Anisotropy and Voiding at High Strain Rates in a Mg Alloy Extrudate

INTRODUCTION

The low density of magnesium (Mg) alloys (1.74 g/cm^3) makes them attractive for structural automotive applications due to improved fuel economy and vehicle performance through reduced weight. However, the deformation mechanisms that dominate in crash-type scenarios (high strain rates ($\dot{\varepsilon}$)) are not well known. At low $\dot{\varepsilon}$, the accommodation of plastic deformation in Mg hexagonal close packed (HCP) crystals is typically accomplished through twinning. In order to provide a shape change in the hexagonal crystal, Mg alloys tend to twin on:

1) $\{10\bar{1}2\}$ planes to extend the c-axis (“extension” twins), or
2) $\{10\bar{1}1\}$ planes followed by re-twinning on $\{10\bar{1}2\}$ planes to contract the c-axis (“contraction” twins).

PROCEDURE

Tensile bars were sectioned from an AM30 double-hat extrudate (typical crumple zone geometry) in two orientations relative to the extrusion direction (ED):

1) parallel (||ED)
2) perpendicular (⊥ED).

The bars were tested in tension at *high strain rates* (~500s^{-1}) using a modified flywheel rotary hammer and at *low strain rates* (0.01s^{-1}) using traditional tensile testing equipment.

The crystallographic texture was measured using electron backscattered diffraction (EBSD). The extrudate had a strong preferred orientation with the basal planes being parallel to the ED (see ***Figure 1***).

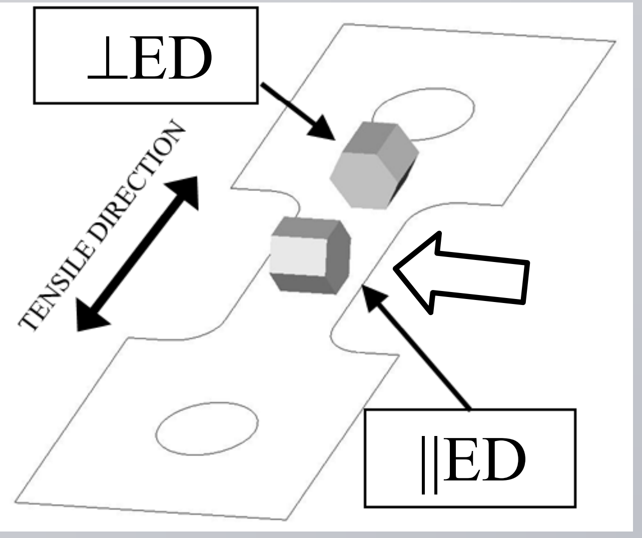

Fig. 1: Orientation of the HCP crystal in the ||ED and ⊥ED tensile bars. The white arrow indicates the viewing plane of the micrographs in Figures 2-8.

ILLUMINATION TECHNIQUE

Due to anisotropy in Mg HCP crystals, the microstructure was best viewed using:

a) bright field illumination (**BF**) ||ED
b) polarized light (**POL**) ⊥ED

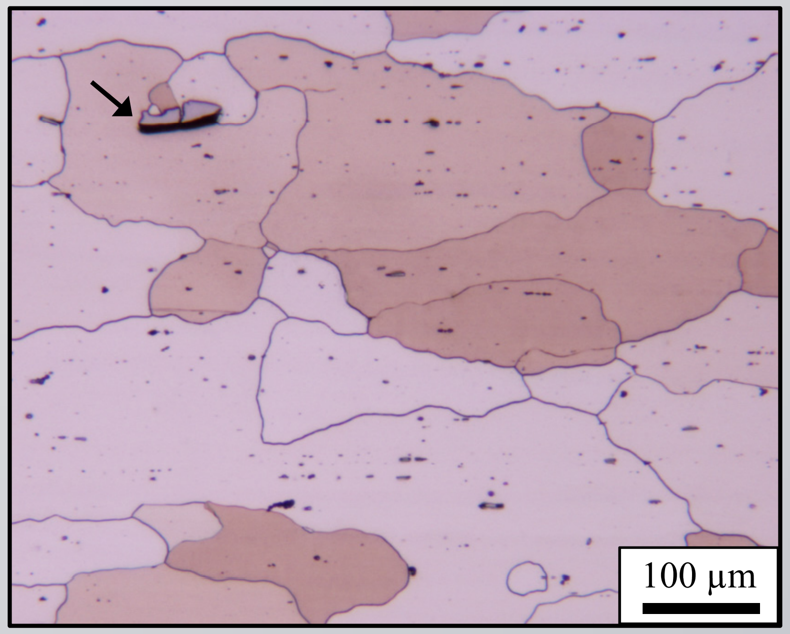

Fig. 2: As-extruded microstructure ||ED (BF).

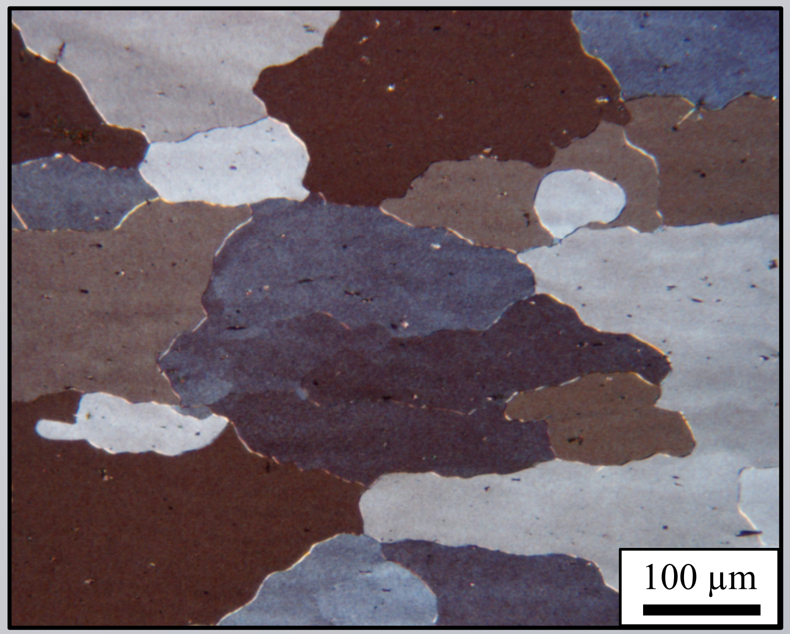

Fig. 3: As-extruded microstructure ⊥ED (POL).

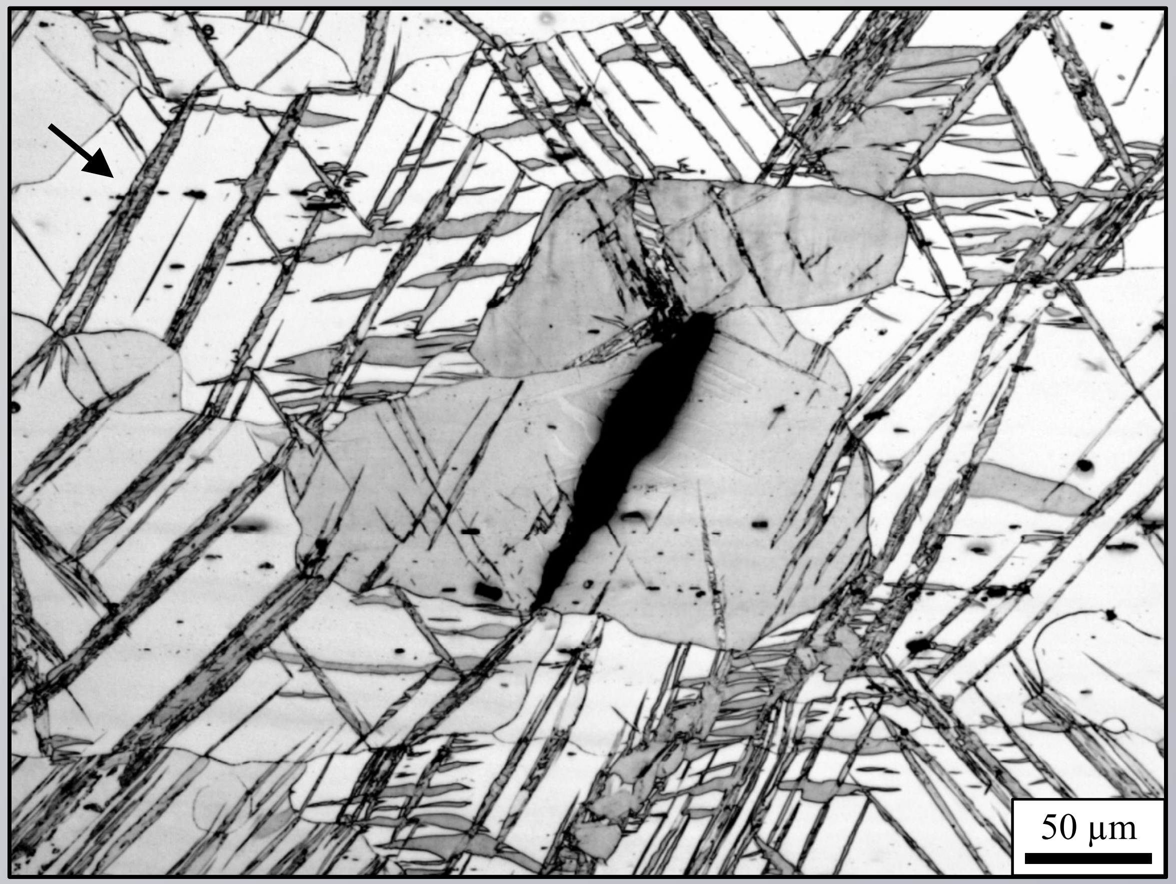

Fig. 4: High $\dot{\varepsilon}$ tension ||ED (BF). Contraction twins (arrow) and voiding.

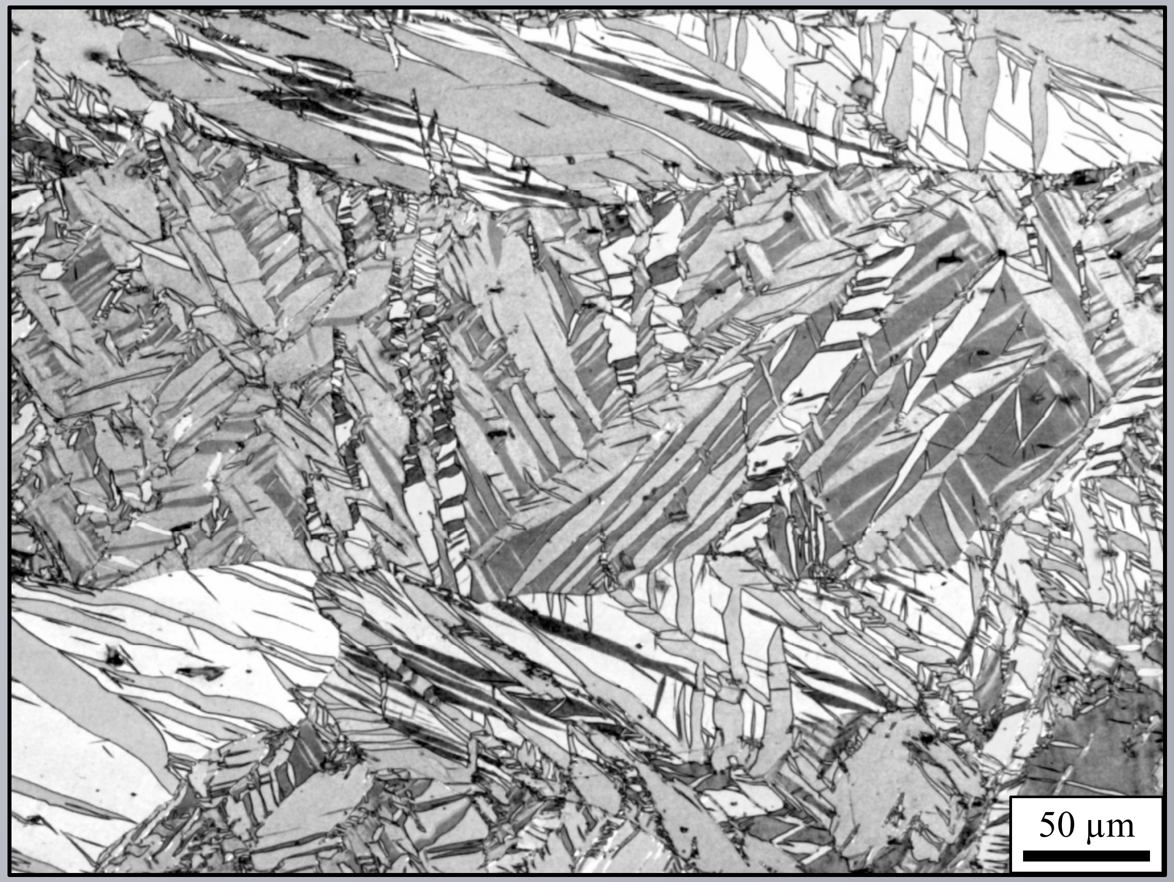

Fig. 5: High $\dot{\varepsilon}$ tension ⊥ED (POL). Extension twins and double twinning.

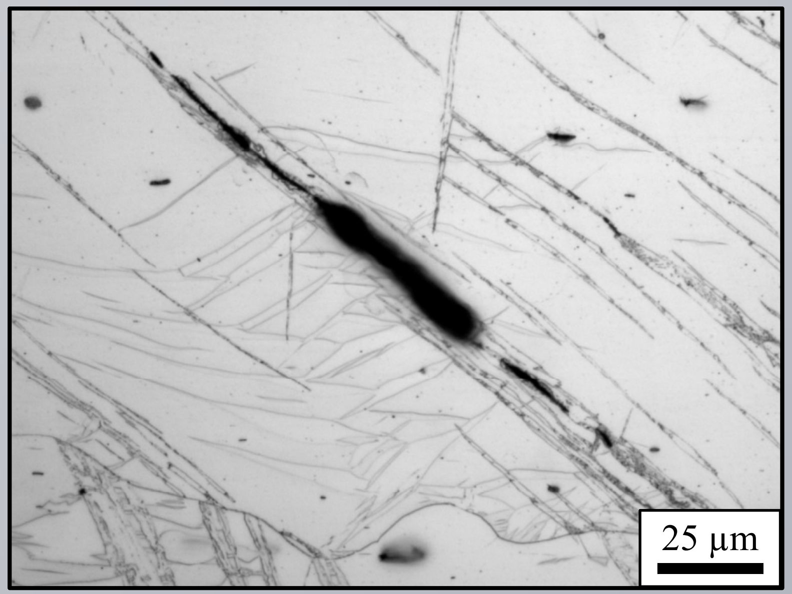

Fig. 6: Voiding in contraction twins (BF). ||ED. High $\dot{\varepsilon}$.

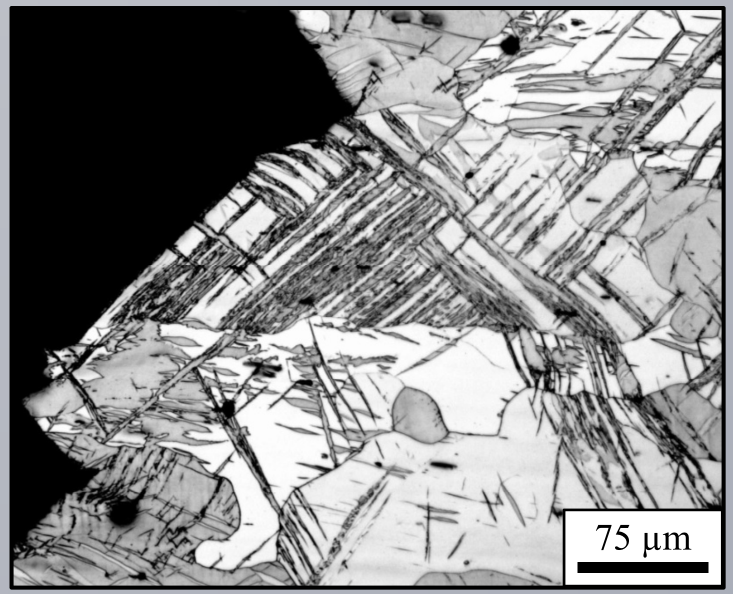

Fig. 7: *High $\dot{\varepsilon}$*: Transgranular failure due to contraction twinning (BF). ||ED.

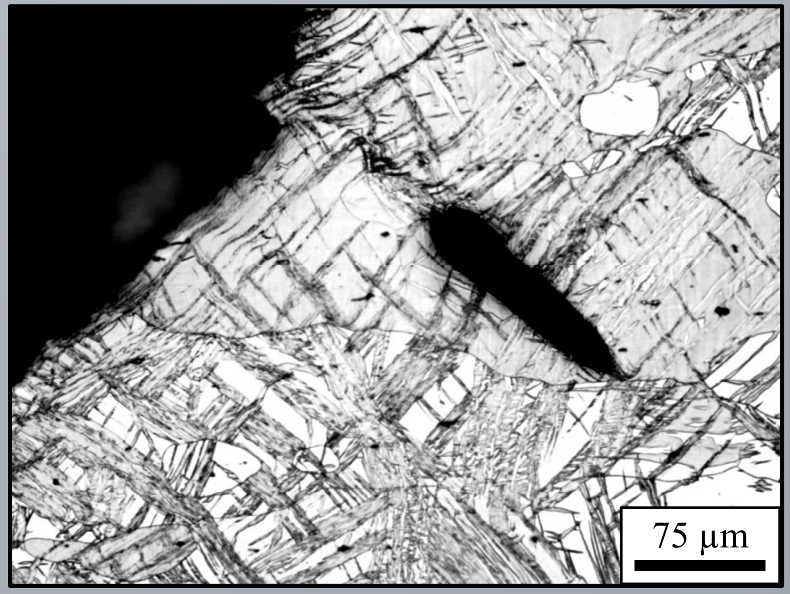

Fig. 8: *Low $\dot{\varepsilon}$*: Voiding and transgranular failure due to contraction twinning (BF). ||ED.

ANISOTROPY

As-extruded microstructures (***Figure 2 and Figure 3***)
- Very similar in both orientations.
- No deformation twins.

After loading in tension at high $\dot{\varepsilon}$
- ||ED: Contraction Twins (arrow in ***Figure 4***)
  - *Thin, dark, compress c-axis.*
- ⊥ED: Extension Twins (***Figure 5***)
  - *Wide, clean inside, elongate c-axis.*

VOIDING / FAILURE

- Voids form in contraction twins (***Figure 6***)
- Voids are arrested by grain boundaries (***Figure 4***)
- Voids lead to a reduction in cross sectional area, stress concentrations, and premature failure
- Contraction twins lead to transgranular failure ||ED
  - Same failure mode at:
    - High $\dot{\varepsilon}$ (~500s^{-1}) (***Figure 7***)
    - Low $\dot{\varepsilon}$ (0.01s^{-1}) (***Figure 8***)

METALLOGRAPHIC SPECIMEN PREPARATION

Challenges to preparing magnesium alloys:

1) The material is soft and prone to smearing and scratching.
2) Large hard intermetallic particles (arrow in ***Figure 2***) can pull out and contaminate cloths.
3) Grinding and polishing can induce deformation twins.
4) Magnesium stains readily when exposed to water.

A preparation technique was developed for Mg alloy AM30 that can be applied to other similar wrought magnesium alloys.

Grinding

Grinding was performed automatically using low pressures starting with 320 grit SiC grinding paper lubricated with ethylene glycol, followed by subsequent 400 and 600 grit grinding steps for 48 seconds each (steps were repeated as necessary).

Mechanical Polishing

Automatic polishing was done using an alcohol based 6µm diamond suspension for 6 minutes with low pressure on a Struers DP-Dur™ cloth. Next, the mount was hand polished using a 6µm diamond paste on a Buehler Microcloth™ (to remove staining), an alcohol based 3 µm diamond spray on a Struers Mol™ cloth, and a 1 µm diamond spray on a Struers Nap™ cloth for three minutes each.

Chemical Polishing

A solution of 100mL methanol, 12mL HCl and 8mL HNO$_3$ for 10 sec. produced a flat, stain, and scratch free surface.

Etching

Acetic picral (4g picric acid, 5mL acetic acid, 10mL H$_2$0, 100mL ethanol) for 2-5 seconds until the surface flashed brown.

Cleaning

Cleaning of the mounts after polishing and etching involved dipping in and spraying with ethanol, then ultrasonically cleaning in ethanol and hot air drying. After the chemical polish, methanol was used instead of ethanol.

CONCLUSIONS

Different twinning modes significantly change the yielding behavior:

- ||ED: crystallographically “hard” orientation
  - High yield strength, softens after yielding
  - Strain localizes around contraction twins
    - Creates voids and leads to transgranular failure
- ⊥ED yields relatively easily
  - Strain hardens to failure
  - High twin volume hinders dislocation motion

Class 1