DMATL
Department of Materials

ETH Zürich

Magnesium alloys for biodegradable implants

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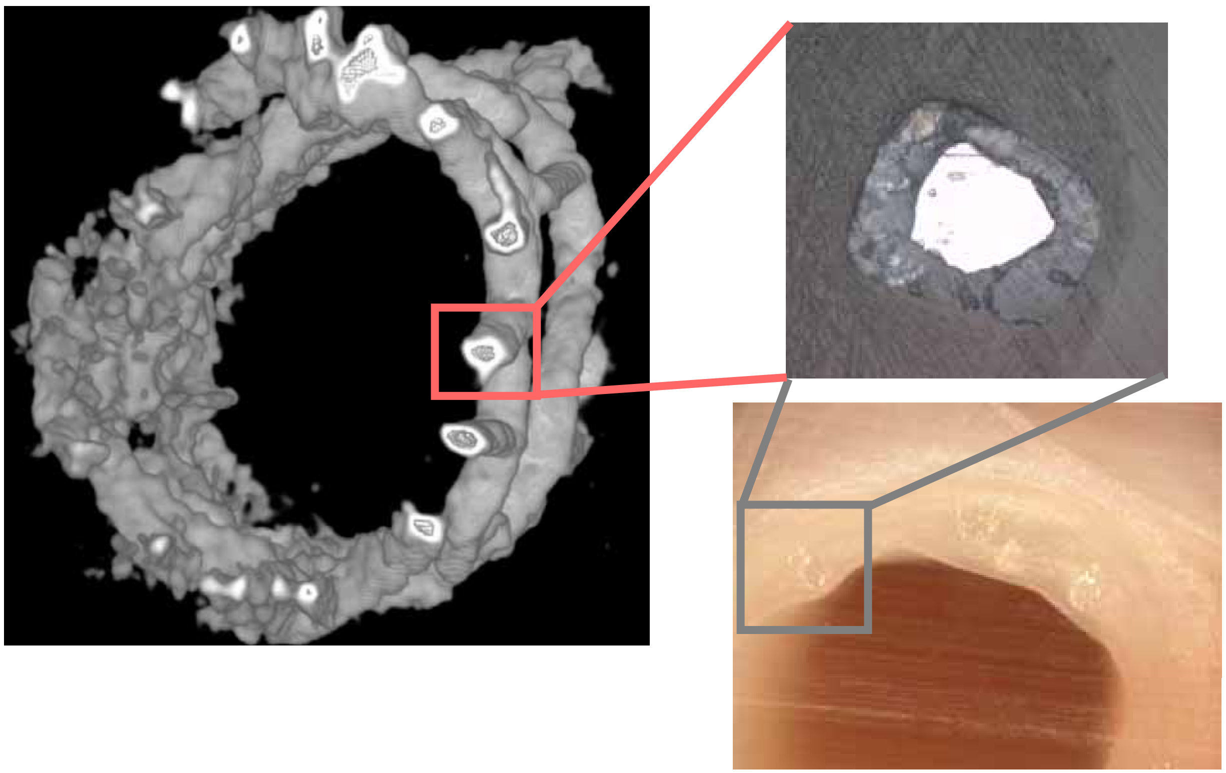
Mg – bioinspired ?

Coronary stent explanted after 1 month in mini pig

Metamorphosis of the Mg alloy to Ca-P-compound

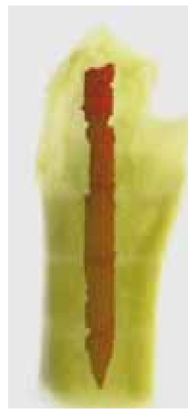


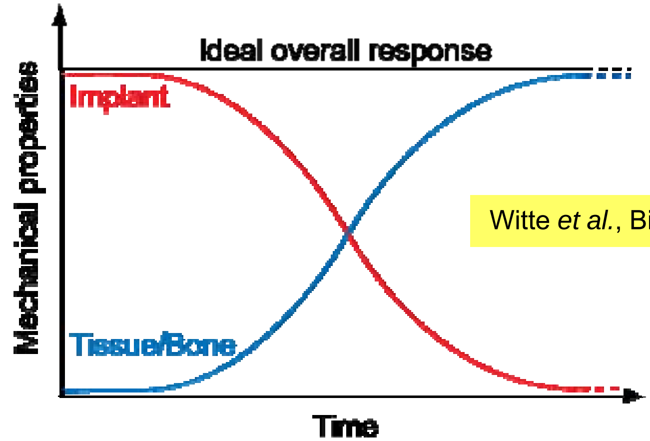
Micro-CT and LM-Image after 28 days in mini pig.

Formation of conversion layer; Ca-P-compound

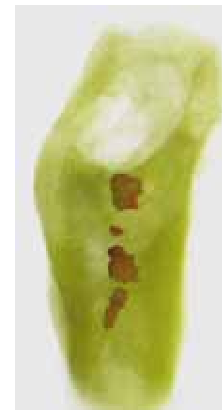
Osteosynthesis

Biodegradable implants:
- No removal surgery
- Avoidance of long-term adverse reactions (chronic inflammation)
- Early load transfer
- Applications in pediatrics

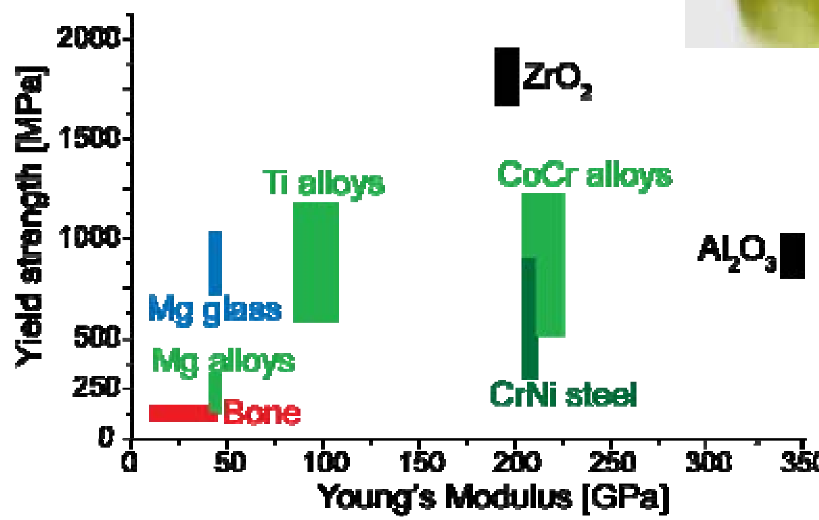




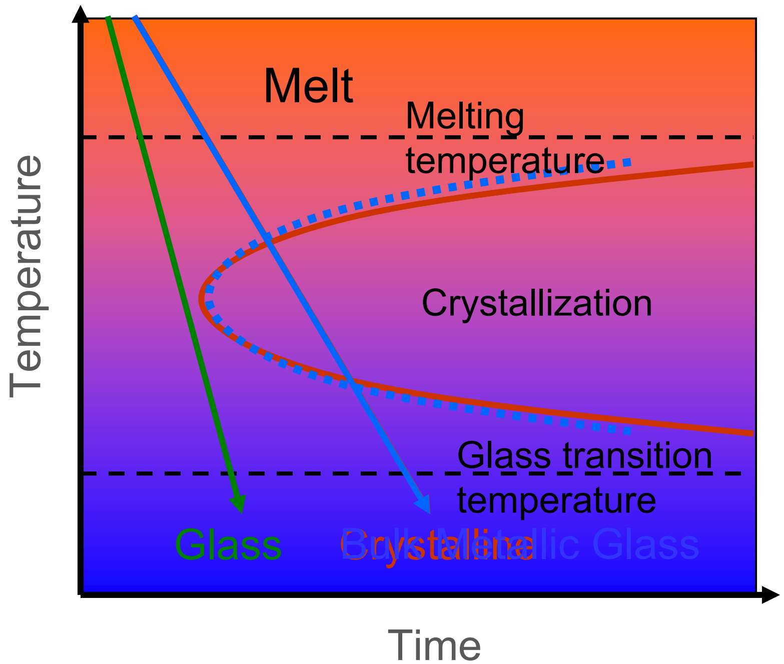
Witte *et al.*, Biomaterials, 2005

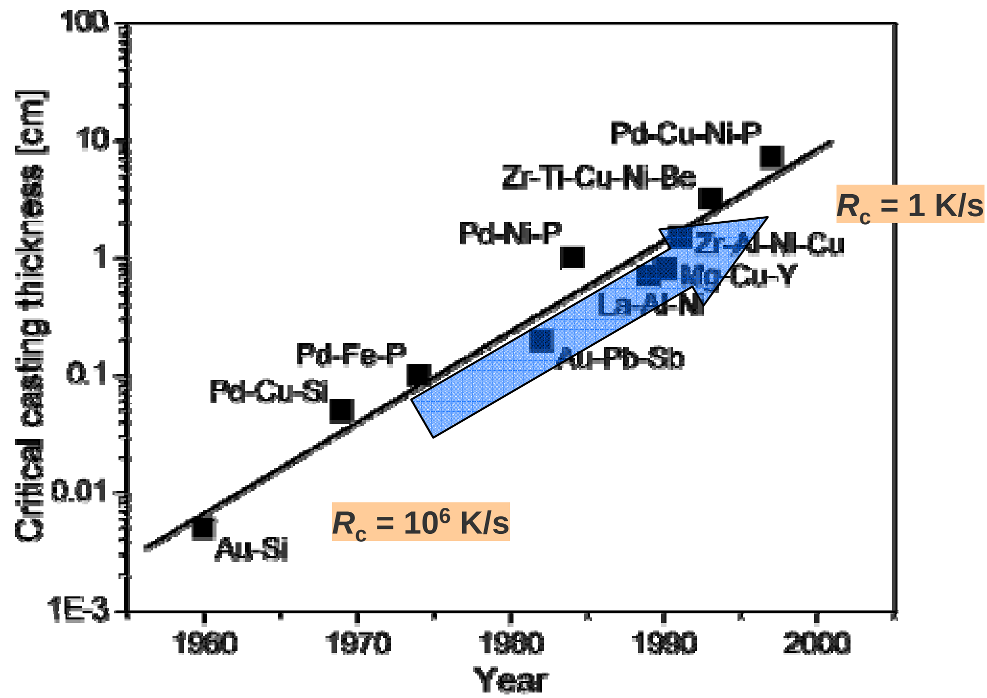


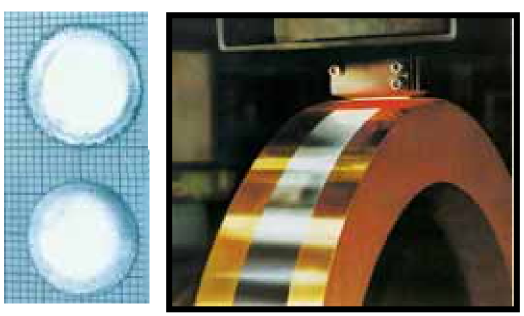
Magnesium:
- Low corrosion resistance
- High biocompatibility
- Favorable mechanical properties
- Young's modulus similar to bone



From glassy ribbons to bulk metallic glasses



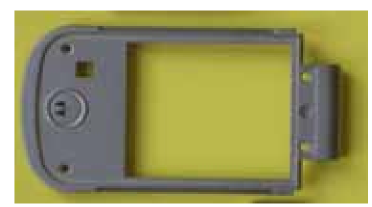




Glass: Splats, ribbons (μm)

Pressure sensor

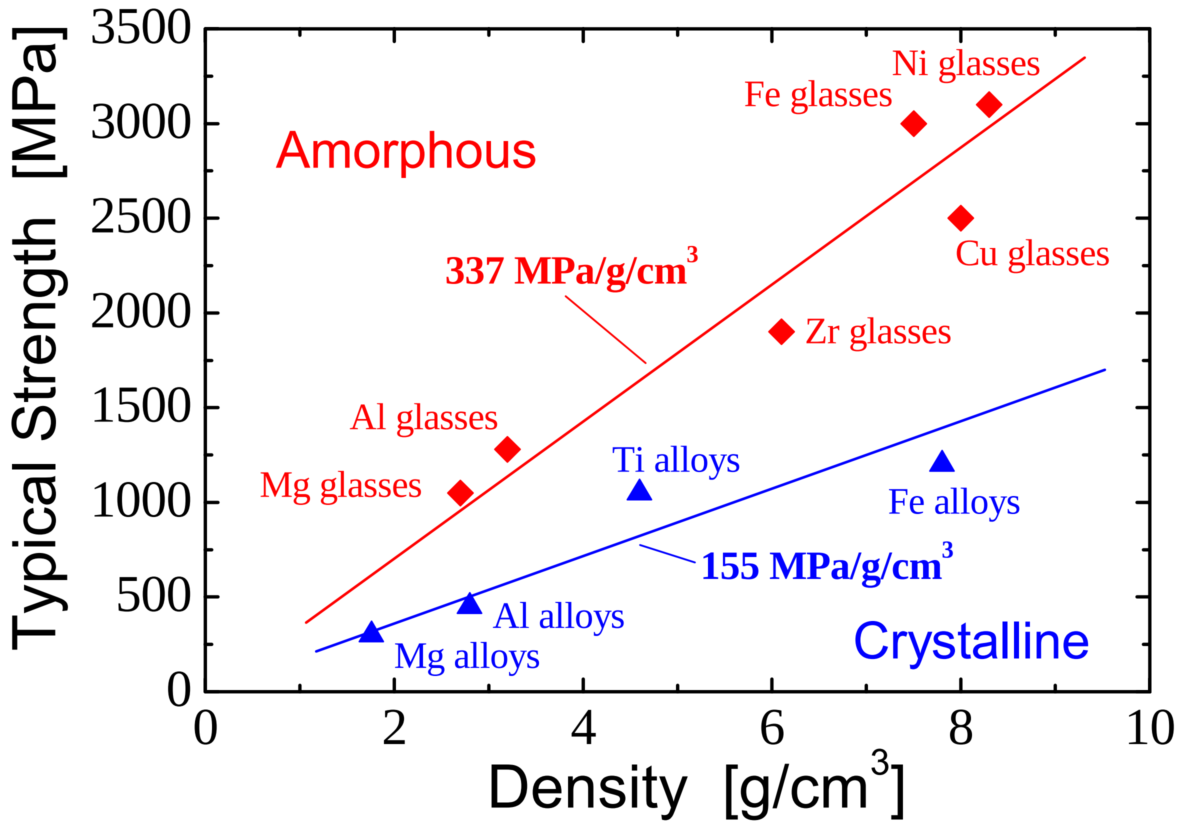
Bulk metallic glass (cm)



Cellphone casing

J. F. Löffler in *Encyclopedia of Materials Science*; reprinted in *Intermetallics* 2003.

Mechanical properties of metallic glasses



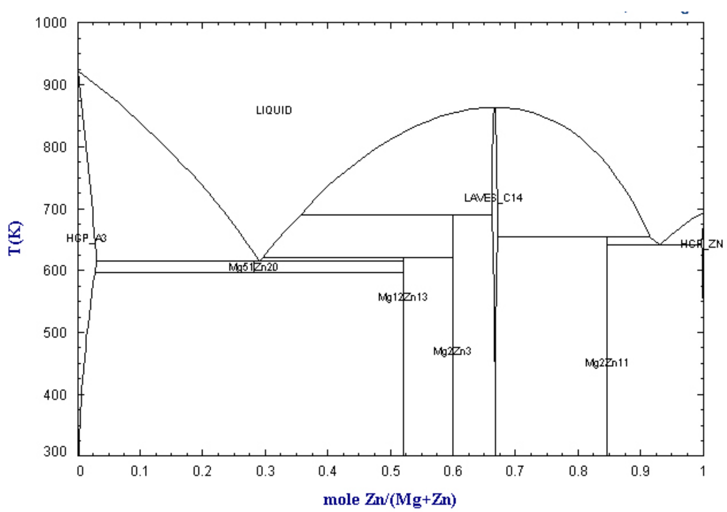
- Specific strength:
  Glasses: 337 MPa/g/cm³
  > Crystalline alloys:
  155 MPa/g/cm³
- High hardness
- High elastic limit, ε_{el} ~ 2%
  Elastic energy density:
  $\frac{1}{2}\,\sigma_y\,\varepsilon_{el} = \frac{1}{2}\,E\,(\varepsilon_{el})^2$
- However: Little plasticity

J. F. Löffler, A. A. Kündig, F. H. Dalla Torre, 'Amorphization, rapid solidification, bulk metallic glass processing and properties' (Ch. 17), in CRC Handbook of Materials Processing (Taylor & Francis).

J. F. Löffler,, *Int. J. Met. Res* .2006

Corrosion of amorphous vs. crystalline Mg

Example: Mg–Zn phase diagram



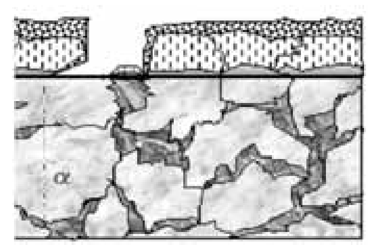
Above 2.4 at.% Zn:
precipitation of intermetallic phases

Metallic glasses:
No such 'phase-diagram limitations'

Song & Atrens, *Adv. Eng. Mater.* **5** (2003) 837.

Oxide layer

Bulk Mg



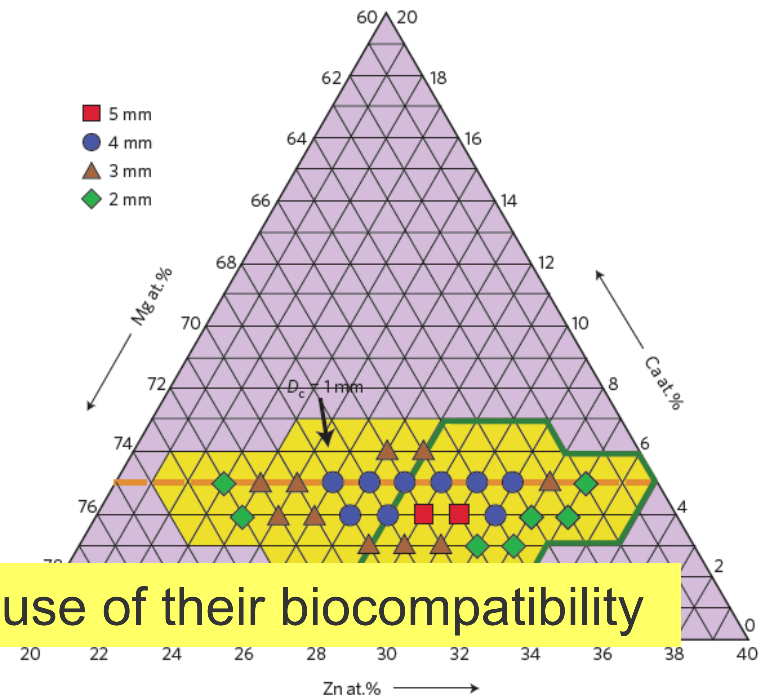
	Crystalline	Glass
Structure	Multigrain, precipitates	Homogeneous, single phase
Alloying elements	< 5 at.%	< 50 at.%
Corrosion	- Galvanic - Instable oxide layer	- Non galvanic - Stable oxide layer

-Corrosion properties in metallic glasses can be tailored

Alloy development

Some Mg-based glasses:

$Mg_{65}Cu_{25}Y_{10}$, $Mg_{85}Cu_5Y_{10}$;
$Mg_{85}Ni_5Y_{10}$;
$Mg_{67}Zn_{28}Ca_5$
(Gu, Shiflet, *et al*., JMR, 2005)



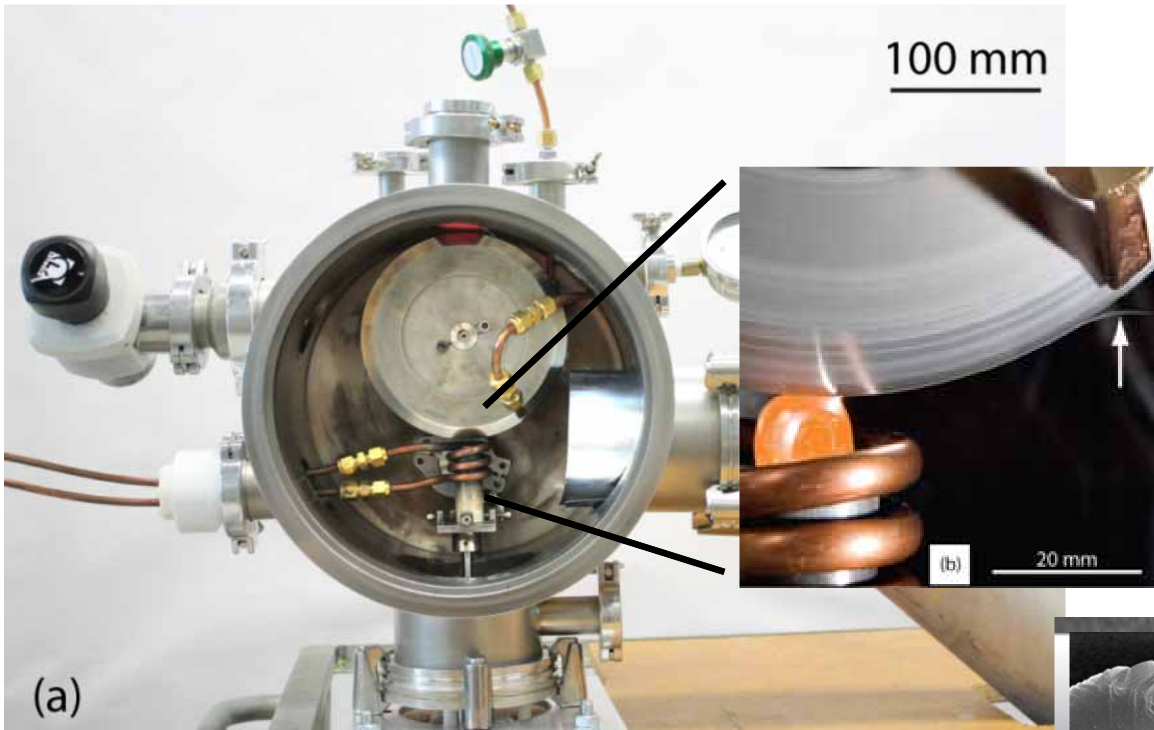
Here: $Mg_{(95-x)}Zn_xCa_5$ glasses because of their biocompatibility

Goals

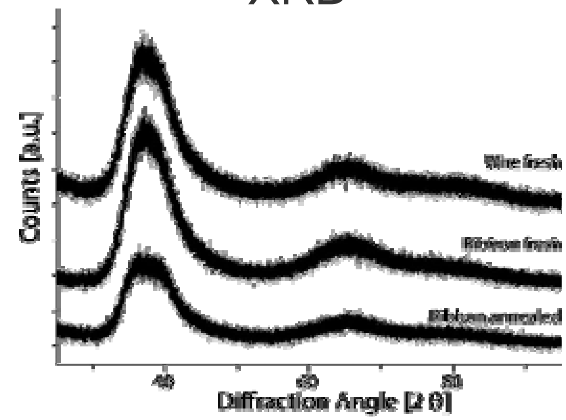
- Produce braided stents from Mg-based glassy wires

- Design Mg-based glasses with minimal degradation-induced H_2 formation for osteosynthesis/fracture fixation

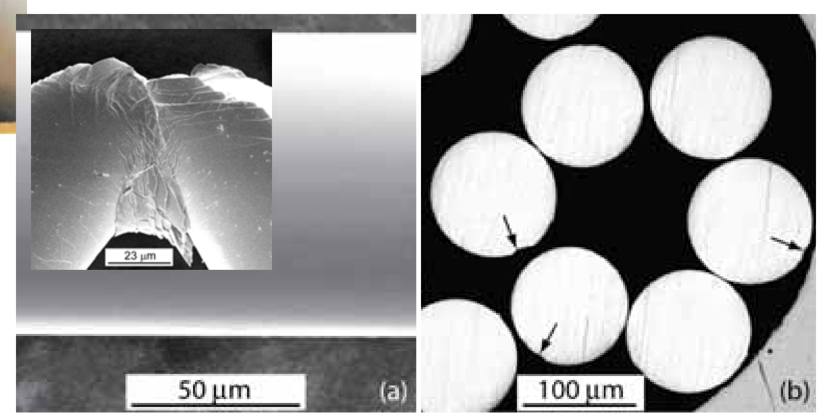
In-house designed melt-extraction setup



XRD



SEM

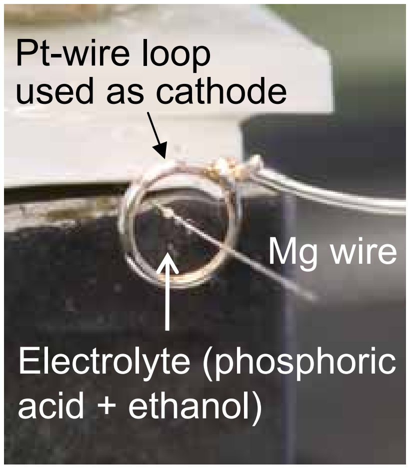


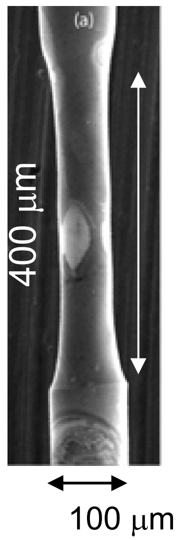
→ Production of 100 m long, 100 µm diameter amorphous wires with flawless surface quality, bending plasticity

B. Zberg, E. R. Arata, P. J. Uggowitzer, J. F. Löffler, *Acta Mater.* 2009

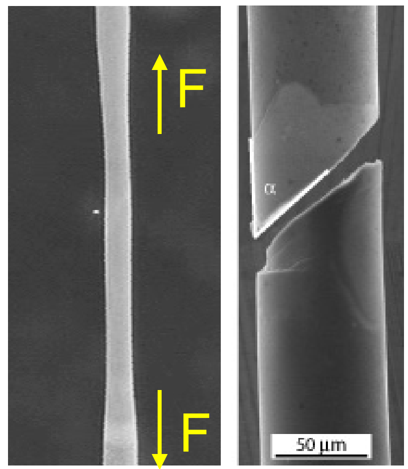
In situ tensile tests of glassy Mg wires

Preparation of dogbone specimens





In-situ tensile testing



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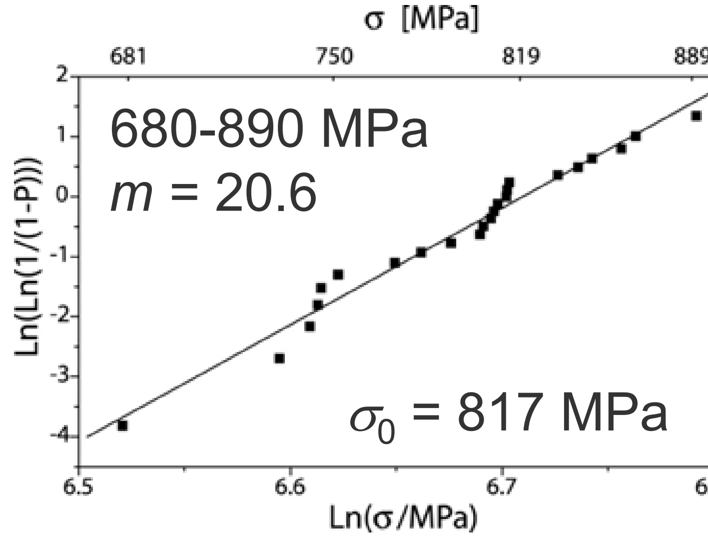
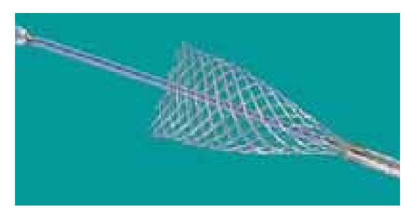
Weibull analysis



$$P_i = 1 - \exp\left[-\left(\frac{\sigma_i}{\sigma_{0,Ld^n}} \right)^m \frac{L_i d_i^n}{L_{av} d_{av}^n} \right]$$

Scaling parameter

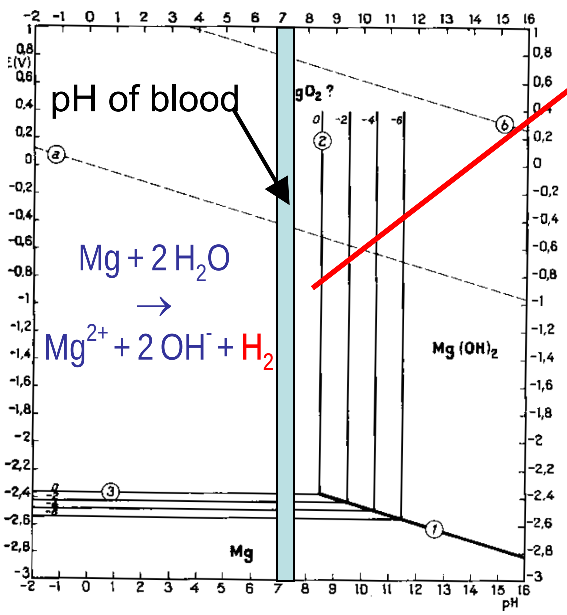
- Very high tensile strength (4x crystalline alloys) and good reliability
- 4–6% plastic deformation in tension
- Biocompatible MgZnCa wires are interesting for biomedical applications , e.g. self-expandable (braided) stents

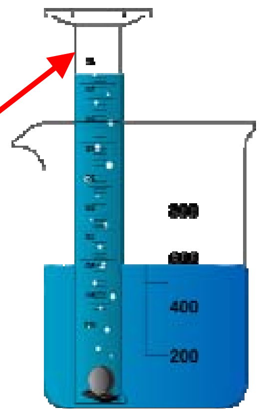


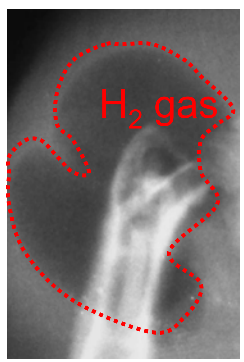
B. Zberg, E. R. Arata, P. J. Uggowitzer, J. F. Löffler, *Acta Mater.* 2009

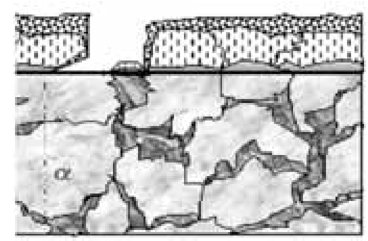
Biodegradable Mg-based glasses for larger implants (bone surgery)

Corrosion properties







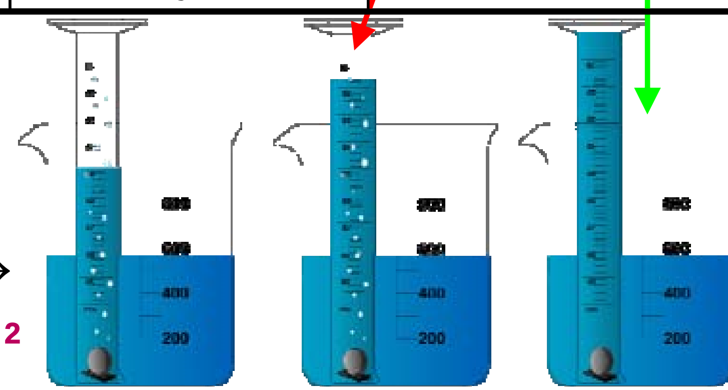


	Crystalline	Glass
Structure	Multigrain, precipitates	Homogeneous, single phase
Alloying elements	< 5 at.%	< 50 at.%
Corrosion	- Galvanic - Instable oxide layer	- No galvanic - Stable oxide layer

Mg-based glasses:

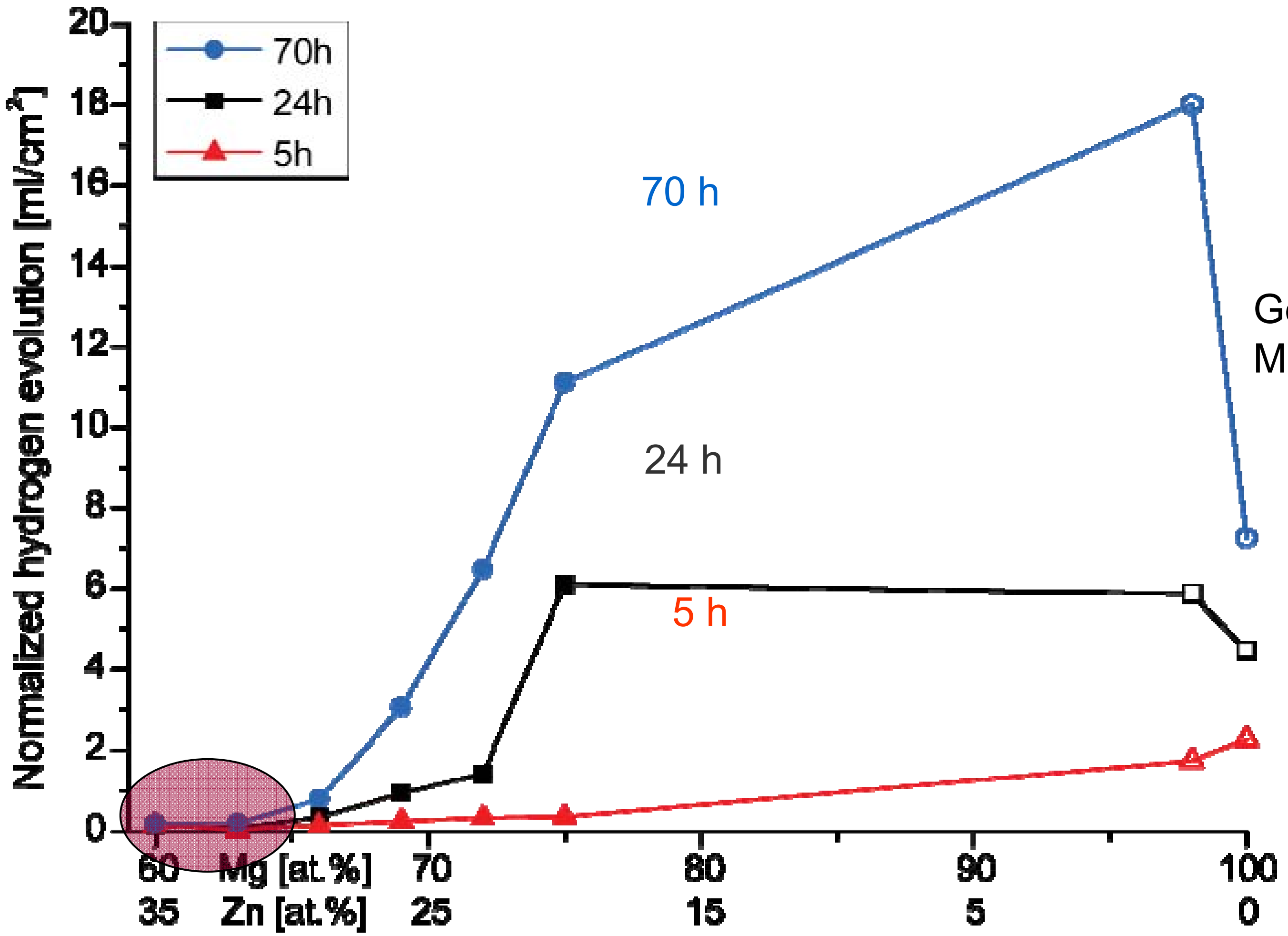
Tailoring of absorption rate
→ Strongly reduced H_2 evolution

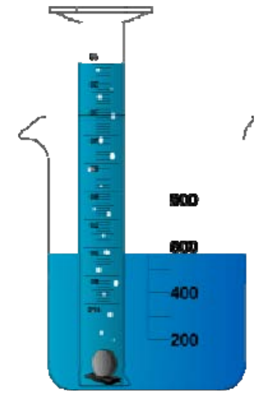
$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$



Immersion tests

Hydrogen evolution during degradation in simulated body fluid



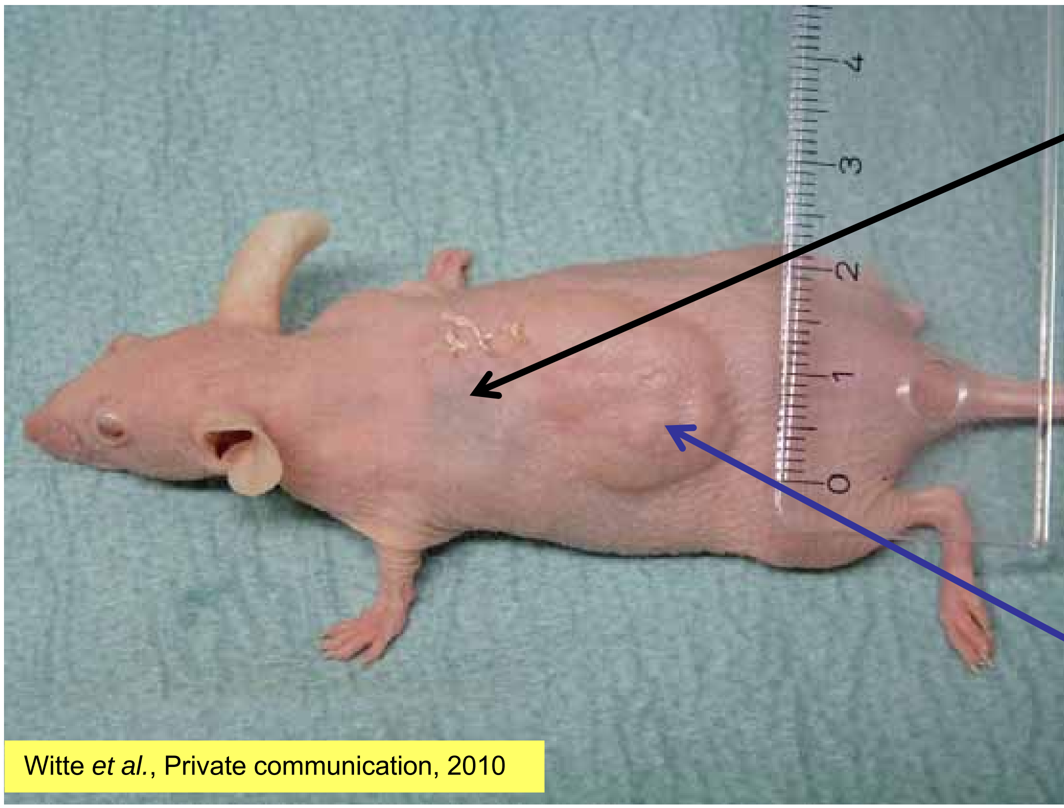


Generally:
$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$

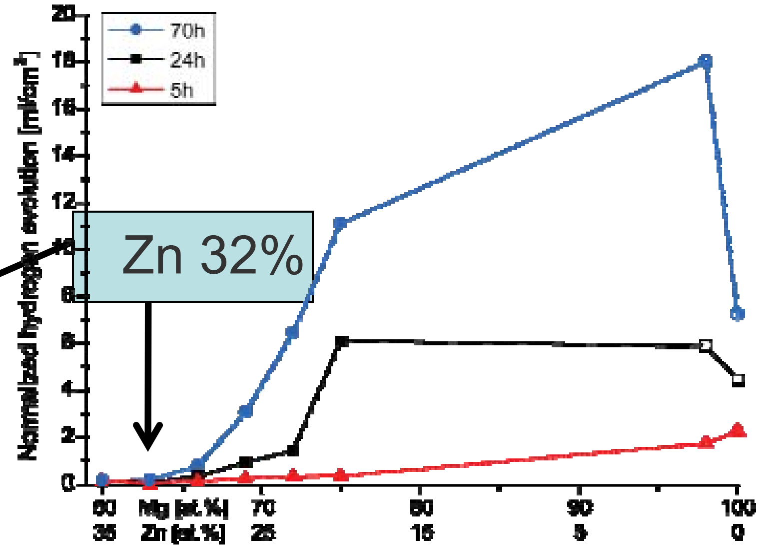
No hydrogen evolution above 28 at.% Zn

In-vivo hydrogen evolution of Mg-based BMGs

8 days post-implantation



Witte *et al.*, Private communication, 2010



Zn 32%

Zn 26%

Correllation of in-vitro and in-vivo hydrogen evolution results

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Corrosion resistance

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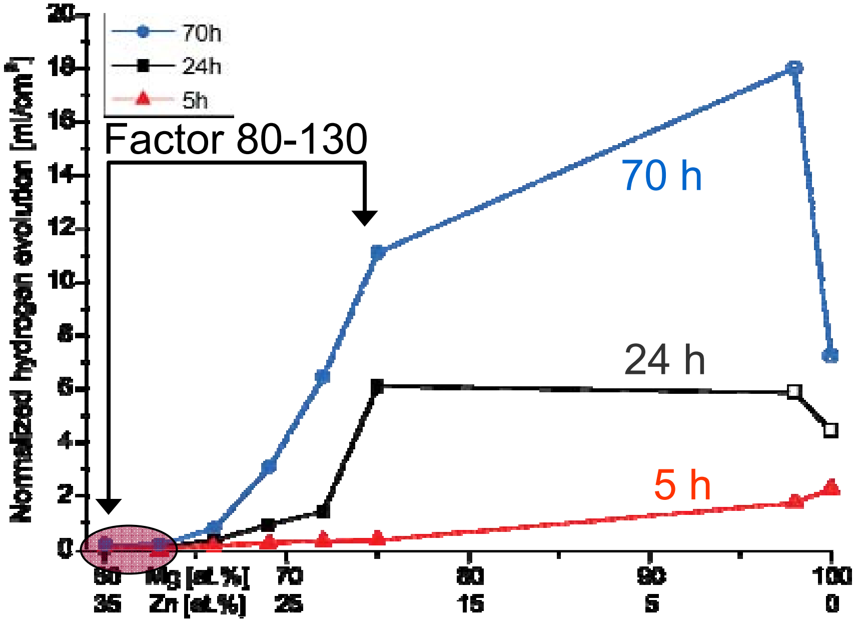
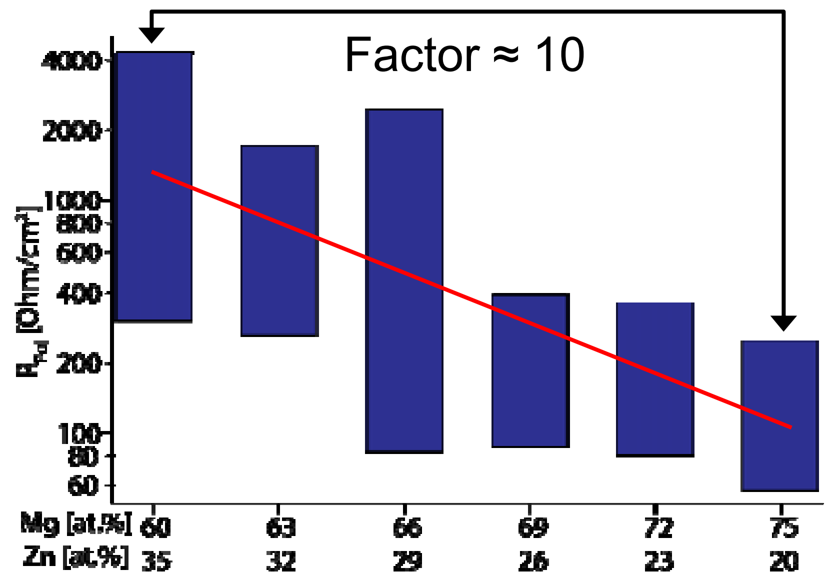
Hydrogen evolution tests

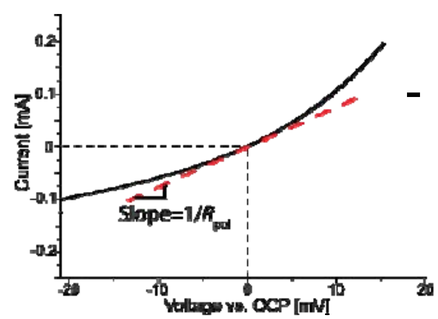


$Mg_{60}Zn_{35}Ca_5$

- H_2 evolution decreases by a factor of 100

Linear polarization resistance

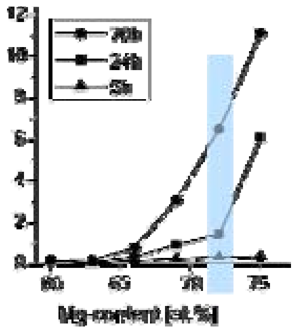




- Polarization resistance increases by a factor of 10

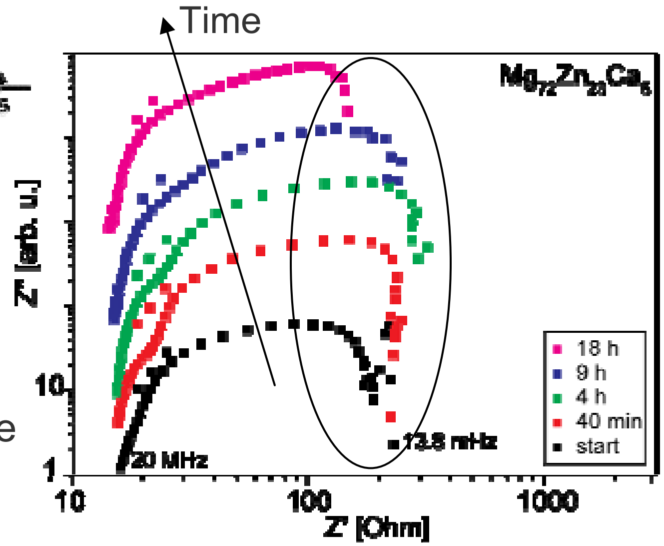
→ Improved corrosion resistance by Zn addition
→ Changing corrosion mechanism due to different surface chemistry

Electrochemical impedance spectroscopy

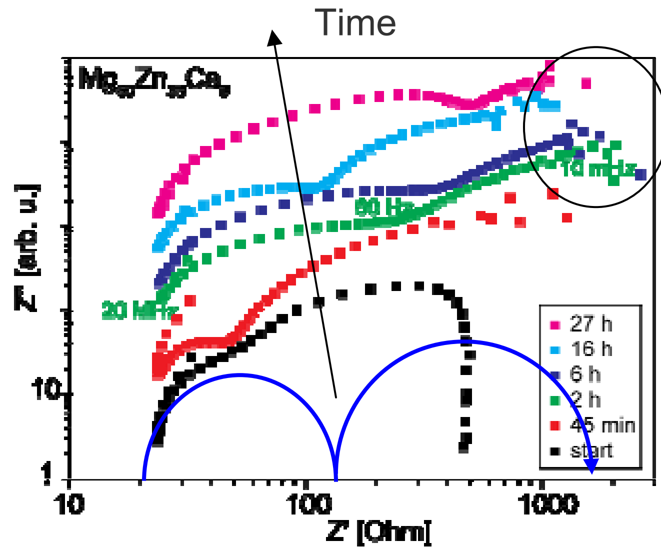


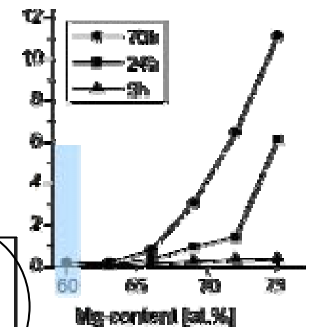
Hydrogen-evolving $Mg_{72}Zn_{23}Ca_5$

Impedance of the sample



Non-hydrogen-evolving $Mg_{60}Zn_{35}Ca_5$





- Impedance ≈ 200 Ω
- No change in curve shape with time

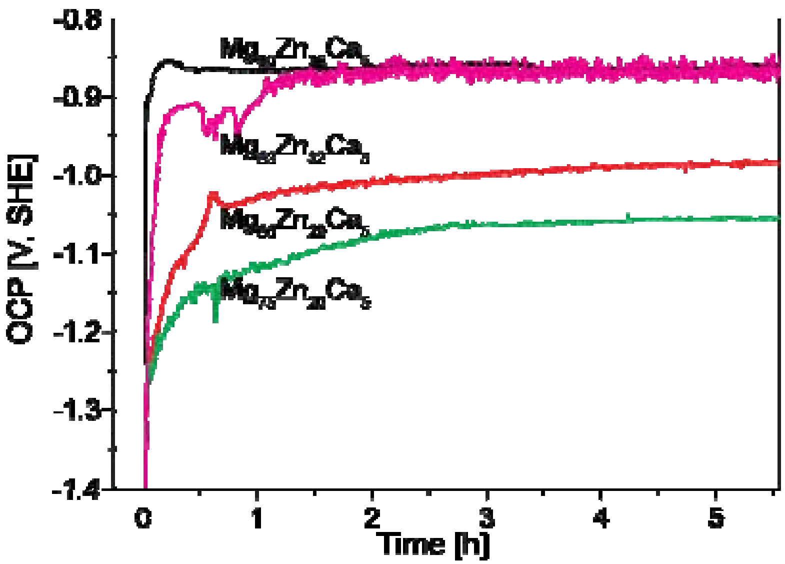
- Impedance > 3,000 Ω after 45 min
- Change in curve shape after 45 min

↓

Buildup of new surface conditions after 45 min

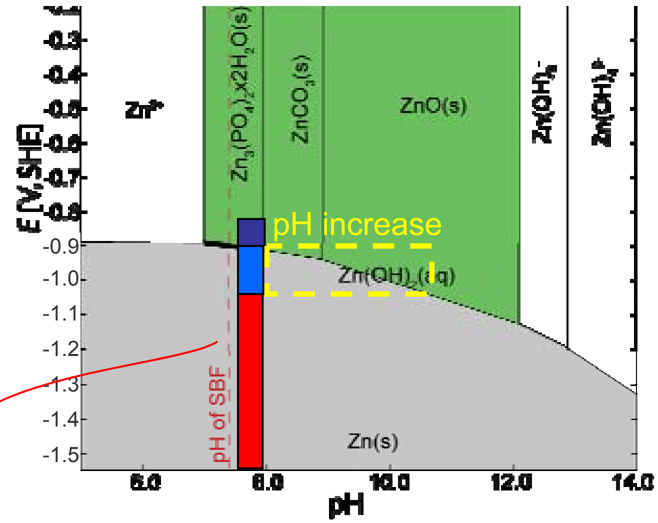
Time-dependence of open-circuit potential

Electrochemical measurements (OCP)



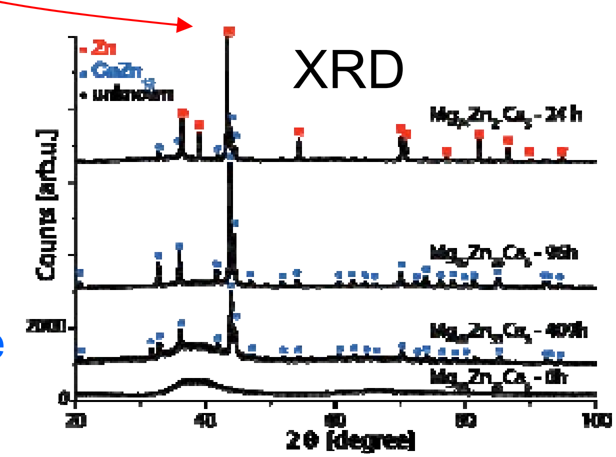
Intermediate state

Pourbaix diagram for Zn (calculated)



- Occurrence of elementary Zn
- Zn is in its non-inert state

→ Change of surface condition



- Low Zn content:
  Slow stabilization of OCP to < -1.0 V (SHE)
- High Zn content:
  Fast stabilization of OCP to -0.85 V (SHE)

- Intermediate Zn-content (28 at.%), OCP ≈ – 1 V

→ Zn can reach its non-inert state upon pH increase

B. Zberg, E. R. Arata, P. J. Uggowitzer, J. F. Löffler, *Nature Materials* 2009

Model for new corrosion mechanism in Zn-rich Mg-based glasses

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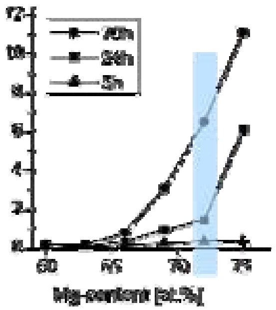
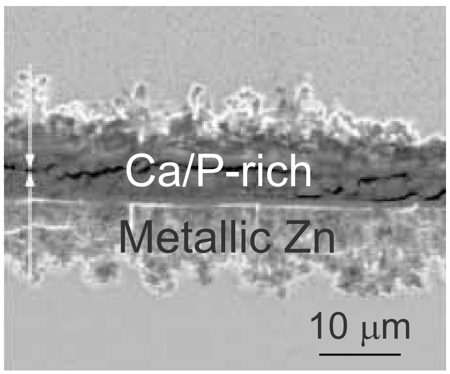
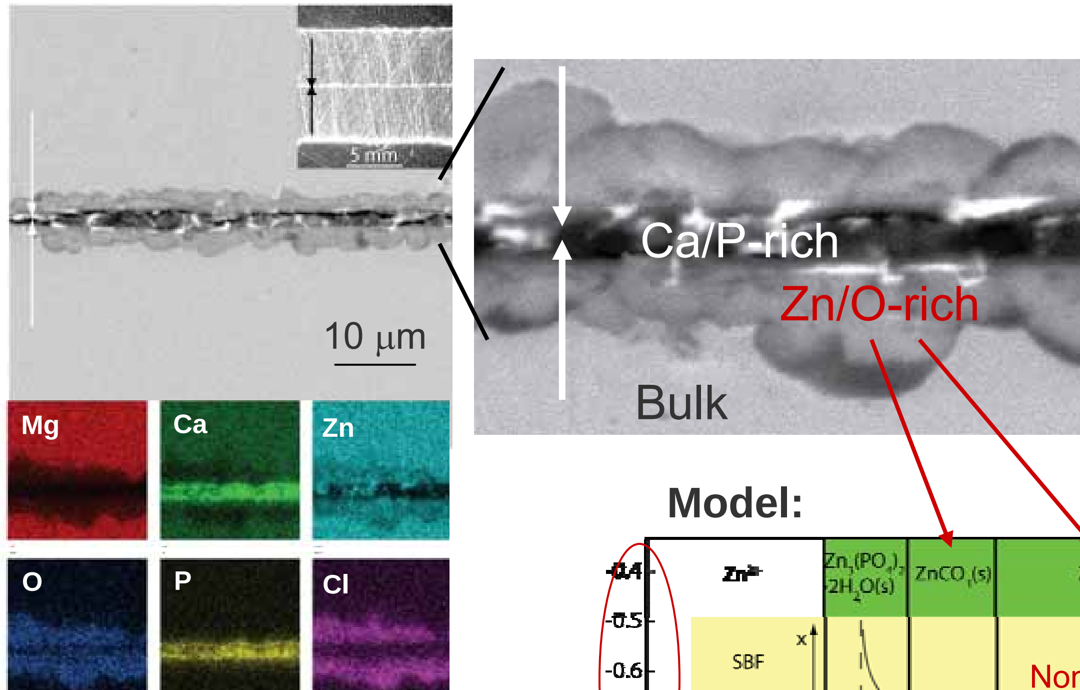
Hydrogen-evolving $Mg_{72}Zn_{23}Ca_5$

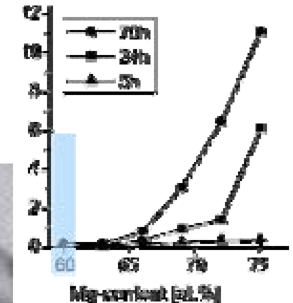


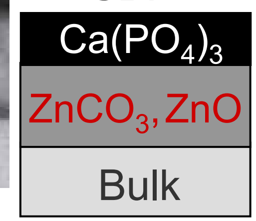


- OCP < - 1.0 V: Zn in its stable metallic form
- Increase of pH: Zn stays in its stable form

Non-hydrogen-evolving: $Mg_{60}Zn_{35}Ca_5$

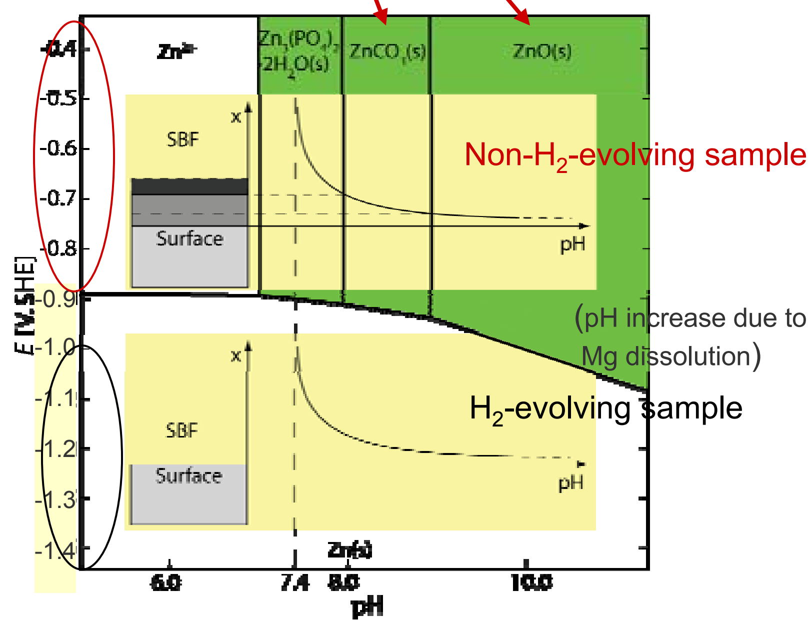






- OCP > - 0.9 V: Zn is always in its non-inert state → dense oxide layer

Model:



B. Zberg, E. R. Arata, P. J. Uggowitzer, J. F. Löffler, *Nature Materials* 2009

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In-vivo animal studies

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Implantation of Mg in various tissues of domestic pigs

4 tissue types:

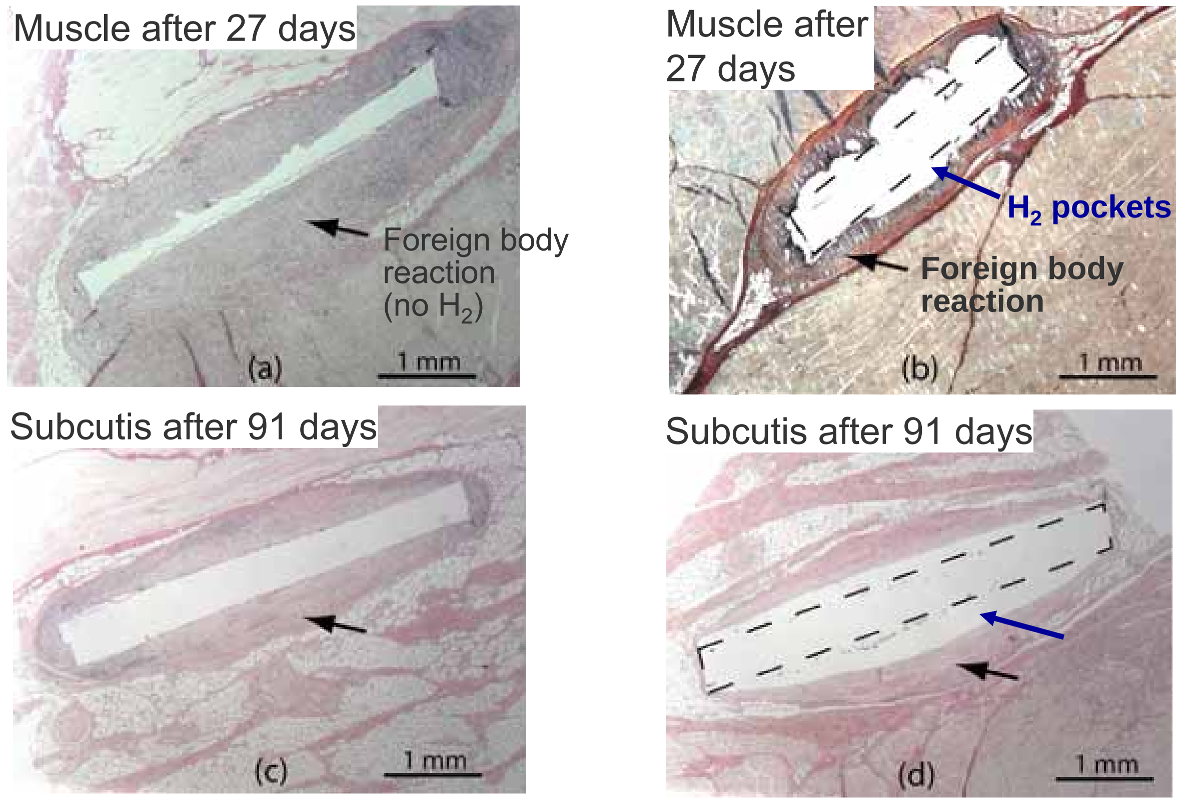
- Subcutis
- Muscle
- Liver
- Omentum

2 times:

- 27 days
- 91 days

$Mg_{60}Zn_{35}Ca_5$ glass

Crystal. Mg reference alloy



- All samples show adequate tissue healing reactions, i.e. fibrous capsule foreign-body reaction and neovascularization
- Mg-glasses do not show any *in-vivo* hydrogen evolution

B. Zberg, E. R. Arata, P. J. Uggowitzer, J. F. Löffler, *Nature Materials* 2009, highlighted in *Nature* 461, 2009.

Summary

• Mg(95-x)ZnxCa5 metallic glasses were produced and their degradation properties studied in-vitro and in-vivo

•A detailed model of the degradation mechanism was developed based on electrochemical, structural, and spectroscopic analysis of samples for various Zn-content

•Alloys with Zn-content above 28 at.% displayed no clinically observable hydrogen evolution in-vivo

•Alloy wires were used to produce bradied stents, and BMG pins are currently being developed for ostesynthesis/fracture fixation

Mg-based metallic glasses could be the next generation of biodegradable implants!

Acknowlegdements

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- The ‘‘BioCompatible Materials and Applications” project (BCMA) initiated by the Austrian Institute of Technology (AIT)
- The Staub/Kaiser foundation (Switzerland) is gratefully acknowledged.