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Fatigue of ultrafine grained light metals

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Acknowledgements

- Yuri Estrin, Professor, Monash University, Melbourne, Australia
- Kwang Seon Shin, Professor, Seoul National University, Seoul, Korea
- Yoshihito Kawamura, Kumamoto University, Japan
- Dmitry Orlov, Professor, University of Lund, Sweden

Outline

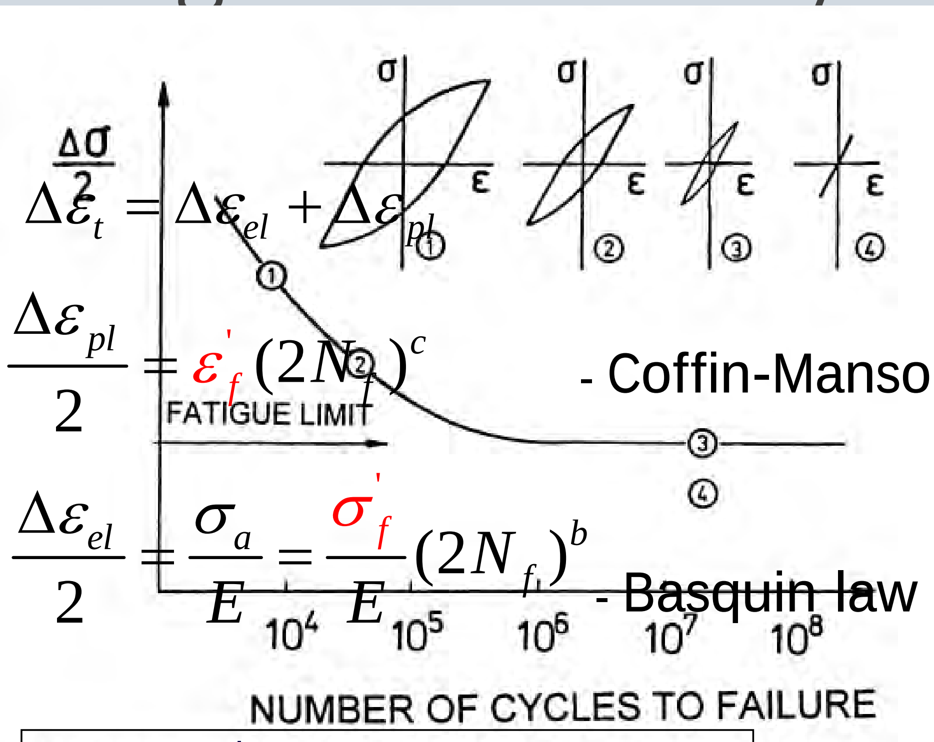
Strength, ductility and fatigue

Severe plastic deformation techniques for grain refinement

Improvement of fatigue properties of light metals

Fatigue of Mg alloys – effect of severe plastic deformation and grain refinement

Fatigue Life and Hysteresis



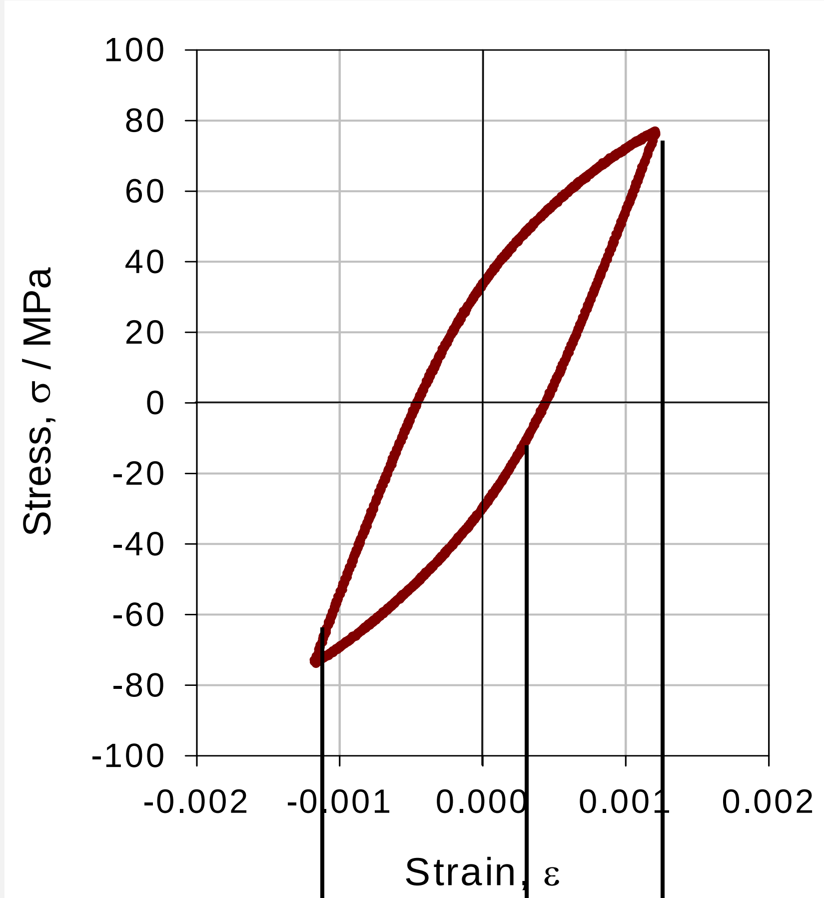
$$\Delta\varepsilon_t = \Delta\varepsilon_{el} + \Delta\varepsilon_{pl}$$

$$\frac{\Delta\varepsilon_{pl}}{2} = \varepsilon'_f (2N_f)^c$$ - Coffin-Manson law

$$\frac{\Delta\varepsilon_{el}}{2} = \frac{\sigma_a}{E} = \frac{\sigma'_f}{E}(2N_f)^b$$ - Basquin law

$$\frac{\Delta\varepsilon_t}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f (2N_f)^c$$

Fig. 2 Schematic representation of a Wöhler curve with fatigue limit. Inserts show schematically hysteresis loops (not drawn to scale!) for different stress levels, from Ref. [10].



$\Delta\varepsilon_{pl}$ $\Delta\varepsilon_{el}$

$\Delta\varepsilon_t$

[H. Mughrabi, Int. J. of Fatigue (1999)]

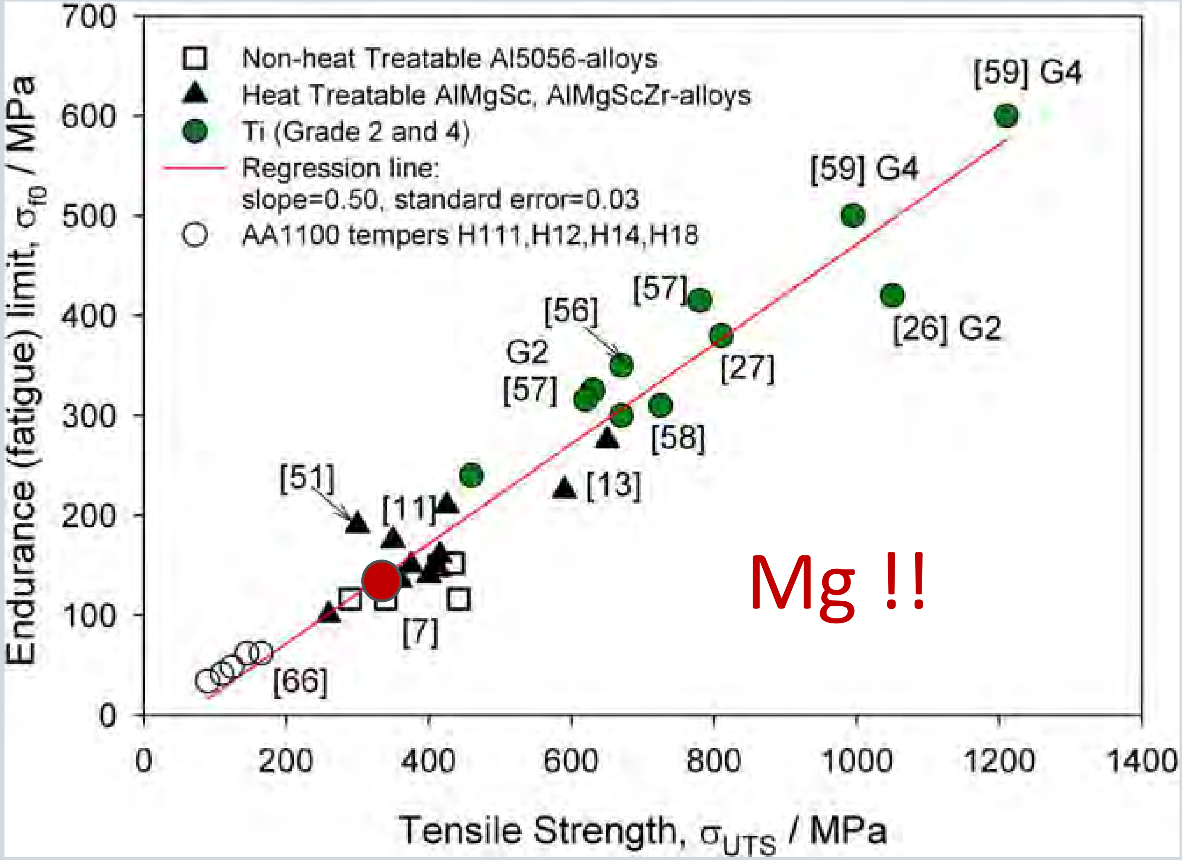
Cyclic and Monotonic Strength

$$\frac{\Delta\varepsilon_t}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

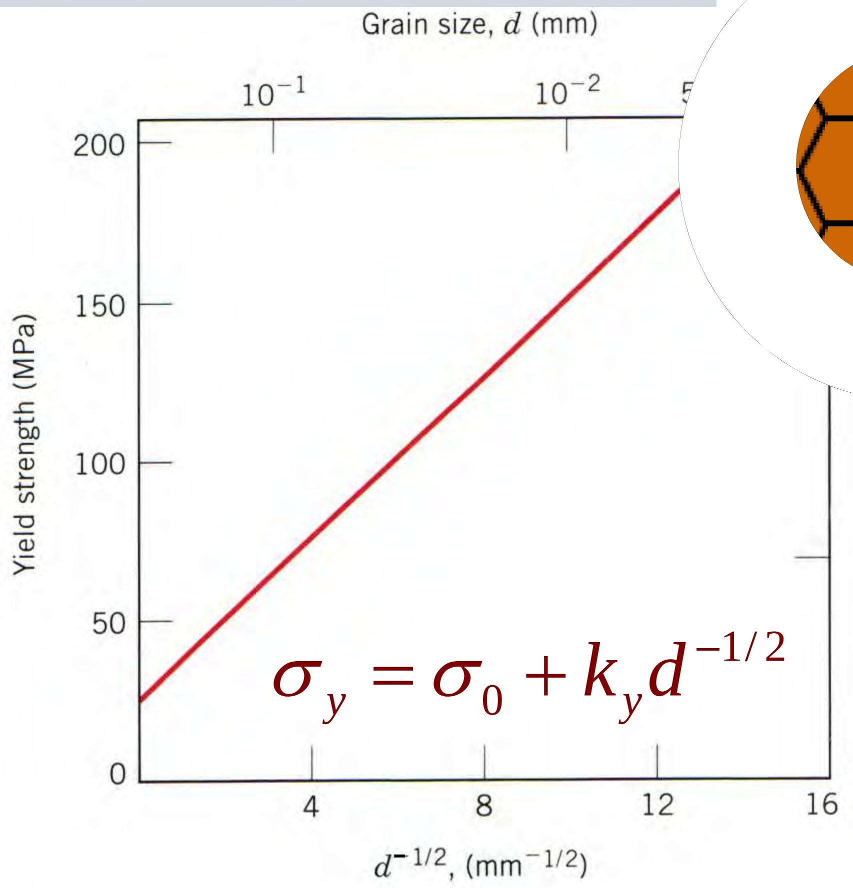
- In order to enhance the fatigue performance in both high cyclic and low cyclic regimes we need to improve both
  STRENGTH and DUCTILITY

- One of these properties is often improved at the expense of the other

- SPD, in principle, can give rise to improvement of both Strength and Ductility

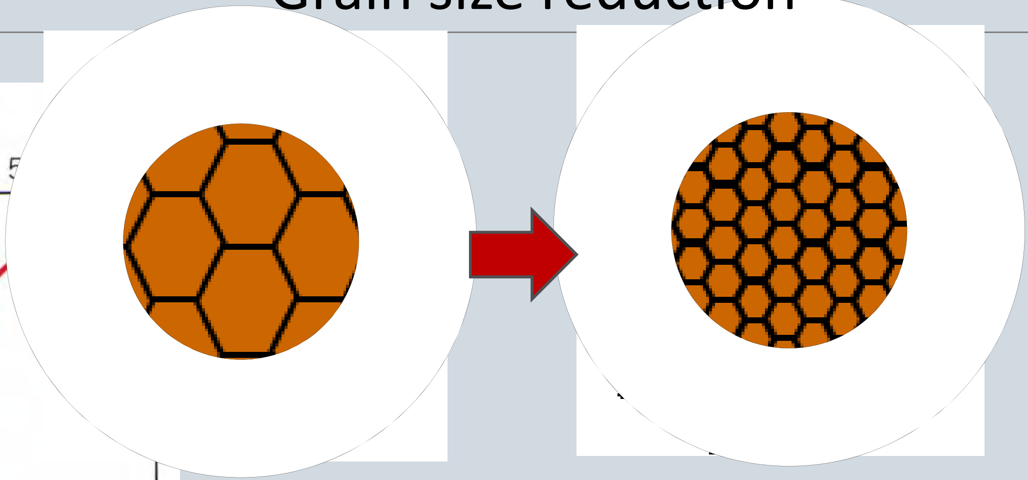


Hall-Petch relationship: clue for strength enhancement

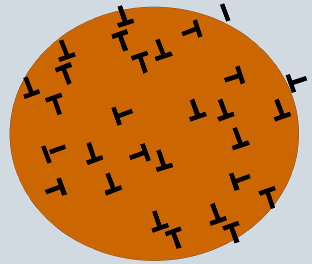


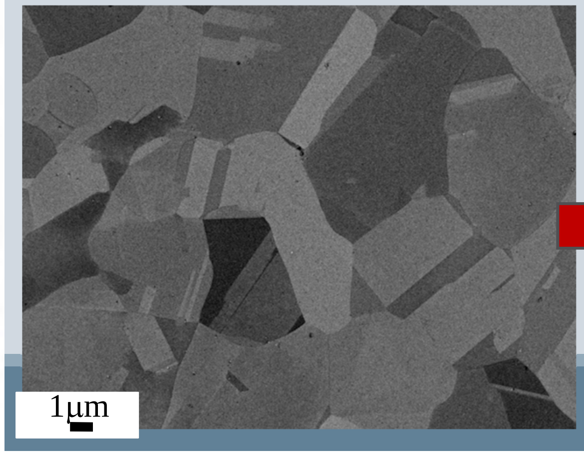
$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

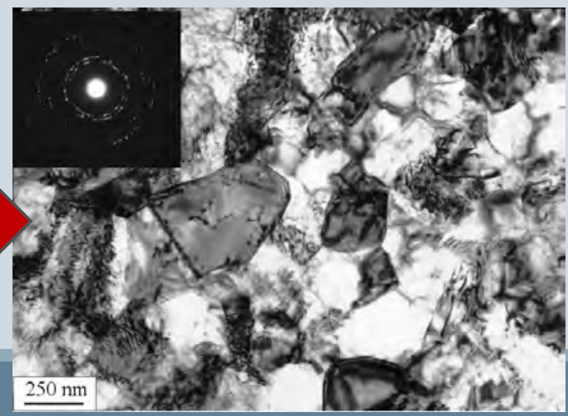
Grain size reduction



Dislocation Strengthening

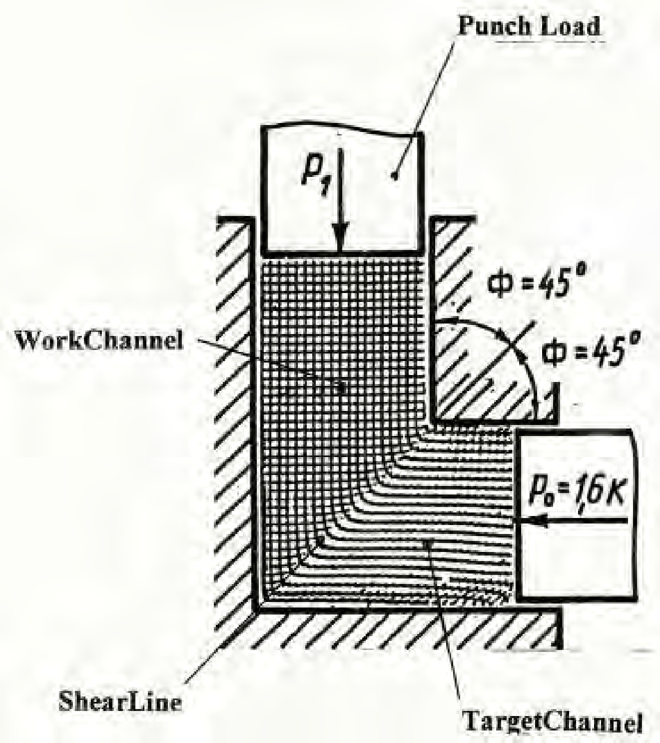


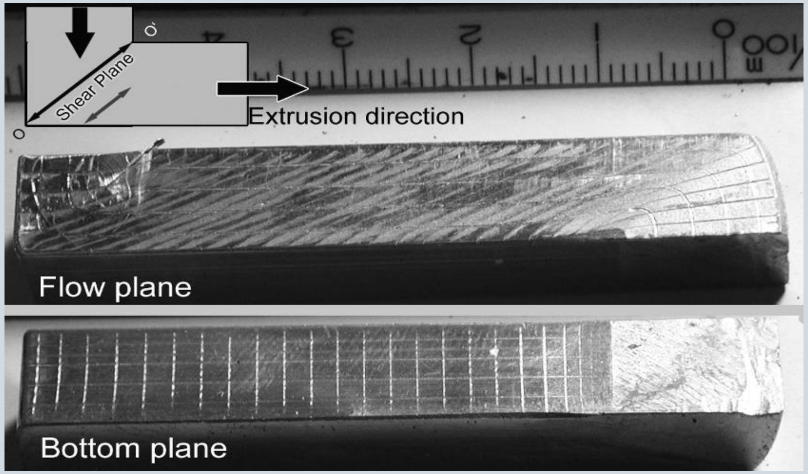




Severe Plastic Deformation – technique of choice for grain refinement

- 1972, V.M.Segal, Minsk, USSR - Equal Channel Angular Pressing
- 1986, V.V. Rybin, Large Plastic Deformations and Fracture of Metals – Mechanisms of grain refinement
- 1988, R. Z. Valiev et al., Dokl Akad Nauk SSSR



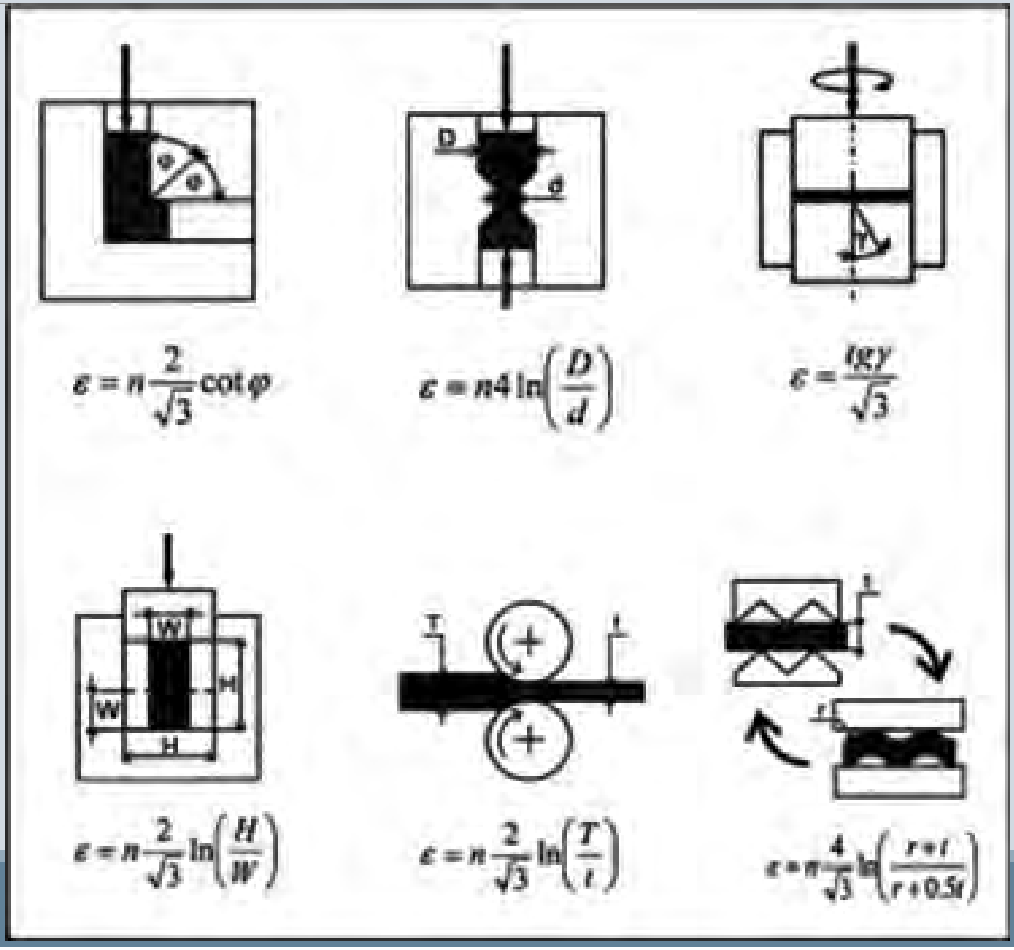


ECAP is much more efficient in straining than rolling and furthermore the dimensions of the working billet do not alter!

Severe Plastic Deformation Techniques

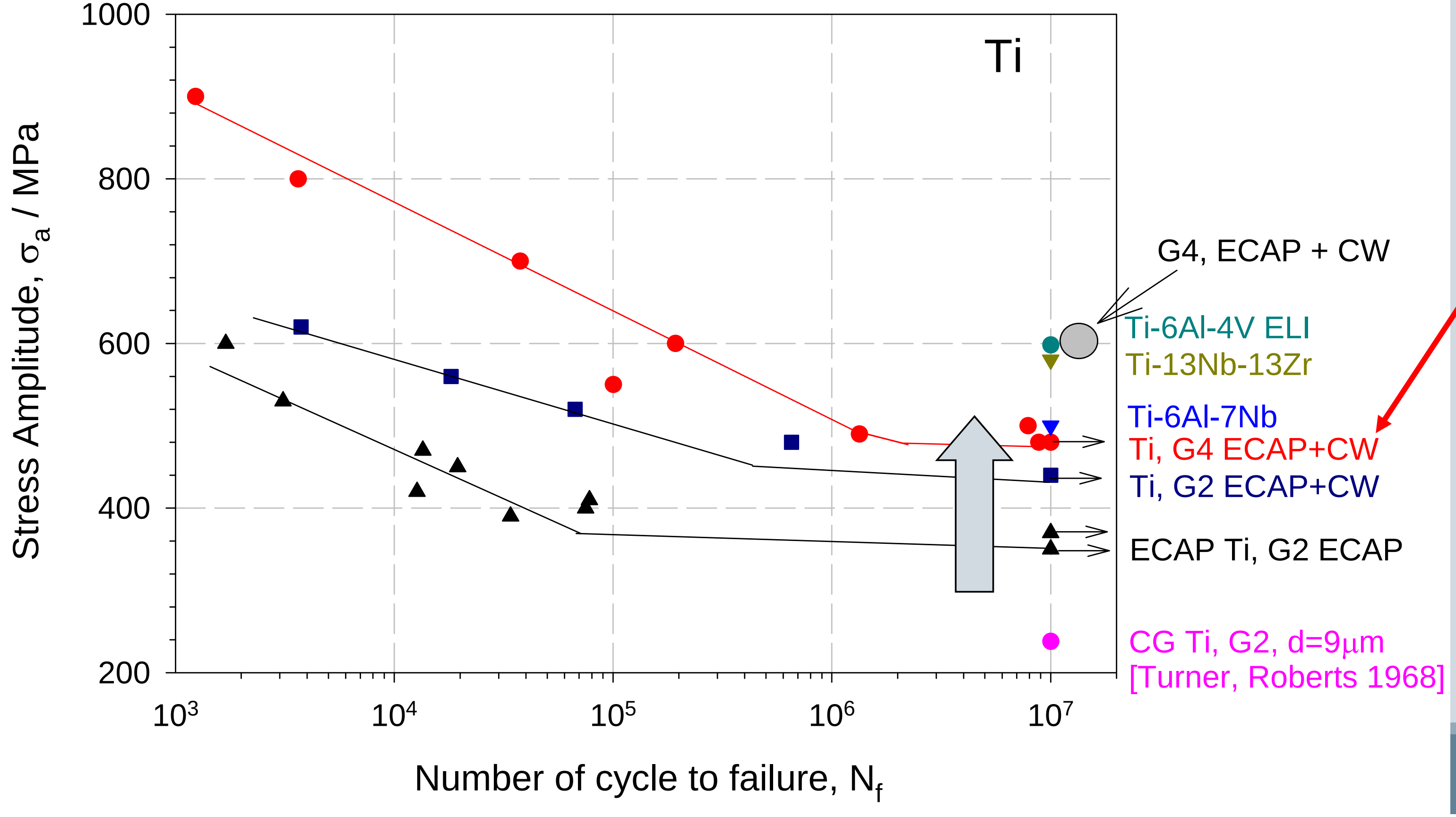
- A broad variety of severe plastic deformation is available nowadays

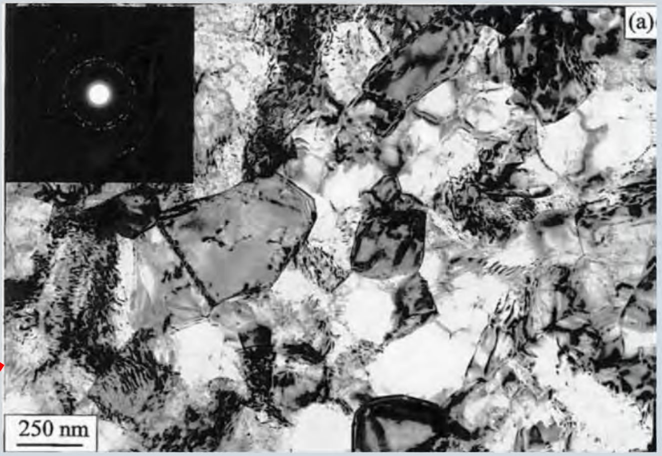
- Up-scaling is still an issue, but technologically available solutions have been proposed



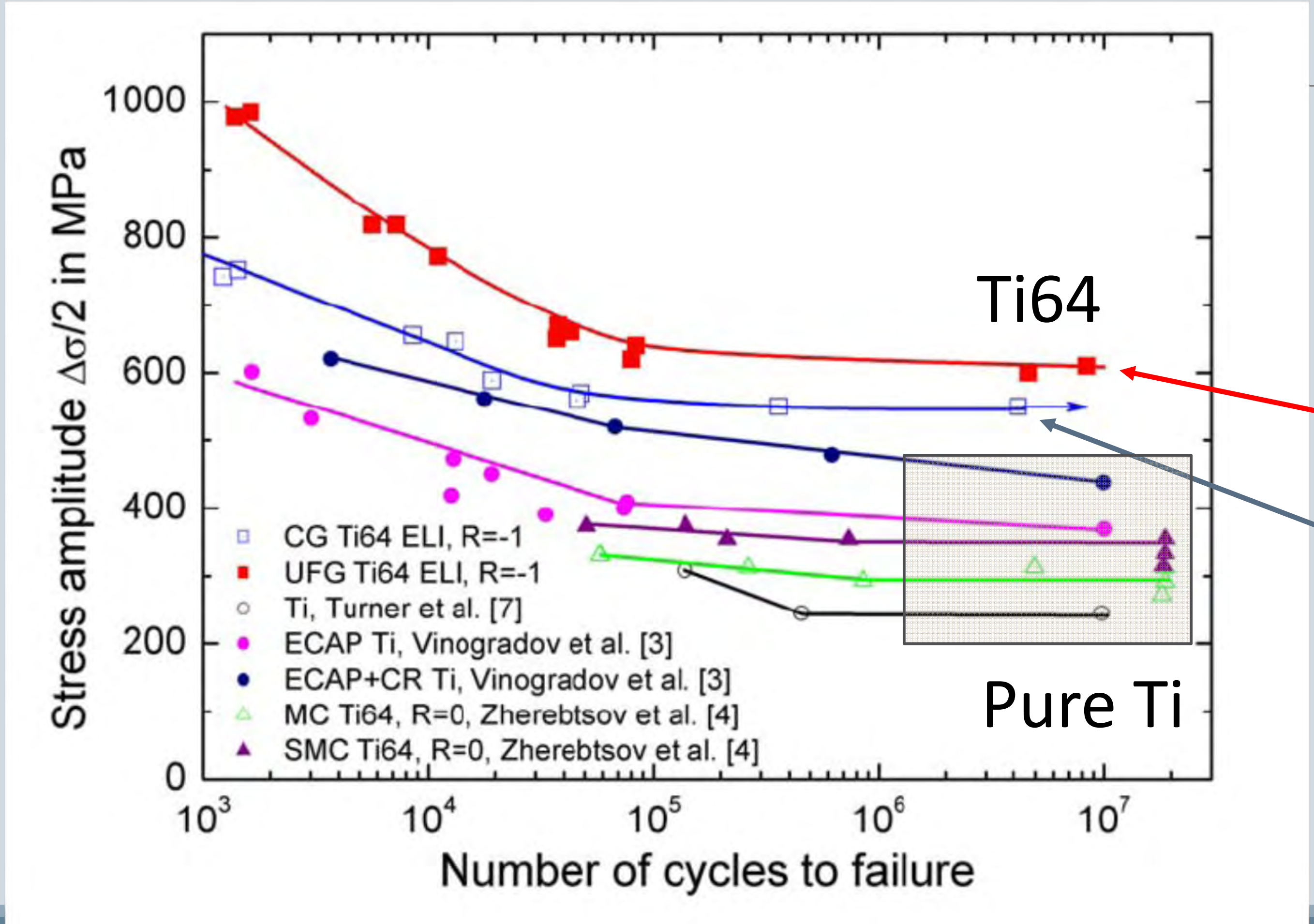
[Y. Estrin, A. Vinogradov, Acta Mater (2011)]

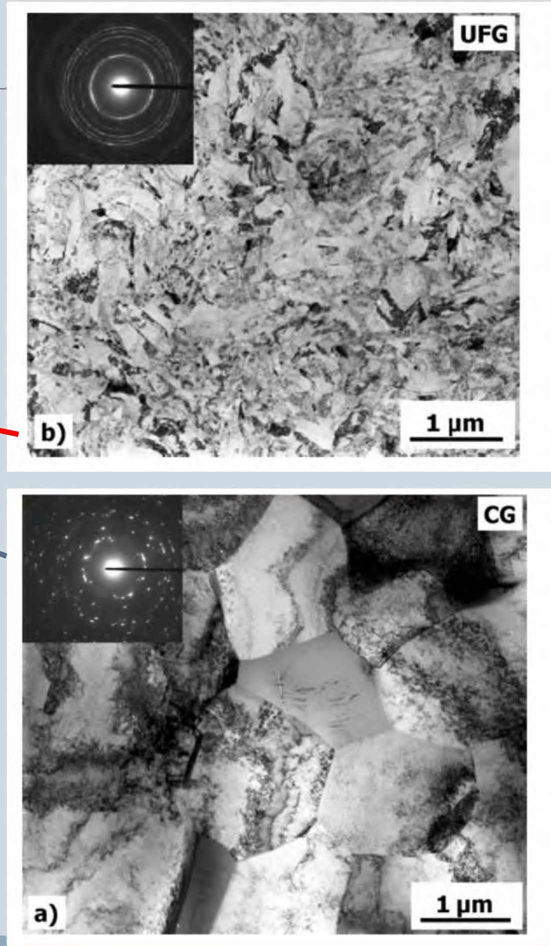
Enhancement of fatigue of Titanium





Ultrafine grained Ti-6Al-4V (Eli)





[L. Saitova et al. , Mat Forum (2008)]

Mg Alloys

Fine grain AZ31 Alloy

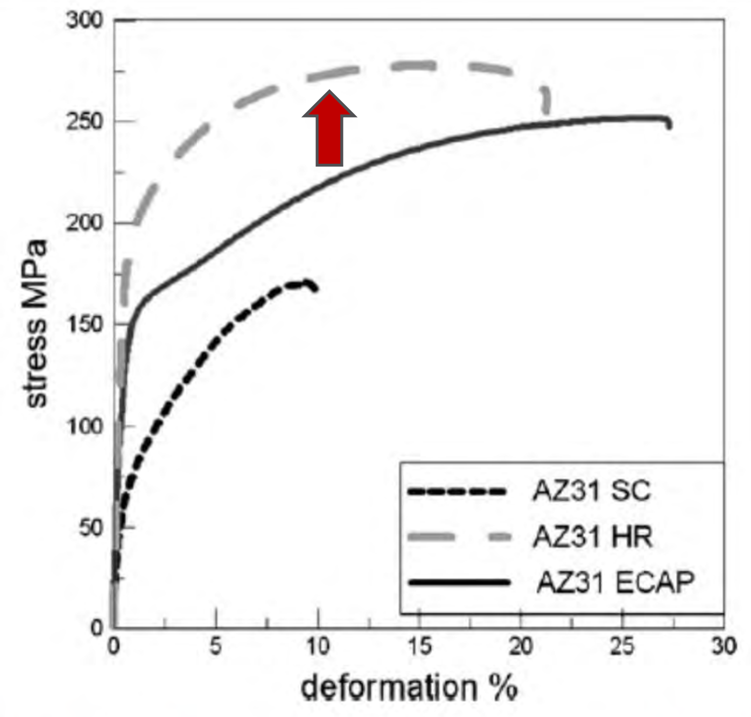


Fig. 4—Tensile curves of AZ31 in squeeze-cast, hot-rolled, and ECAP conditions.

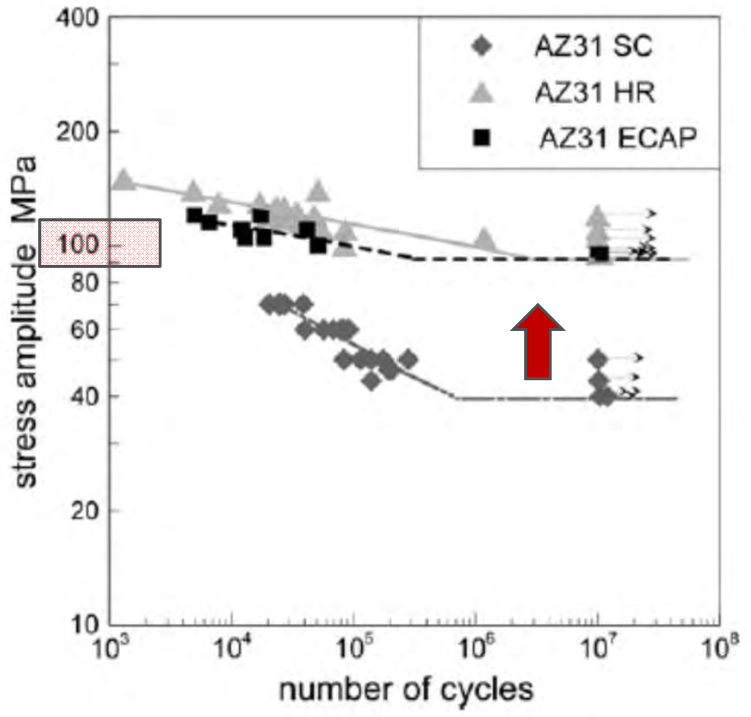
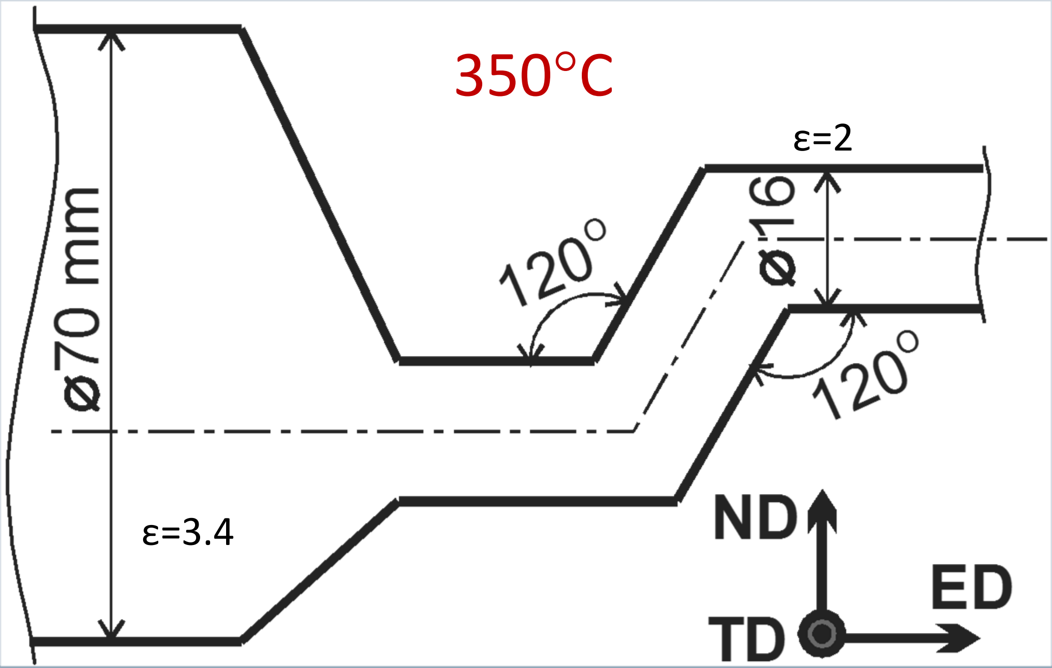


Fig. 5—Comparison of fatigue life of AZ31 in squeeze-cast, hot-rolled, and ECAP conditions.

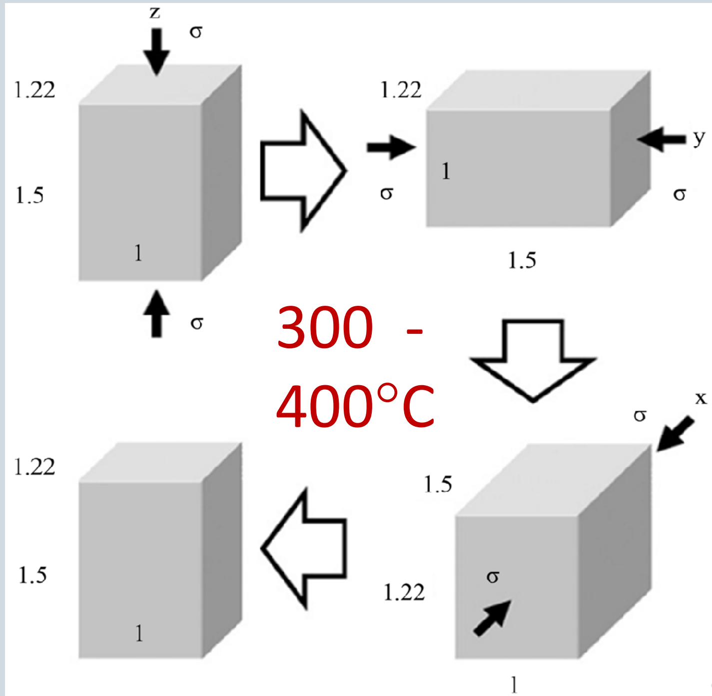
[Zuberova et al., Met Mat Trans A (2007)]

Processing of Mg-alloys

Integrated Extrusion + ECAP



Multi-axial Isothermal Forging (MIF)

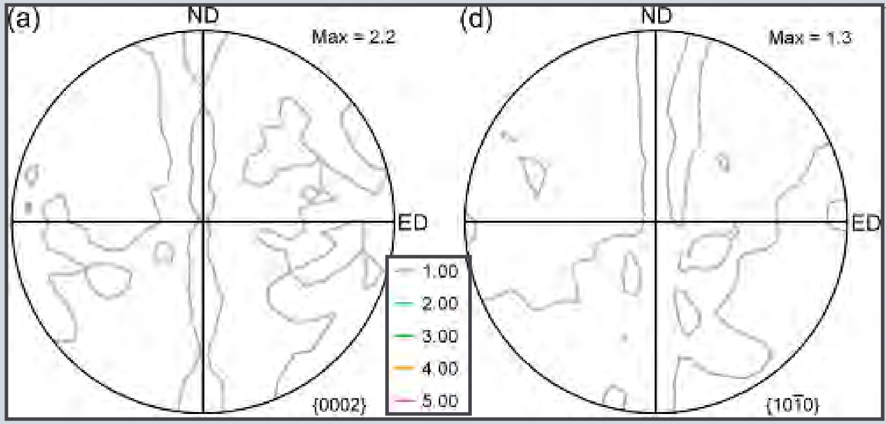


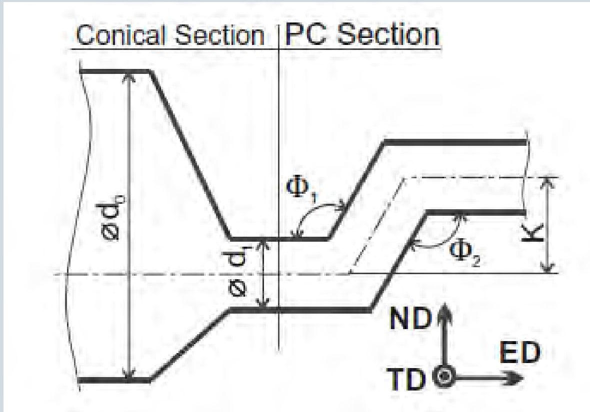
[Orlov et al., Acta Mat (2011)]

[D. Nugmanov et al. , Metals (2015)]

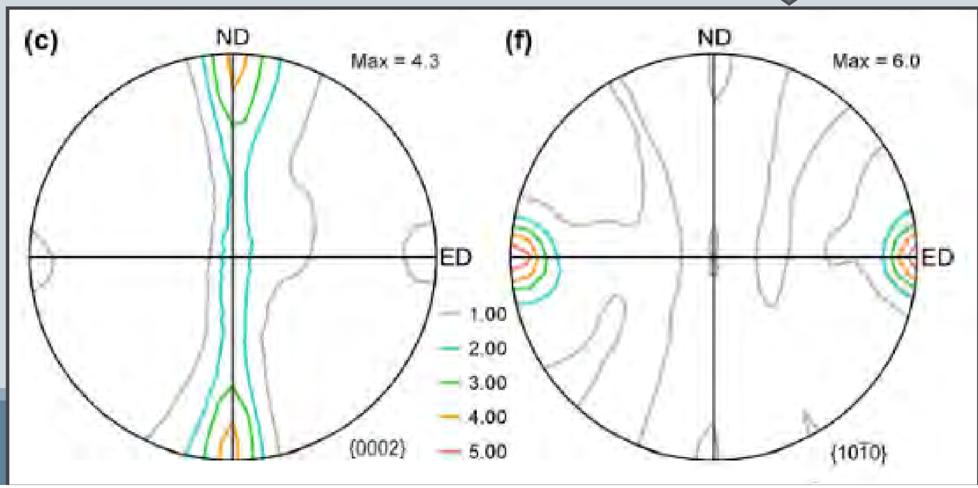
Severe Plastic Deformation of Mg-Zn-Zr alloy ZK60. Integrated Extrusion +ECAP

Orlov et al, Acta Mater. 2011





- Weak texture ,
  70 μm grain size (coarse grain)



- Strong texture,
  2 μm grain size after IE (fine grain)

Improvement of monotonic and fatigue properties

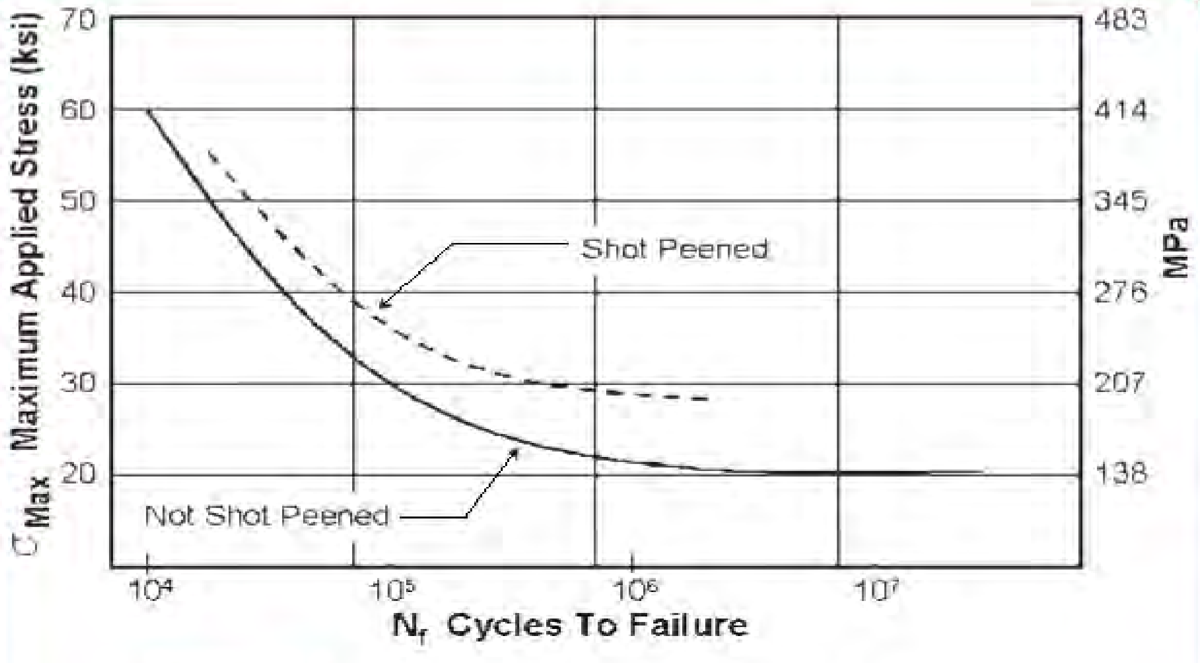
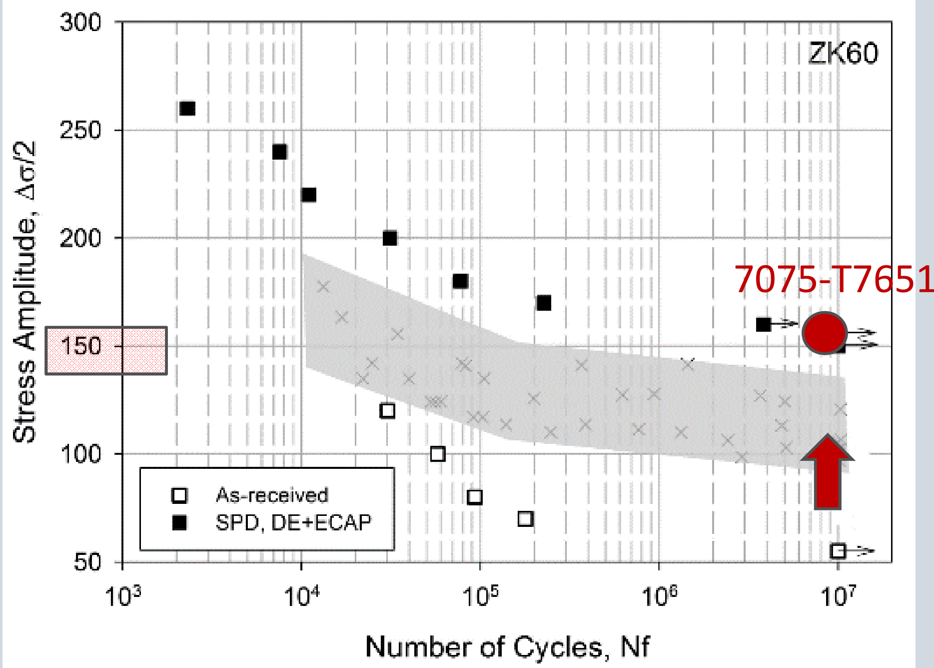


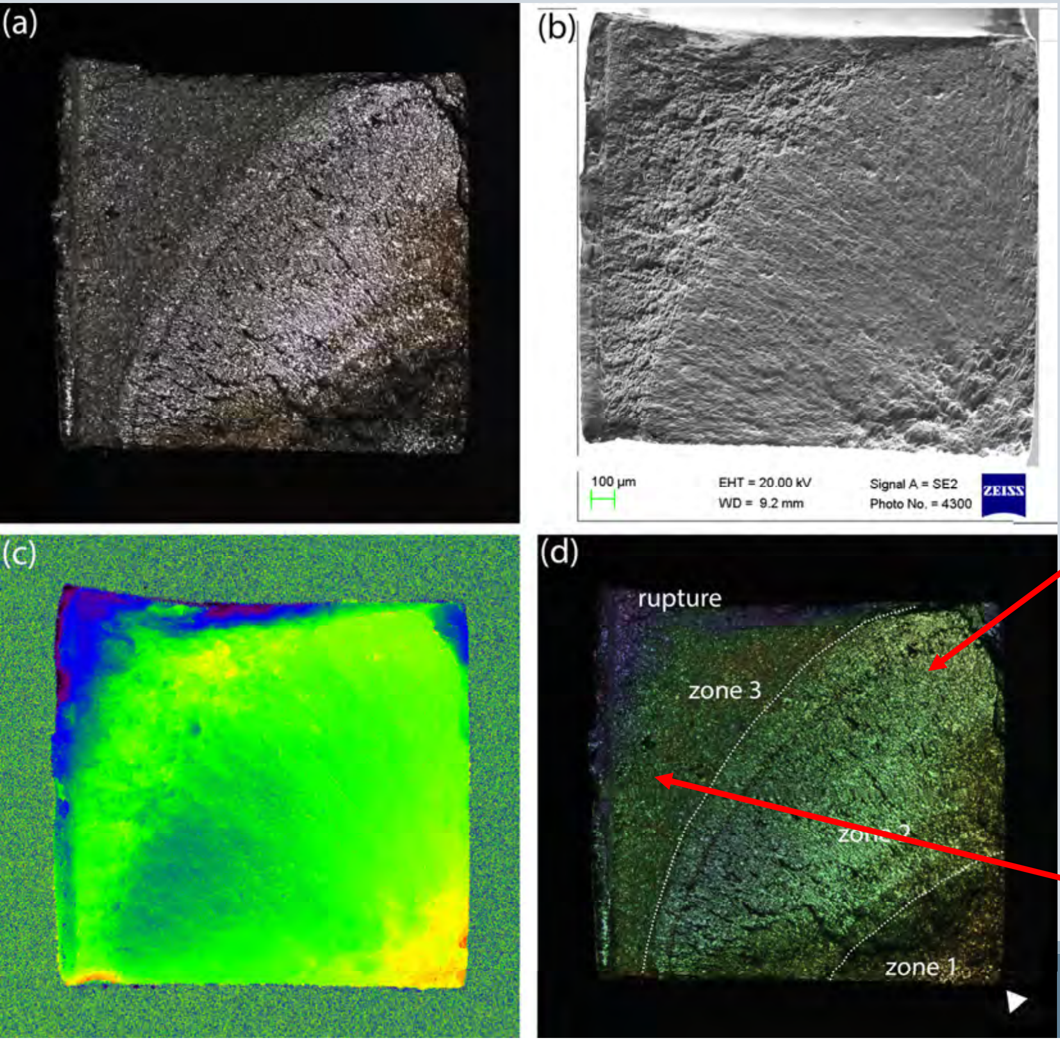
FIGURE 2-3 *S-N Curves for Shot Peened Aluminum Alloy 7050-T7651*

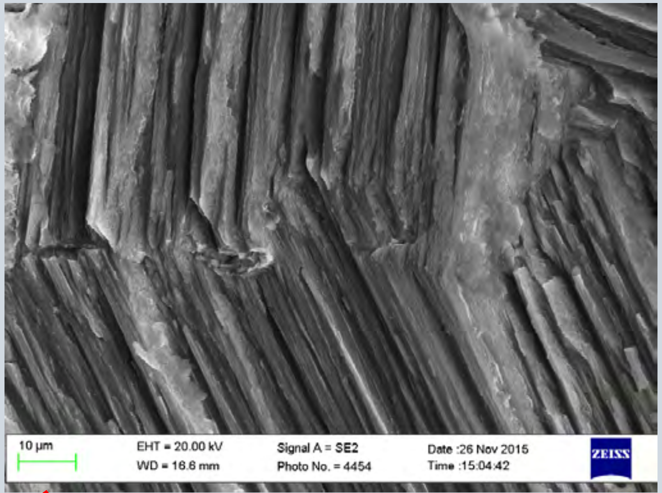


[Orlov et al., Acta Mater, 2011]

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

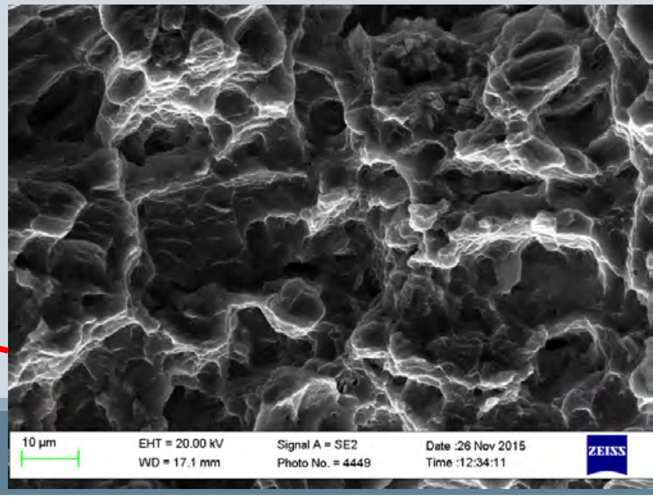
Fatigue Fractography





Stable crack

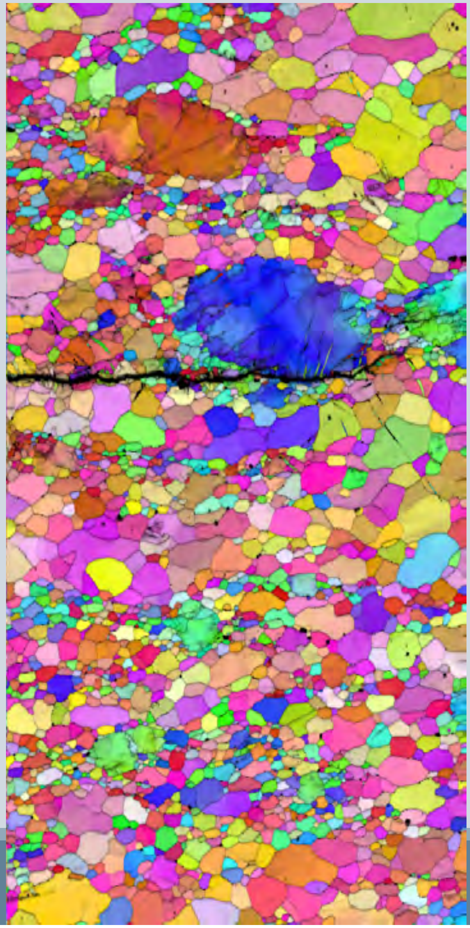
Basal slip

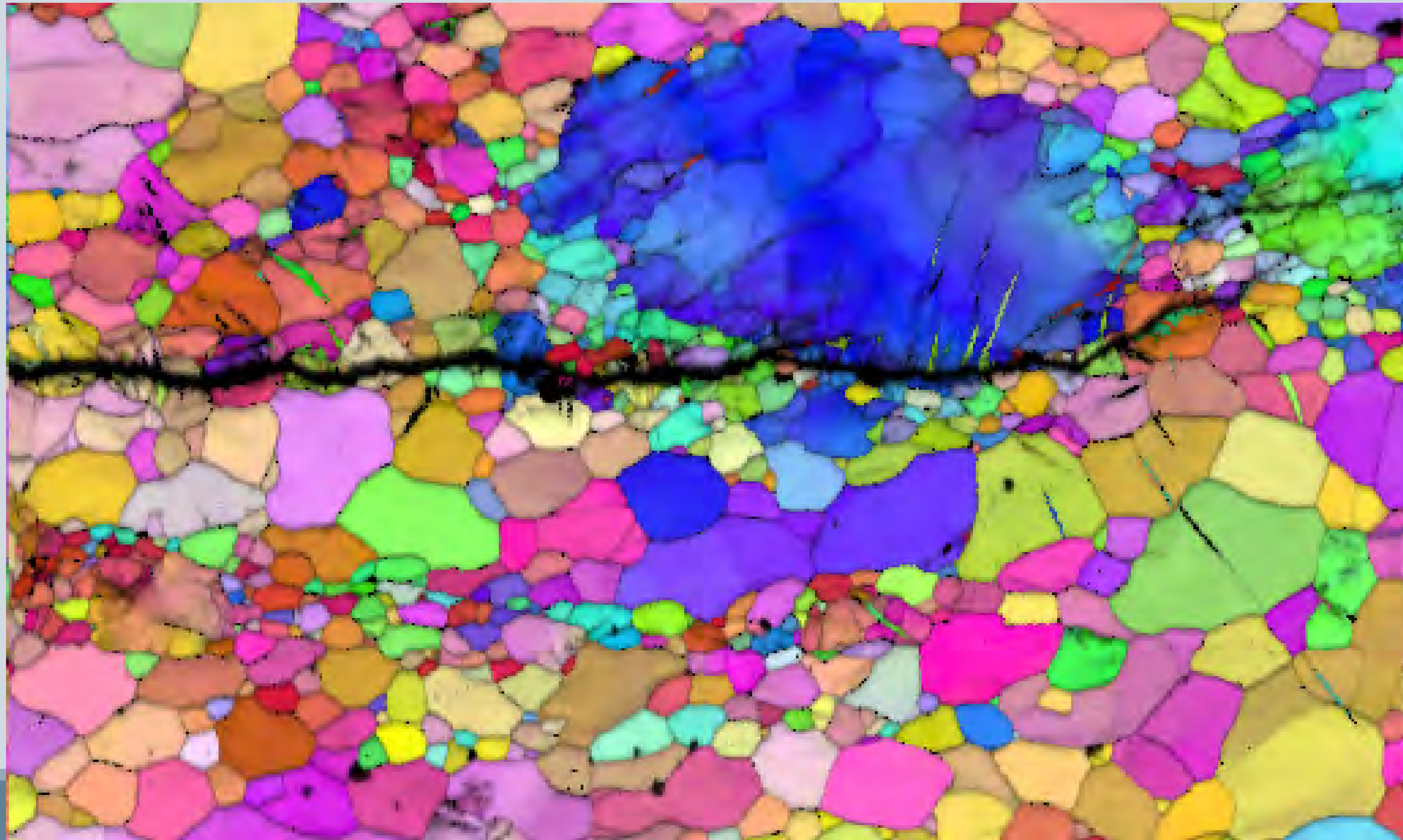


Rupture

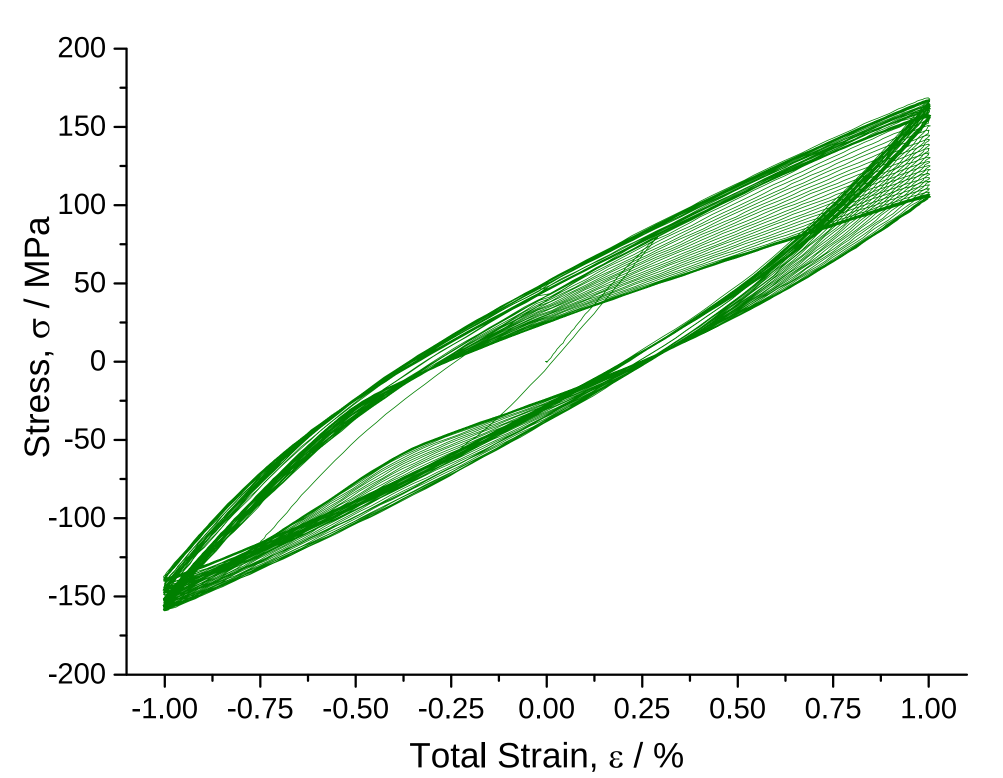
Dimples

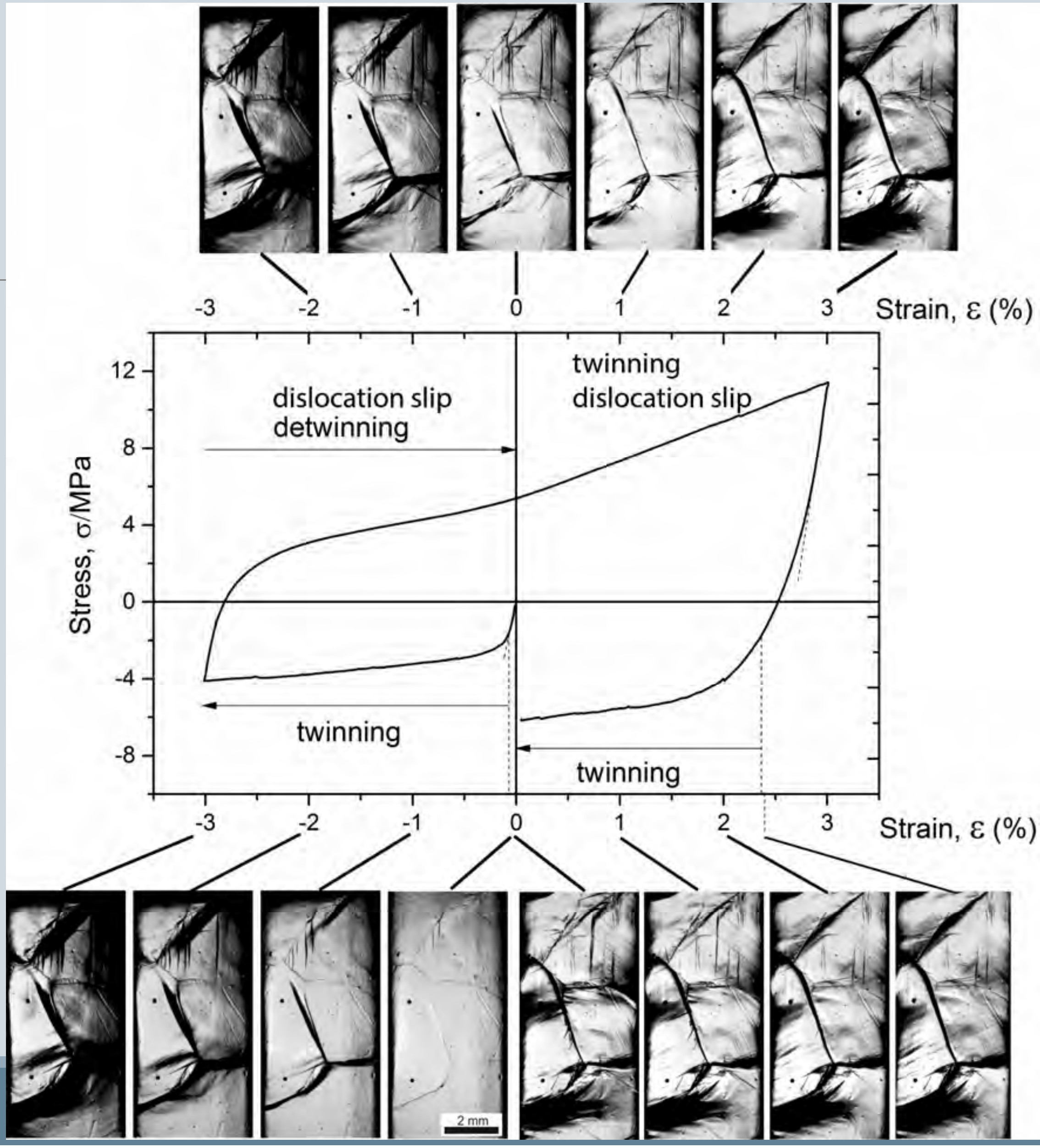
Fatigue crack propagation



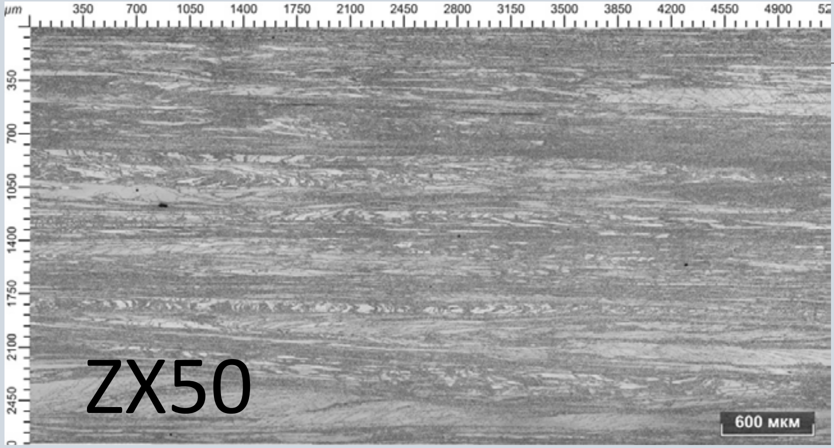


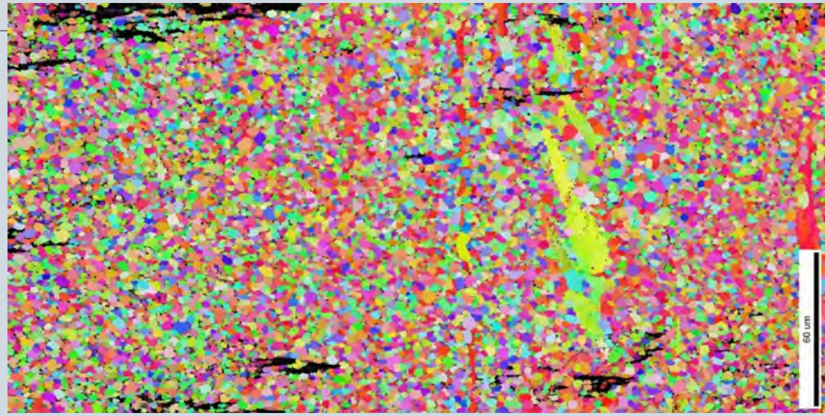
Key importance of twinning-dislocation Interaction

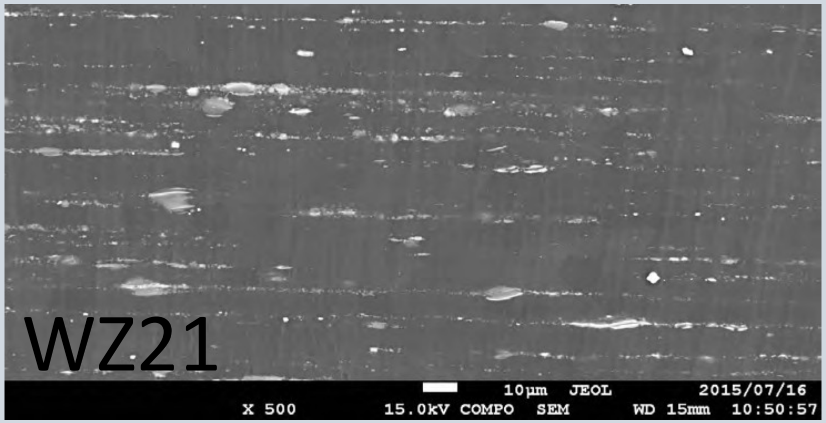


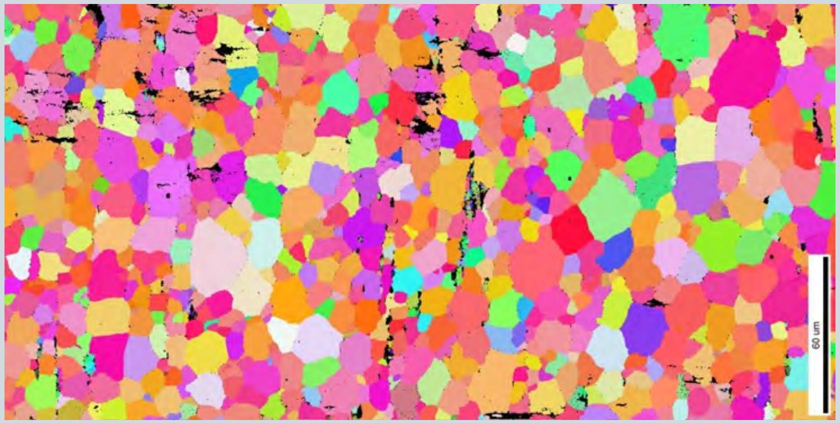


Microstructure (Extrusion)

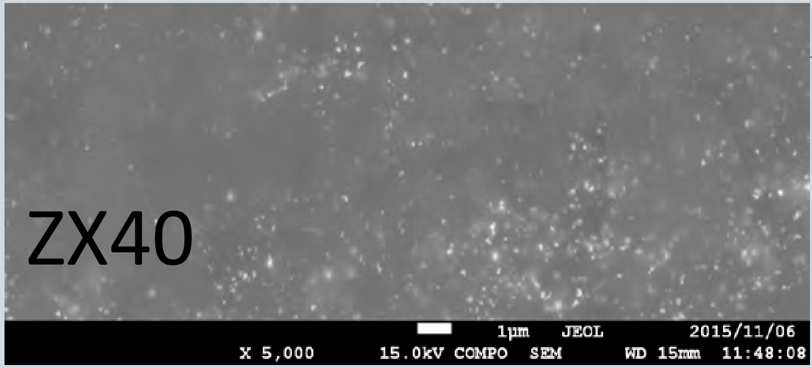


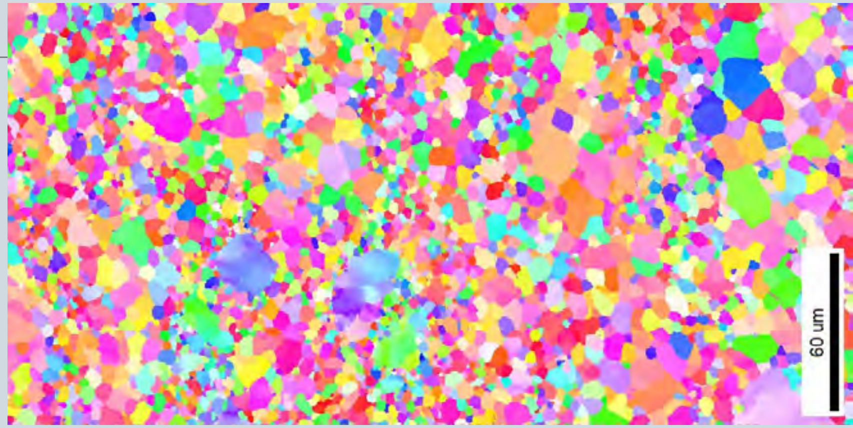




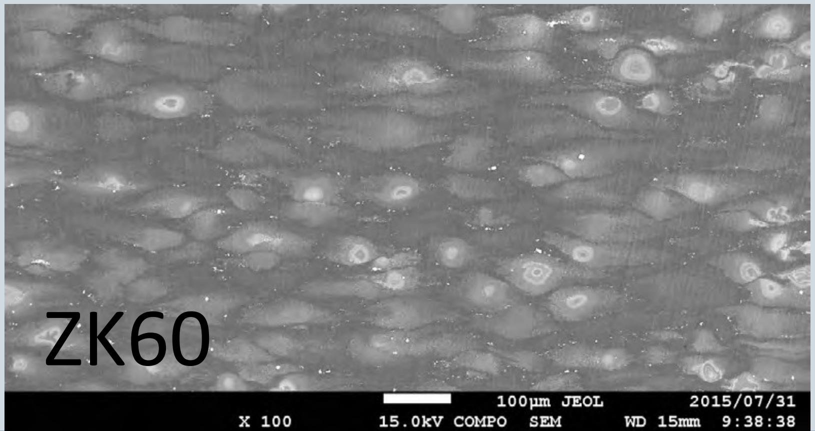


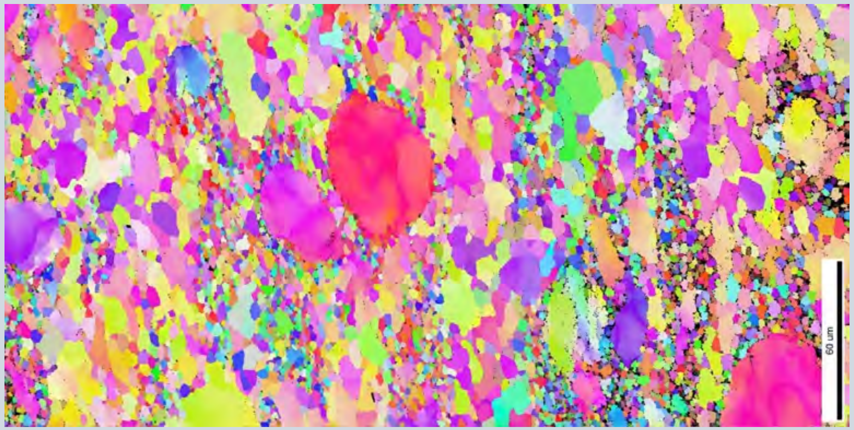
Microstructure





Mg-4Zn-0.56Ca
ECAP (320 C)





Mg-6Zn-0.5Zr
MIF (400 C)

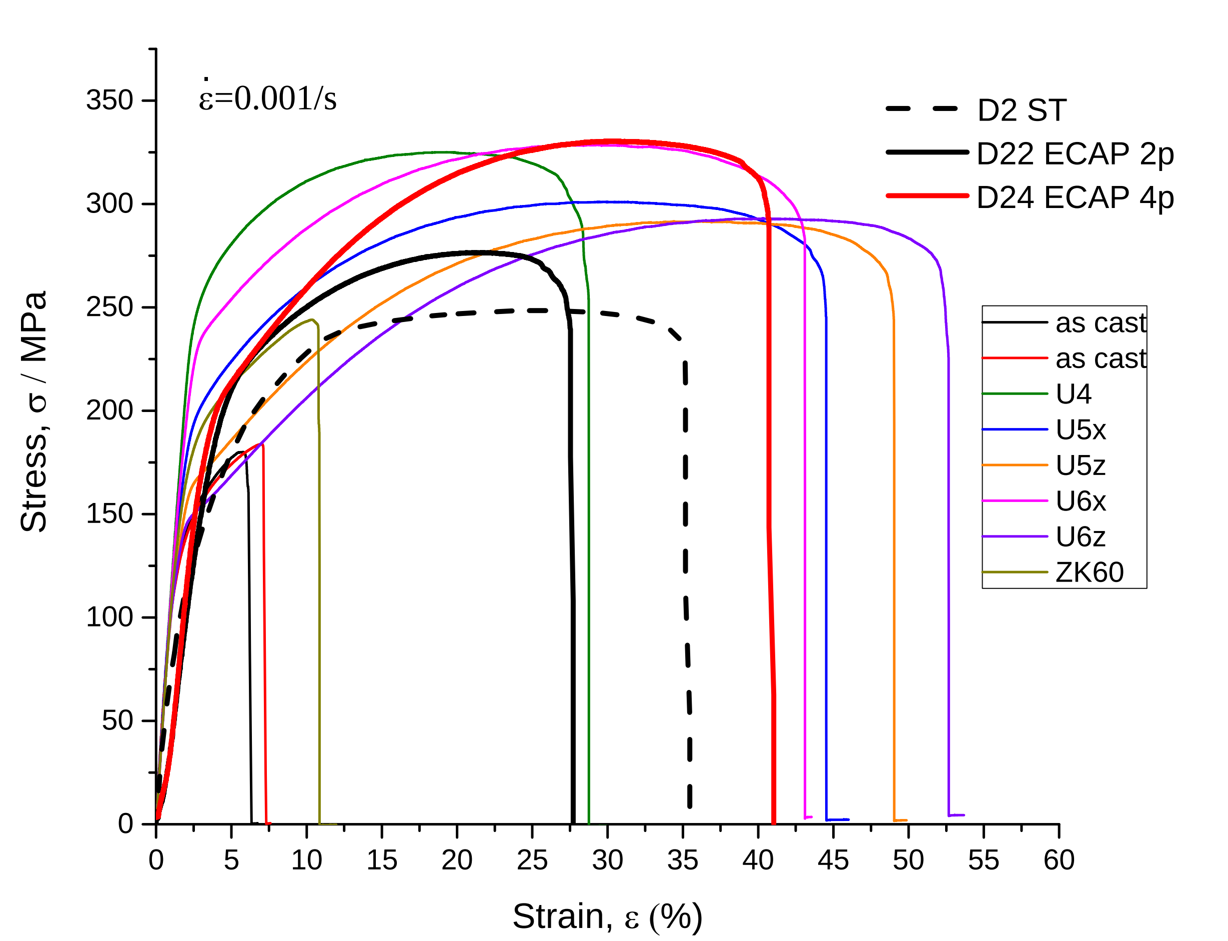
Spectrum of Tensile Stress-Strain Curves

ZK60

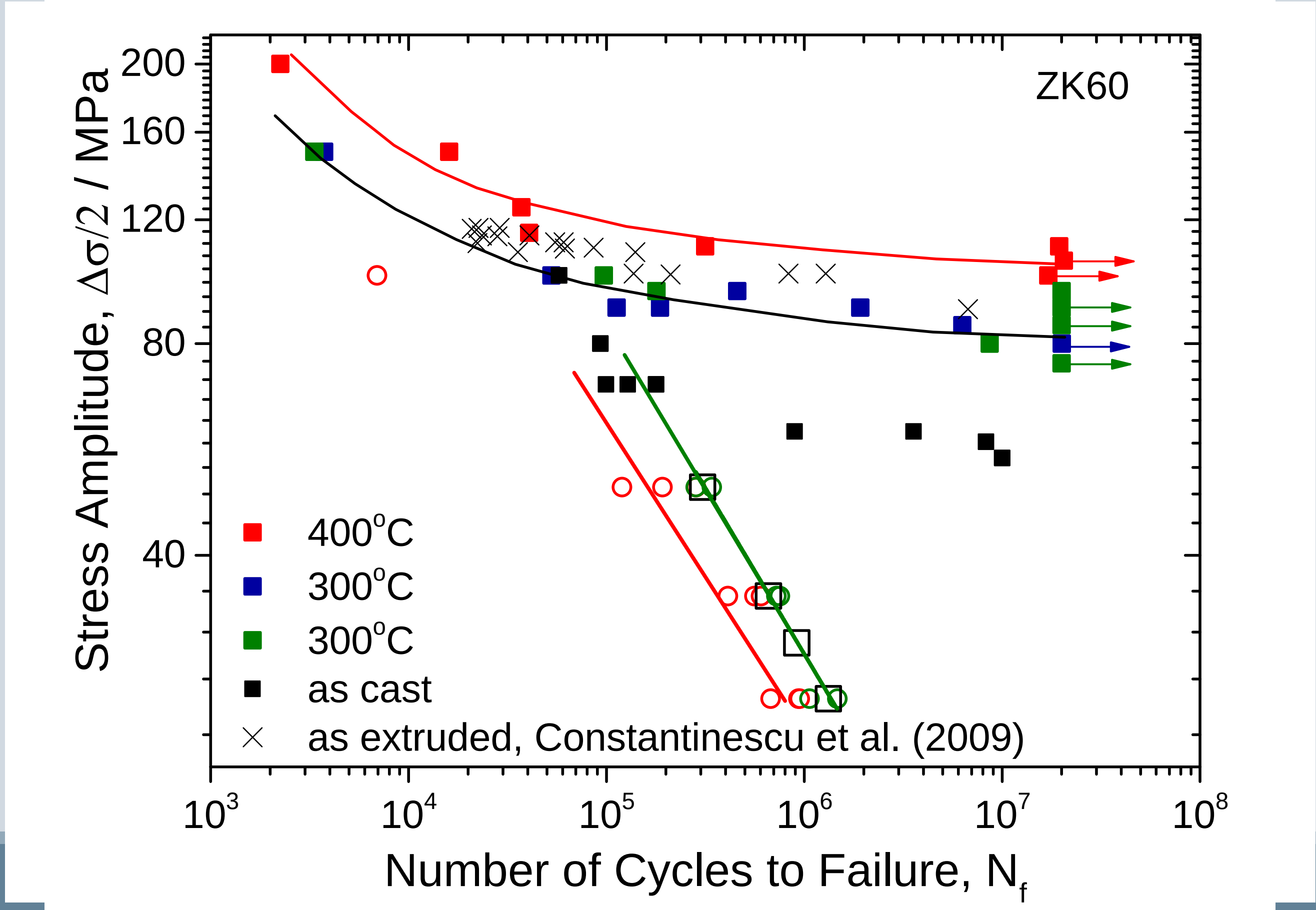
Effect of processing

ECAP

MIF

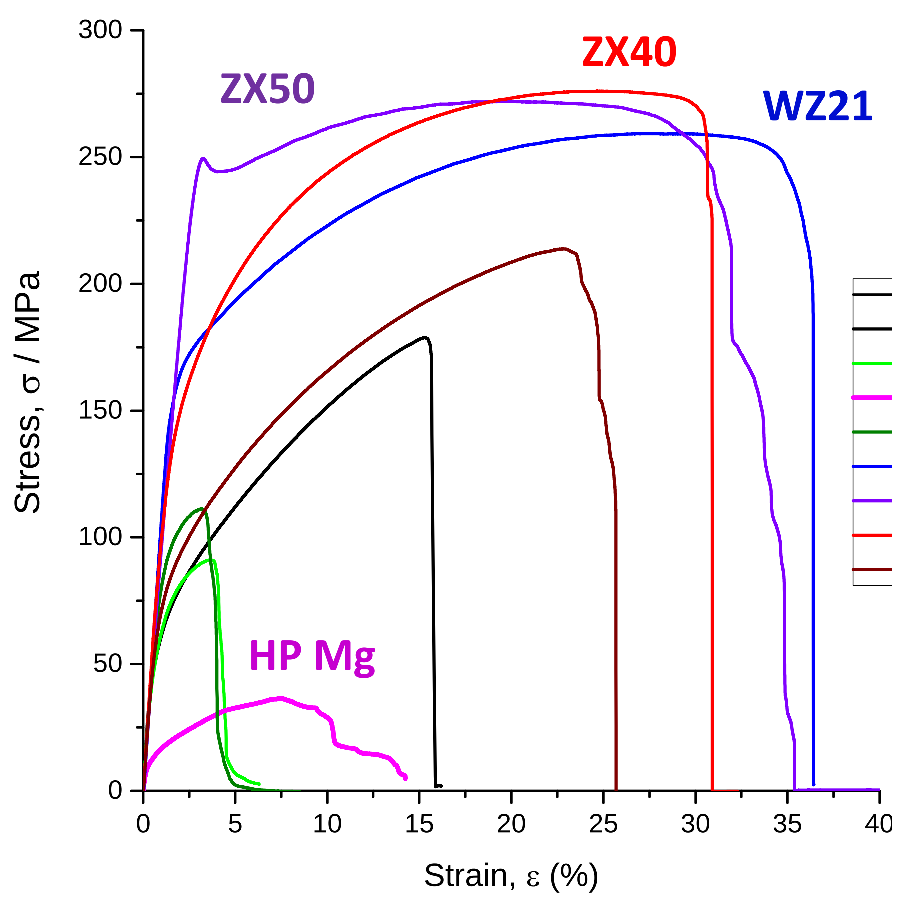


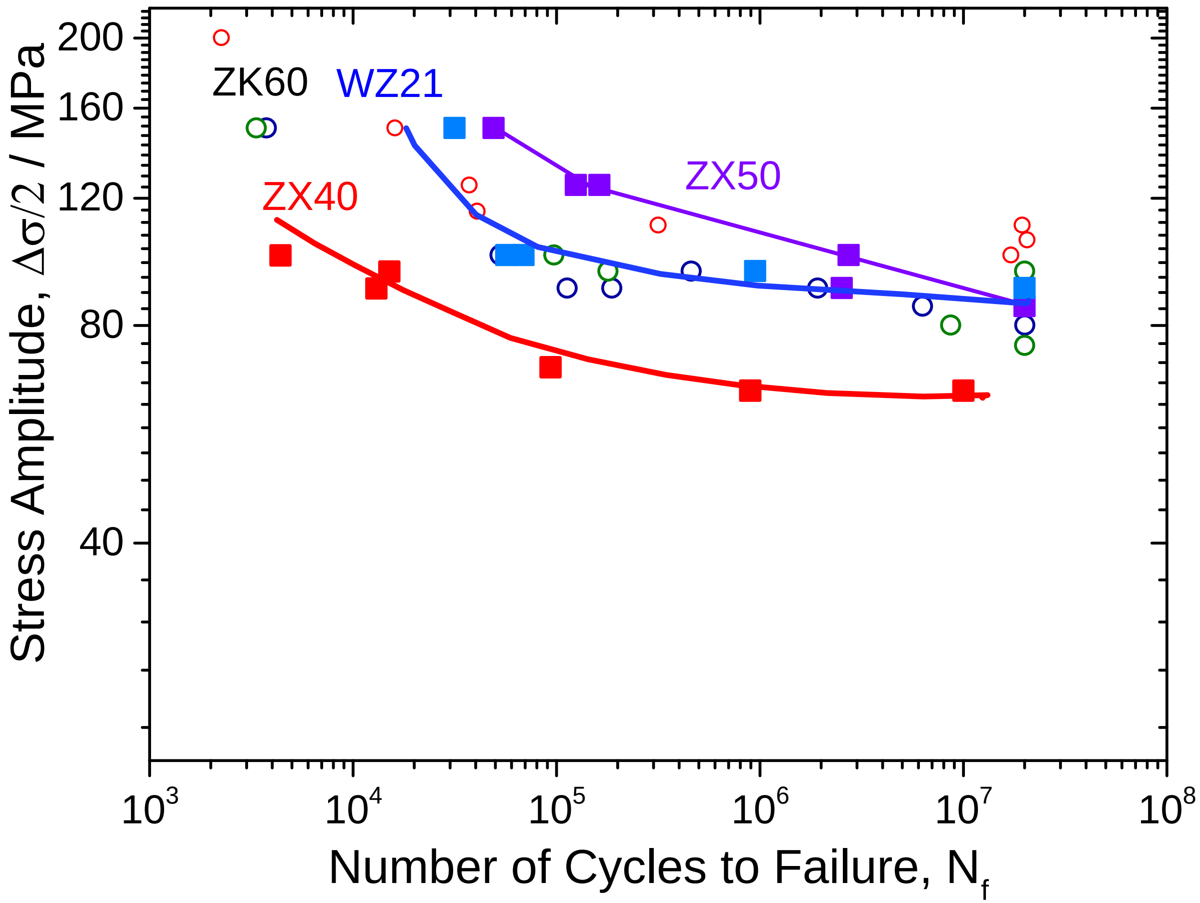
Effect of warm SPD on Fatigue of ZK60 alloy



Standard Saline solution ,
pH=7.0
T=37 °C

Properties of biodegradable alloys





Corrosion Properties

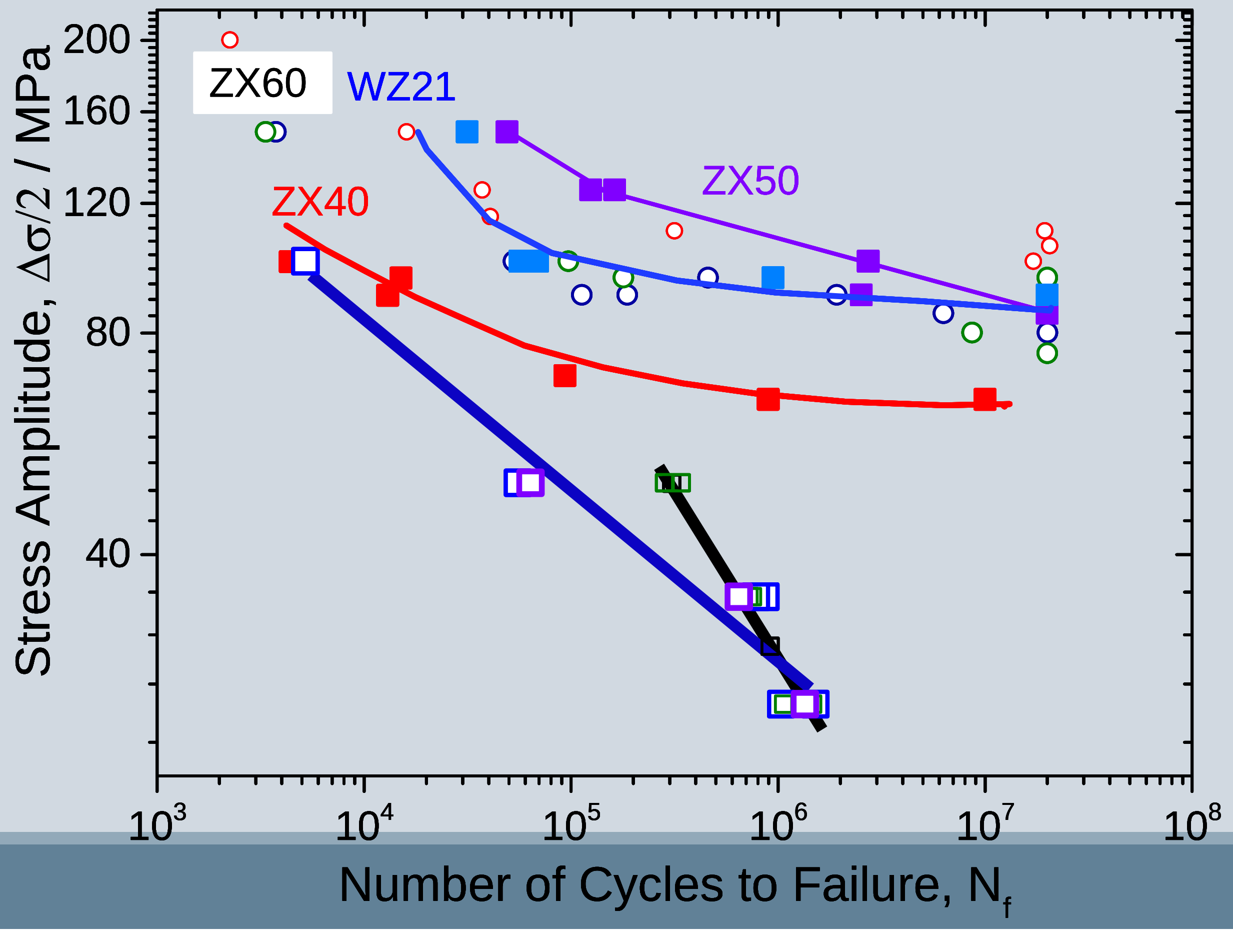
Impedance technique

Standard Saline solution , pH=7.0

T=37 ^{o}C

Alloy	Composition	Corrosion rate, mm/year	Surface roughness, Sq, μm^2
ZK60 Integrated Extrusion + ECAP	Mg-6Zn-0.5Zr	1.01±0.04	3.431
ZK60 MIF 400 C	Mg-6Zn-0.5Zr	0.95±0.01	4.665
ZK60 MIF 300 C	Mg-6Zn-0.5Zr	0.73±0.02	3.344
Mg-4Zn	Mg-4Zn	0.71±0.01	7.168
ZX40 (A) ECAP	Mg-4Zn-0.16Ca	1.36±0.02	3.344
ZX40 (B) ECAP	Mg-4Zn-0.56Ca	1.30±0.12	5.084
ZX50 (XHP) Extruded	Mg-5Zn-0.25Ca	**0.24±0.02**	1.245
WZ21 (extruded)	Mg-1.65Y-0.85Zn-0.25Ca	0.85±0.07	3.246

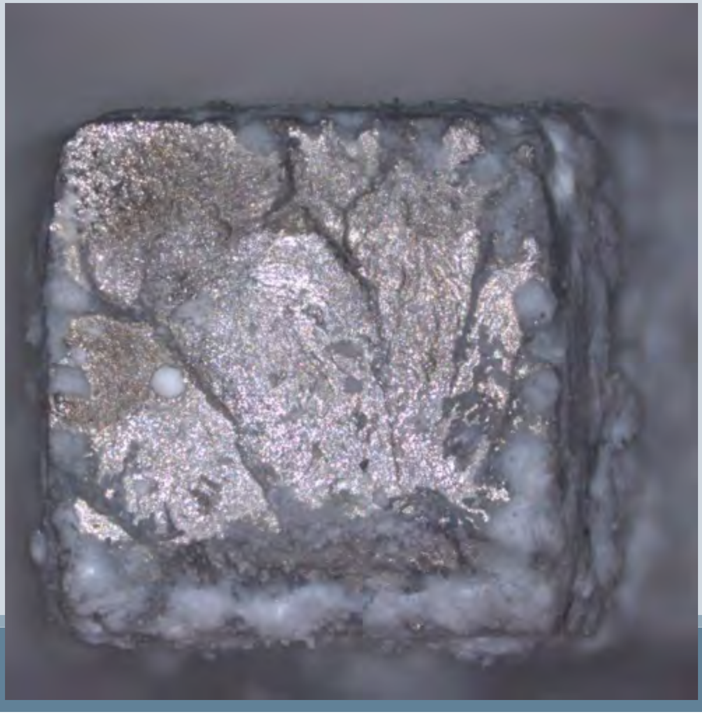
Fatigue and Corrosion Fatigue of Biodegradable Alloys

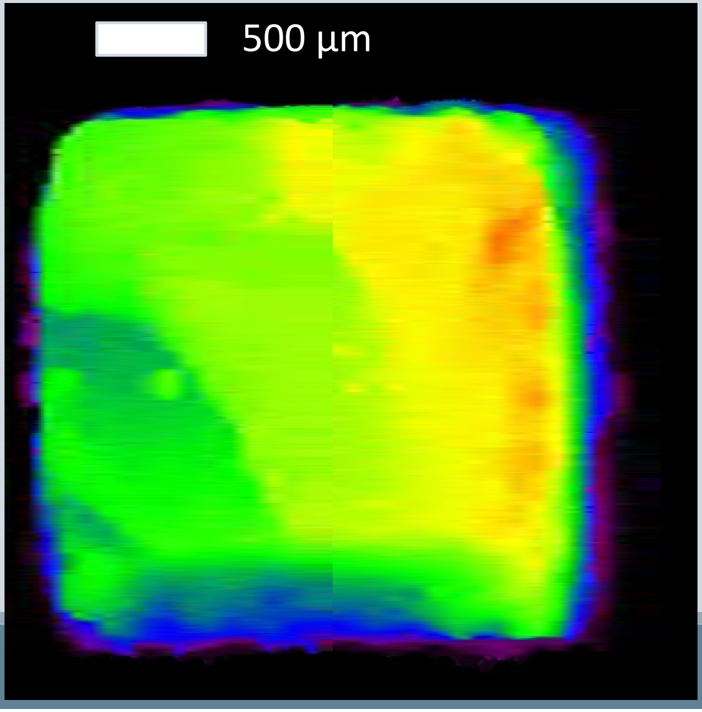


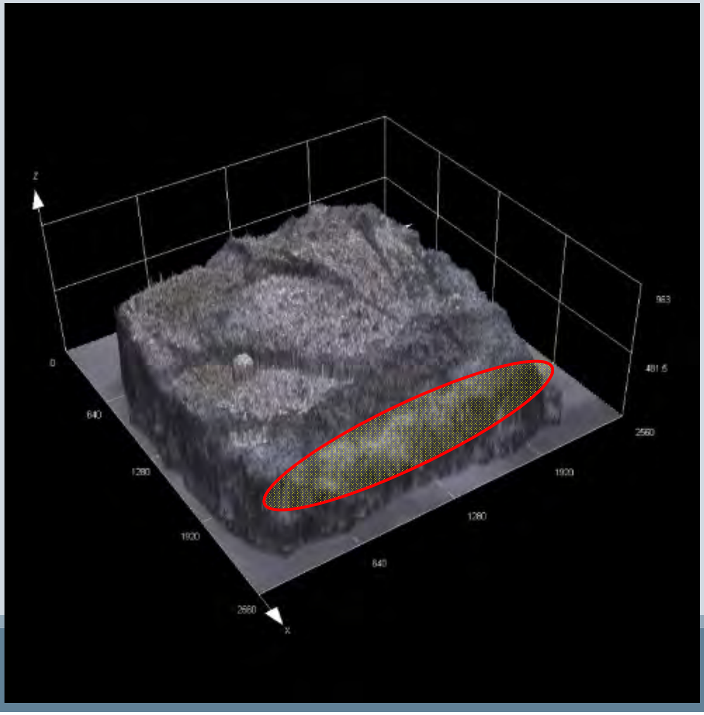
Strong effect of corrosion on crack initiation

Corrosion Fatigue Fractography

- Environment-affected fatigue crack initiates at the surface
- Corrosion process under cyclic stress promotes crack initiation even at very low stress
- Once initiated, the crack dominates the distribution of local stresses and propagates very fast regardless of a particular microstructure of the alloy







LPSO Mg97Y2Zn1

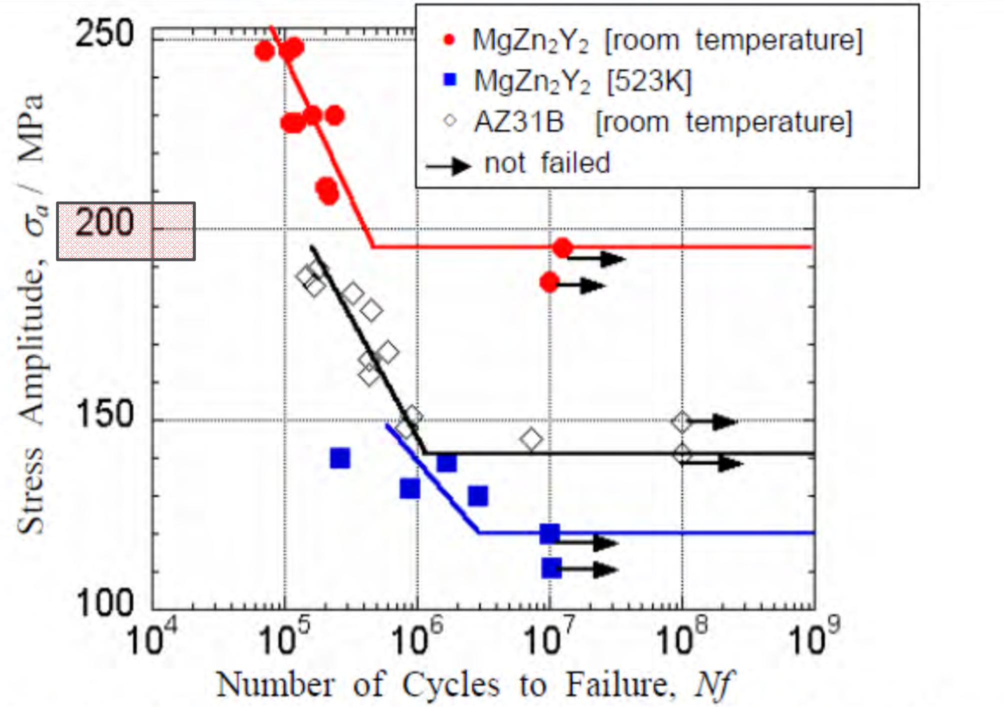
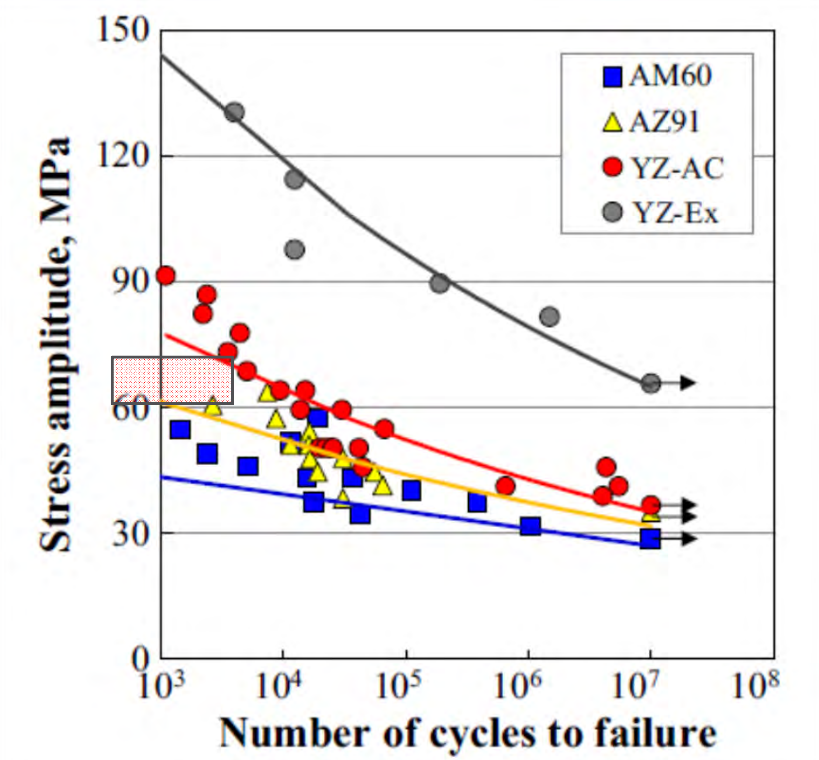


Fig. 4 S-N curves of $Mg_{96}Zn_2Y_2$ alloy and AZ31B alloy.



Conclusions and Open Questions

- ✓ HCF performance of magnesium alloy ZK60 after processing by integrated extrusion+ECAP improves **significantly** to of 160 MPa, which is about three times larger than the value for the initial material.

- ✓ The observed enhancement of endurance and fatigue strength is related to the increase of ductility and ultimate tensile strength as a result of the integrated processing and grain refinement.

- ✓ Nature of fatigue in Mg alloys
  - o Asymmetry of the plastic hysteresis ???
  - o Role of dislocation –twinning interaction ?
  - o De-twinning??
  - o Nature of the Bauschinger effect and the role of microsplasticity ????
  - o LPSO???