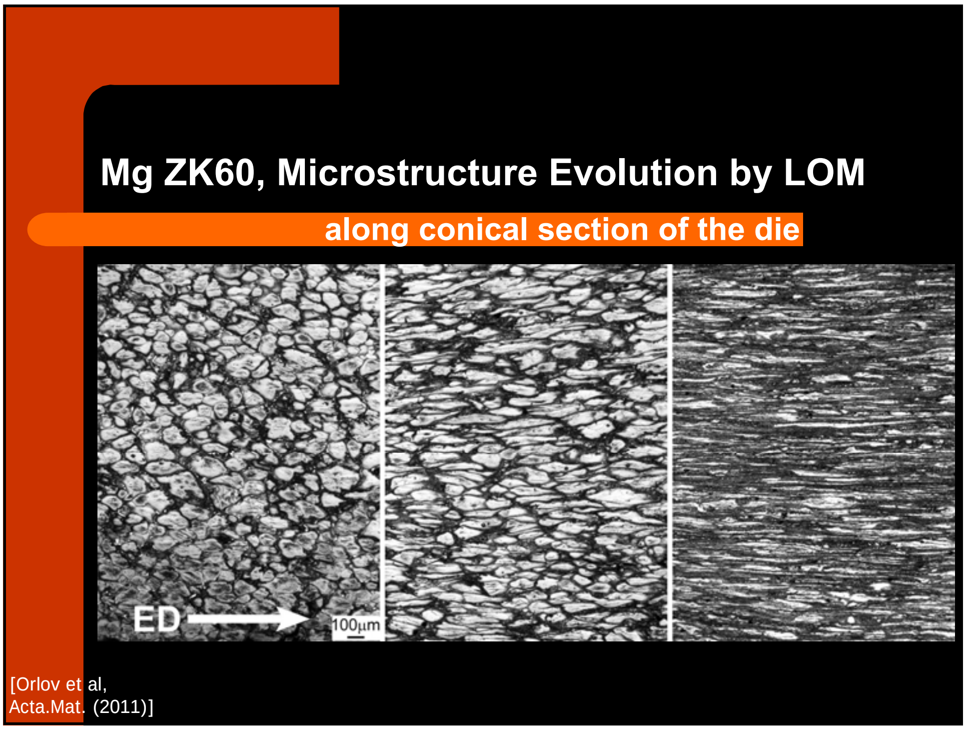


[Orlov et al,
Acta.Mat. (2011)]

Mg ZK60, Corrosion Performance



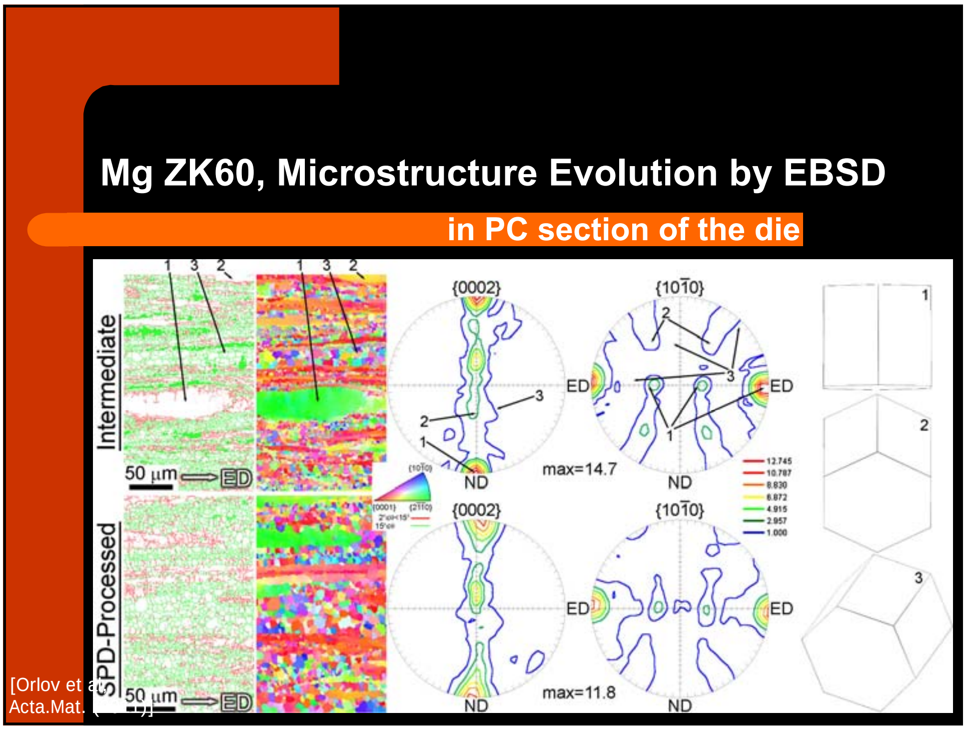
[Orlov et al,
Acta.Mat. (2011)]



Mg ZK60, Microstructure Evolution by LOM

along conical section of the die

[Orlov et al,
Acta.Mat. (2011)]



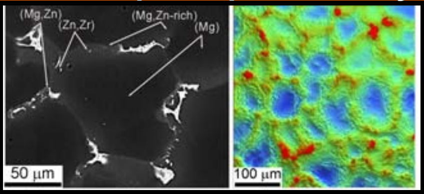
Mg ZK60, Microstructure Evolution by EBSD

in PC section of the die

[Orlov et a
Acta.Mat.

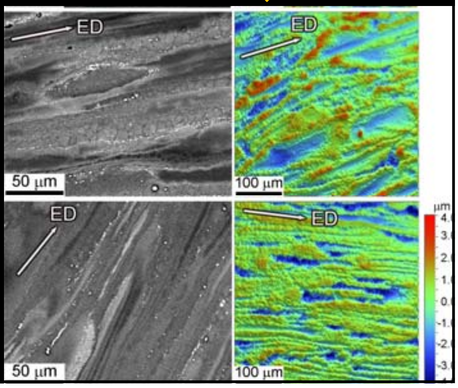
Mg ZK60, Intermetallics Evolution by SEM

and optical profilometry after exposure test



BEFORE

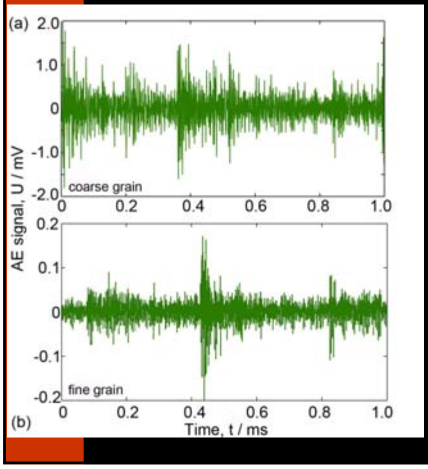
AFTER

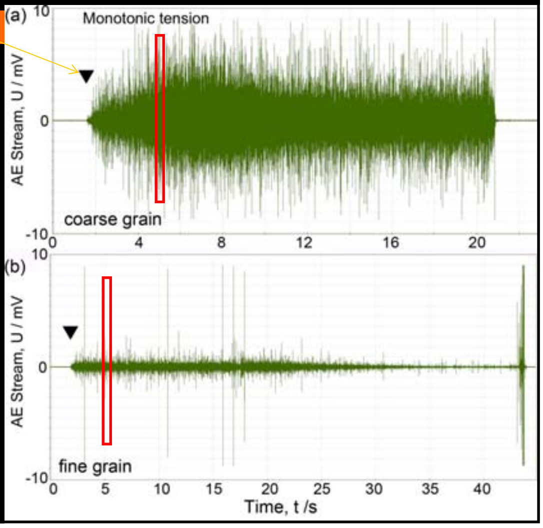


[Orlov et al,
Acta.Mat. (2011)]

AE in Mg ZK60 Alloy

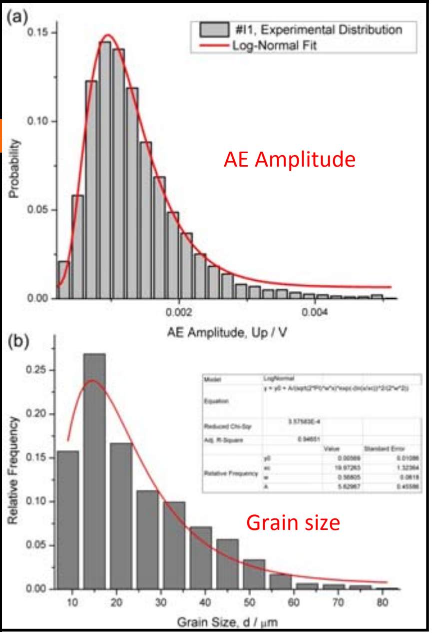
Start of loading





Correlation between the AE amplitude and grain size

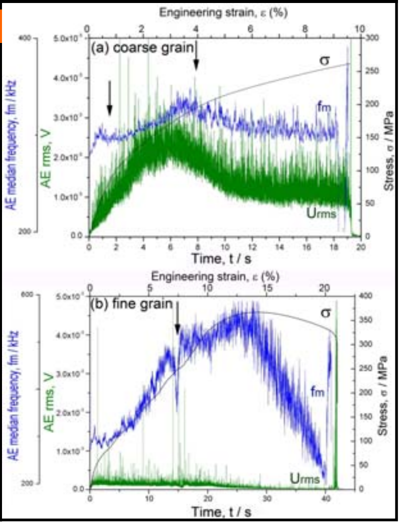
- Both obey log-normal distribution



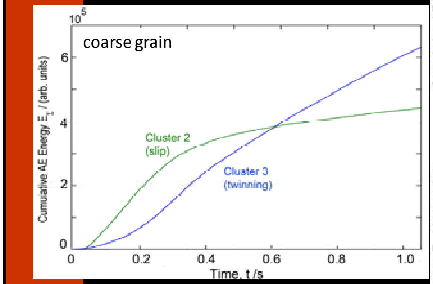
Mg ZK60, AE rms and median frequency

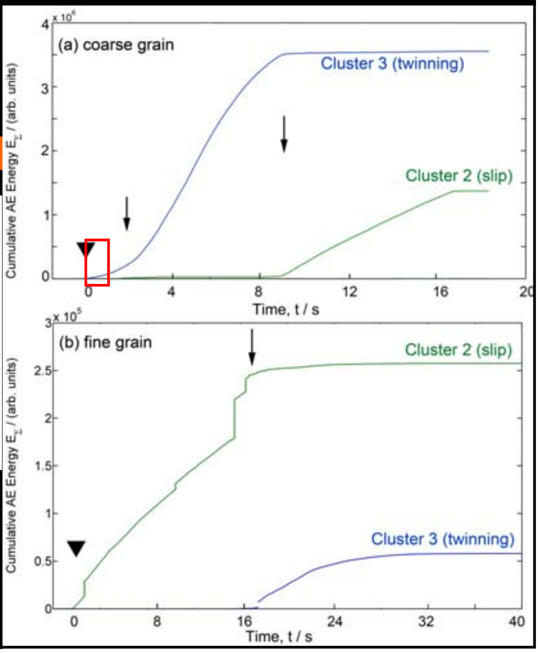
As received

After integrated extrusion



Evolution of AE cluster members





Summary

- Four-meter long bars were manufactured by integrated extrusion and equal channel angular pressing.
- Tensile, fatigue and corrosion properties were simultaneously improved by such processing.
- Corrosion property is controlled by particles redistribution, while mechanical properties depend primarily on microstructure and texture evolution.

Новый проект: цели

- Изучить механизмы деформации в магниевых сплавах используя АЭ и EBSD анализ как основные инструменты;
- Понять параметры обработки и структурного состояния магниевых сплавов определяющие механизмы деформации;
- Научиться управлять механическими и функциональными свойствами магниевых сплавов

Thank you for attention!