A Nanoindentation Study on Shock-compressed Mg Single Crystals

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Introduction

Motivation:

- **Magnesium (Mg) as a structural material:** high strength to weight ratio [1]

  $\rho_{Mg} \approx 1800$ g/cm^3 vs. $\rho_{Steel} \approx 8000$ g/cm^3

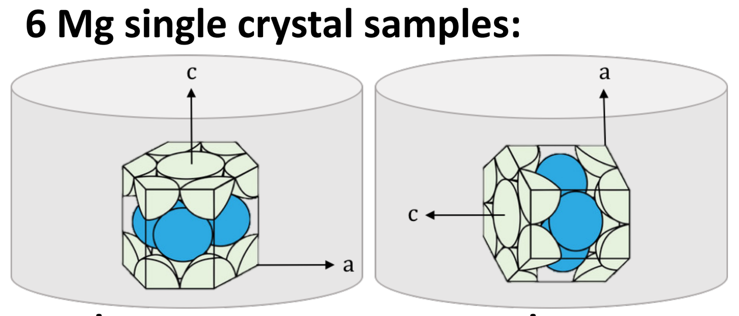
  e.g. increased efficiency in transportation and military vehicles
- **Shock compression induces high strain rates** which permantantly alter a material's internal structure and cause deformations.
- Analogous to the stresses experienced by armor and structural components of military vehicles during warfare.[2]

Fundamental understanding of high strain rate deformation in Mg enables the development of light-weight and high strength armor & structural components.

Strain rate and deformation mode:

- Recent investigations have shown magnesium single crystals to exhibit three variants of deformation twinning at impact speeds of 55-60 m/s.[3]
- Micropillar compression studies carried out at a **very slow strain rate (10^{-5} s^{-1})** displayed only dislocation-based work hardening & no deformation twinning.[4]

6 Mg single crystal samples:



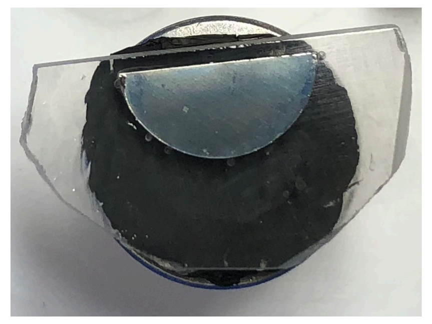
c-axis	a-axis
• 0 m/s (unshocked)	• 0 m/s
• 200 m/s (~450 mph)	• 200 m/s
• 400 m/s (super-sonic)	• 400 m/s

The resulting plasticity and micro-structure of extremely high and super-sonic impact velocities—and their effect on the mechanical properties of magnesium—is currently unknown.

Methods

Sample Preparation:

- Samples prepared and shock compressed by Army Research Laboratory (ARL), Aberdeen Proving Ground (APG).
- Impacts were conducted using a gas gun and tungsten carbide flyer assembly at velocities of 200 and 400 m/s. Following impact, the target assembly was gradually decelerated through a series of foams to minimize secondary impacts.[5]

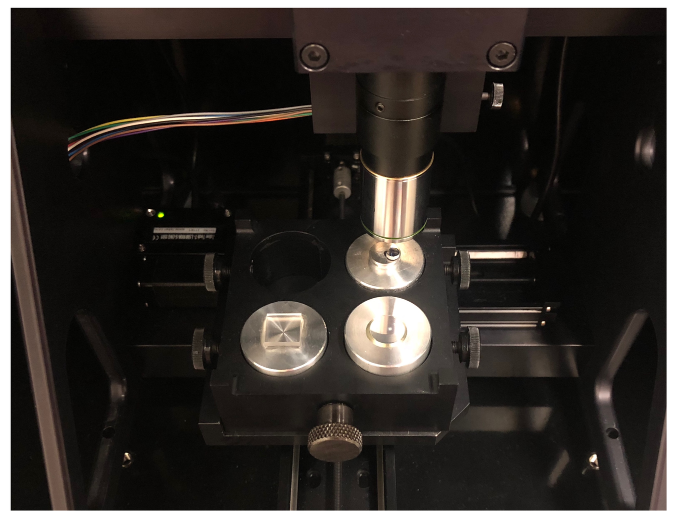


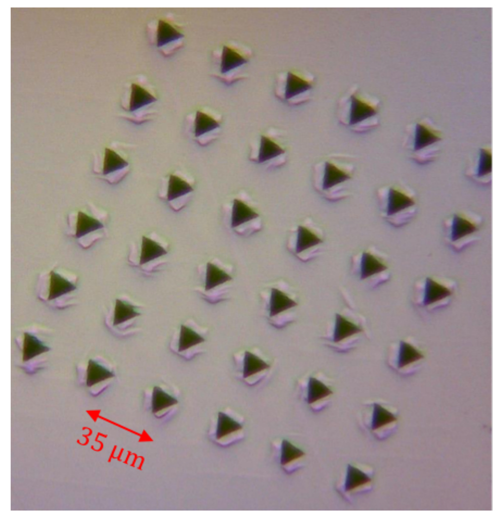
- The samples were polished using a colloidal silica polishing suspension (Buehler MasterMet) and de-ionized water until a visually clean surface was obtained through an optical microscope.

Nanoindentation:

- Produces microscale array of indents on material surface to characterize hardness (H) and Young's Modulus (E)
- 2 rounds of nanoindentation on 6 samples – 12 data sets
- H and E averaged from 1000-1800 nm due to indentation size effects[6]
- To calculate final values for mean hardness and Young's modulus, indentation data from each individual test of each round was pooled

Nanoindentation Specifications	
Tip	Berkovich
Strain Rate	0.200 % s^{-1}
Array Size	6x6 w/35 μm spacing
v_{sample}	0.280
Target Load	45 mN
Target Depth	5000 nm

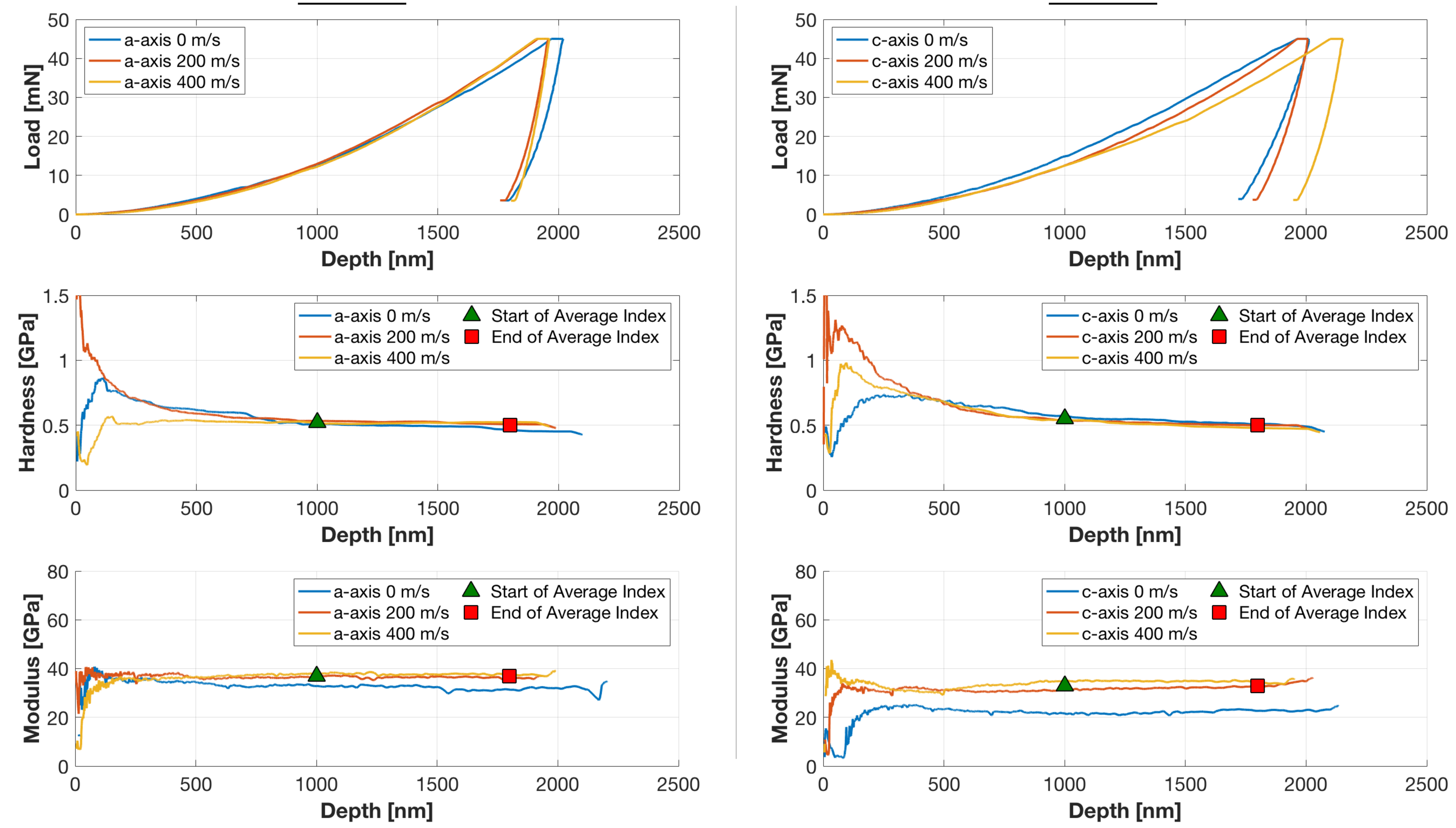




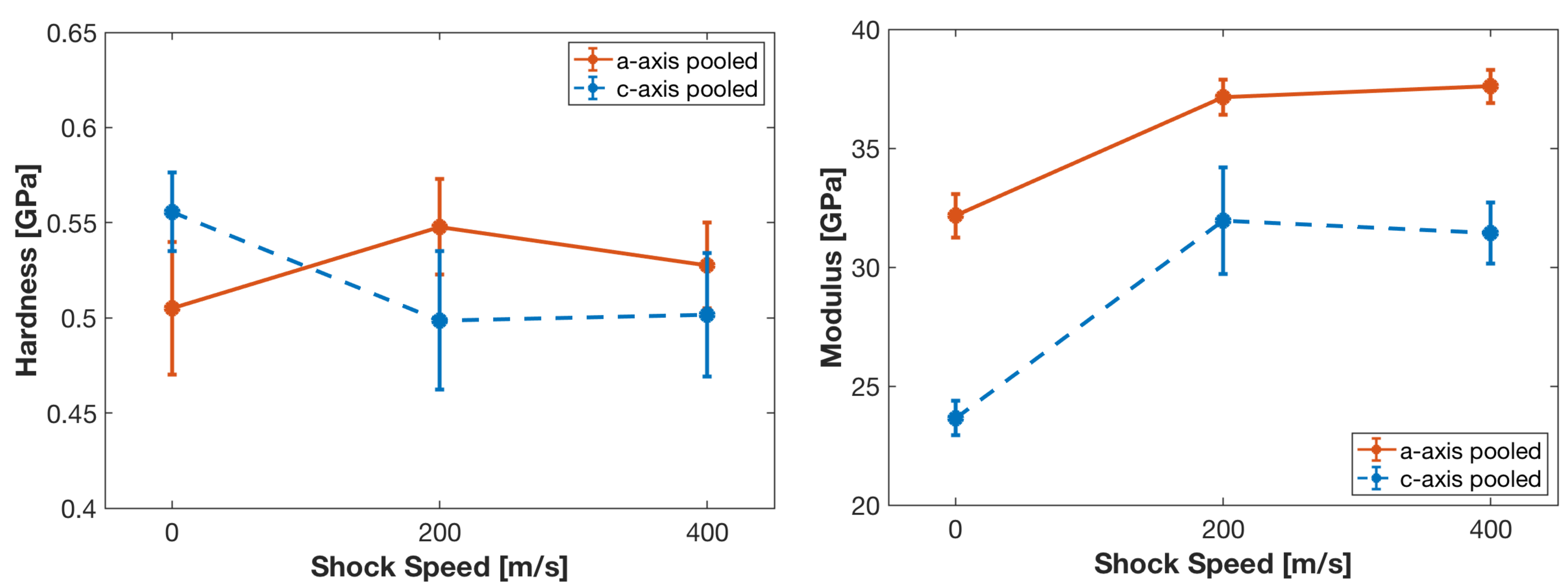
Results

1) Load, hardness, and modulus vs. indentation depth

a-axis **c-axis**



2) Pooled hardness and modulus as a function of shock velocity



3) Optical microscope images of deformation twin bands

a-axis

0 m/s 200 m/s 400 m/s

c-axis

0 m/s 200 m/s 400 m/s

Discussion

1) Dislocation density (Taylor Size Effect Equation)

- Hardness is not a strong function of shock speed along a- or c-axes
- This implies that the dislocation density does not increase after shock-compression

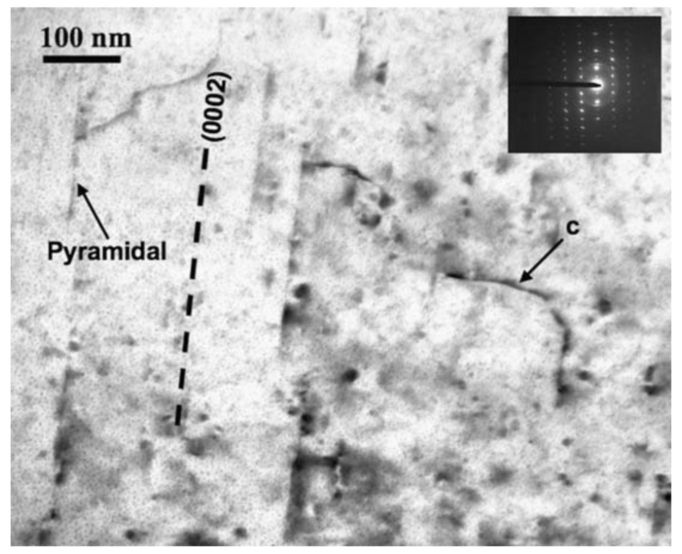
Taylor size effect equation [7]:

$$\sigma_y = \sigma_0 + \alpha G b \sqrt{\rho}$$
$$\vdots$$
$$H \propto \sigma_y \propto \sqrt{\rho}$$

Hardness (*H*) is proportional to sq. root of dislocation density (*ρ*)

Deformation mode may be "purely" deformation-twinning

2) Change in deformation mode under fast strain rate



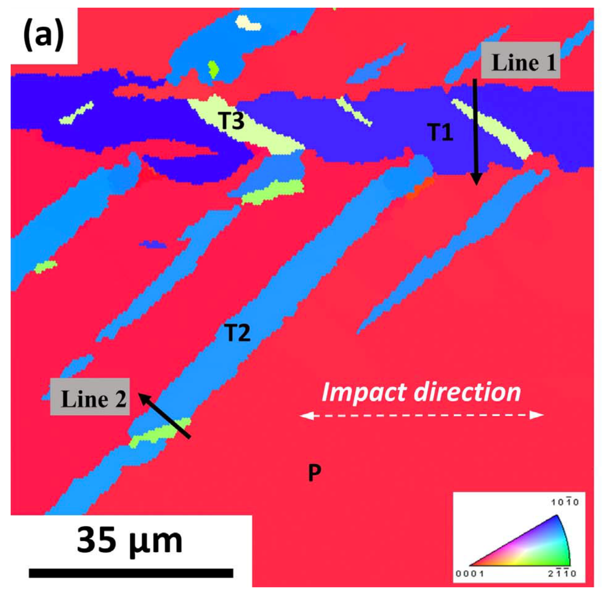
Transmission Electron Microscope (TEM) image of deformed Mg single crystal following micropillar compression. Courtesy of Cynthia M. Byer et al. from "Microcompression of single-crystal magnesium" [4].

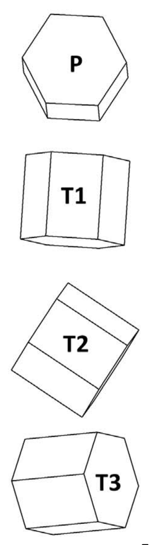
TEM results by Byer et al. indicate that <u>significant strain hardening</u> and <u>no deformation twins</u> are present following compression at a strain rate of 10^{-5} s^{-1}.

This indicates that a deformation mode change from dislocation plasticity to twin plasticity occurs from slow to fast deformation.

3) Crystallographic orientation effects

(a)





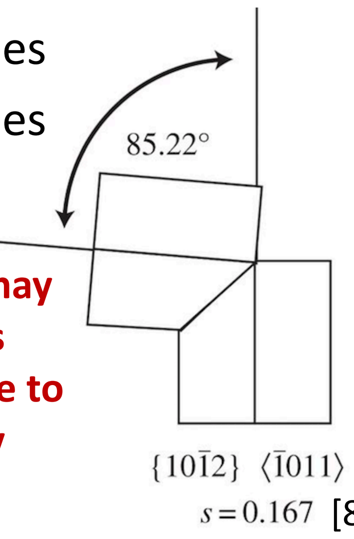
T1 ≃ 86 degree misorientation

T2 ≃ 86 degrees

T3 ≃ 60 degrees

Misorientations may effect hardness measurements due to HCP anisotropy

[3]



[8]

Concluding Remarks & Future Works

- Nanoindentation results indicate no correlation between hardness and speed; Taylor equation implies deformation mode may be "purely" deformation twinning.
- Comparison to previous works by Byer et al. show Mg may undergo a change in deformation mode from slow to fast deformation.
- Crystallographic misorientations from twinning may affect hardness measurements.
- **Future works** include nanoindentation of twinned and un-twinned surfaces independently and TEM analysis of dislocation structure.

Acknowledgment

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