Impulse Manufacturing Laboratory (iml.osu.edu)

ICHSF21 INTERNATIONAL CONFERENCE ON HIGH SPEED FORMING

Separating the roles of speed, strain-rate and shock in interpreting dynamic hardness

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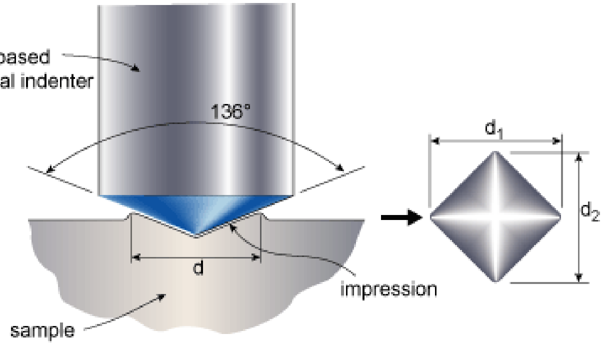
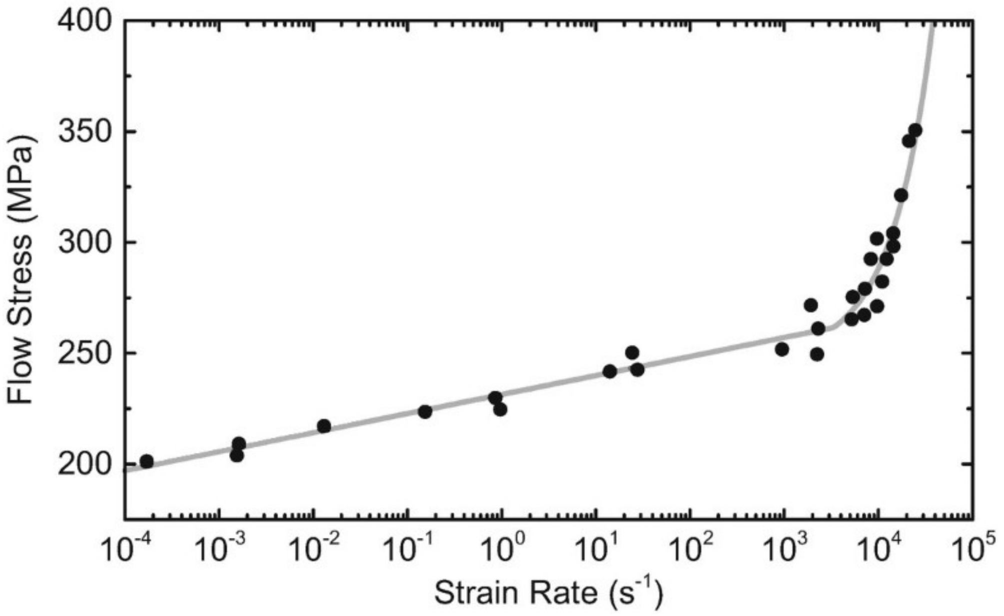
Outline

- Introduction of dynamic hardness
- Hardening phenomenal and existing mechanism
- Simulation approach and results
- Discussion on shock hardening
- Summary and future work

Dynamic hardness: introduction

- Metal behavior changes dramatically at high strain rate vs static.
- Static hardness: $\boldsymbol{H_s = \frac{P}{S}}$
- Hardness ratio: $\boldsymbol{R_H = \frac{H}{\sigma_y}}$
- Dynamic hardness: $\boldsymbol{H_d = \frac{E}{V}}$





Follansbee et al., 1984

$$H_d = \begin{cases} \dfrac{\Delta E_k}{V_{indentation}} =, \text{for dynamic projectile} \\ \dfrac{\Delta E_P}{V_{indentation}}, \text{for static load and indentation} \end{cases}$$

Slip-line field theory: R_H =2.96

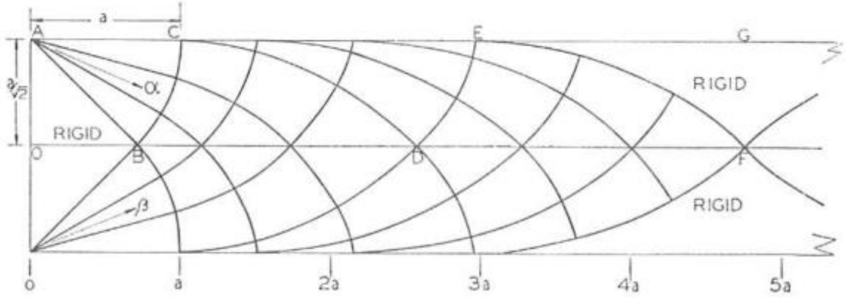
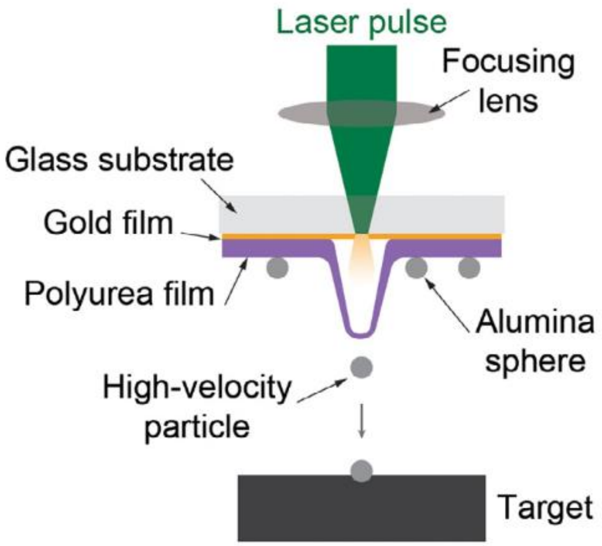
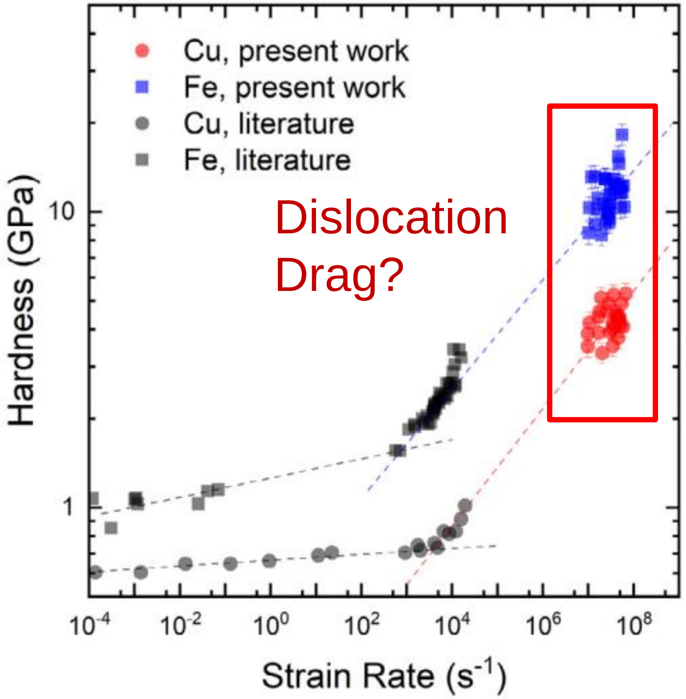


Fig. 7 Showing Slip-Line Field to Scale for Block of Length-Height Ratio 6.72 at Intervals of 15 Deg in ϕ

Hill et al., 1951

Dynamic hardness: mechanism debate





Dislocation Drag?

- Dynamic hardness of 10 times of static hardness is obtained at strain rate of $10^6\ s^{-1}$
- High ratio strength increase suggested to be <u>Dislocation Drag</u>.

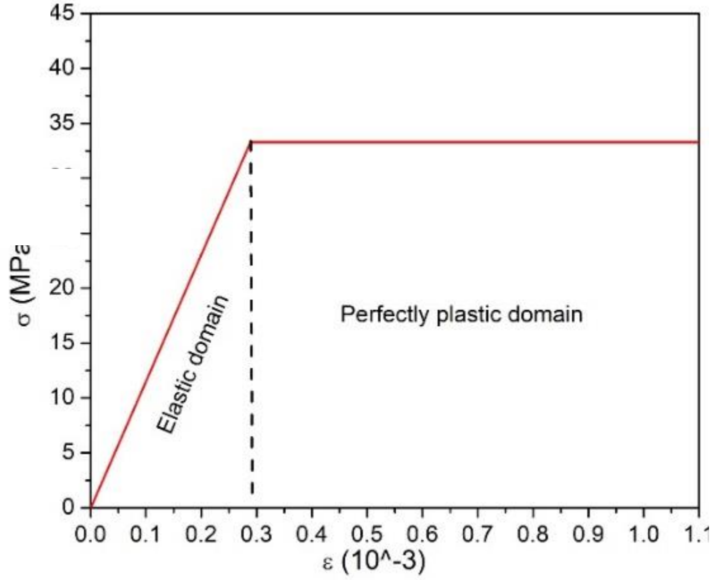
$$Hardness = \frac{W_{plastic}}{V_{indentation}} = \frac{(1/2) \times m_p \times \left(v_i^2 - v_r^2\right)}{V_{indentation}}$$

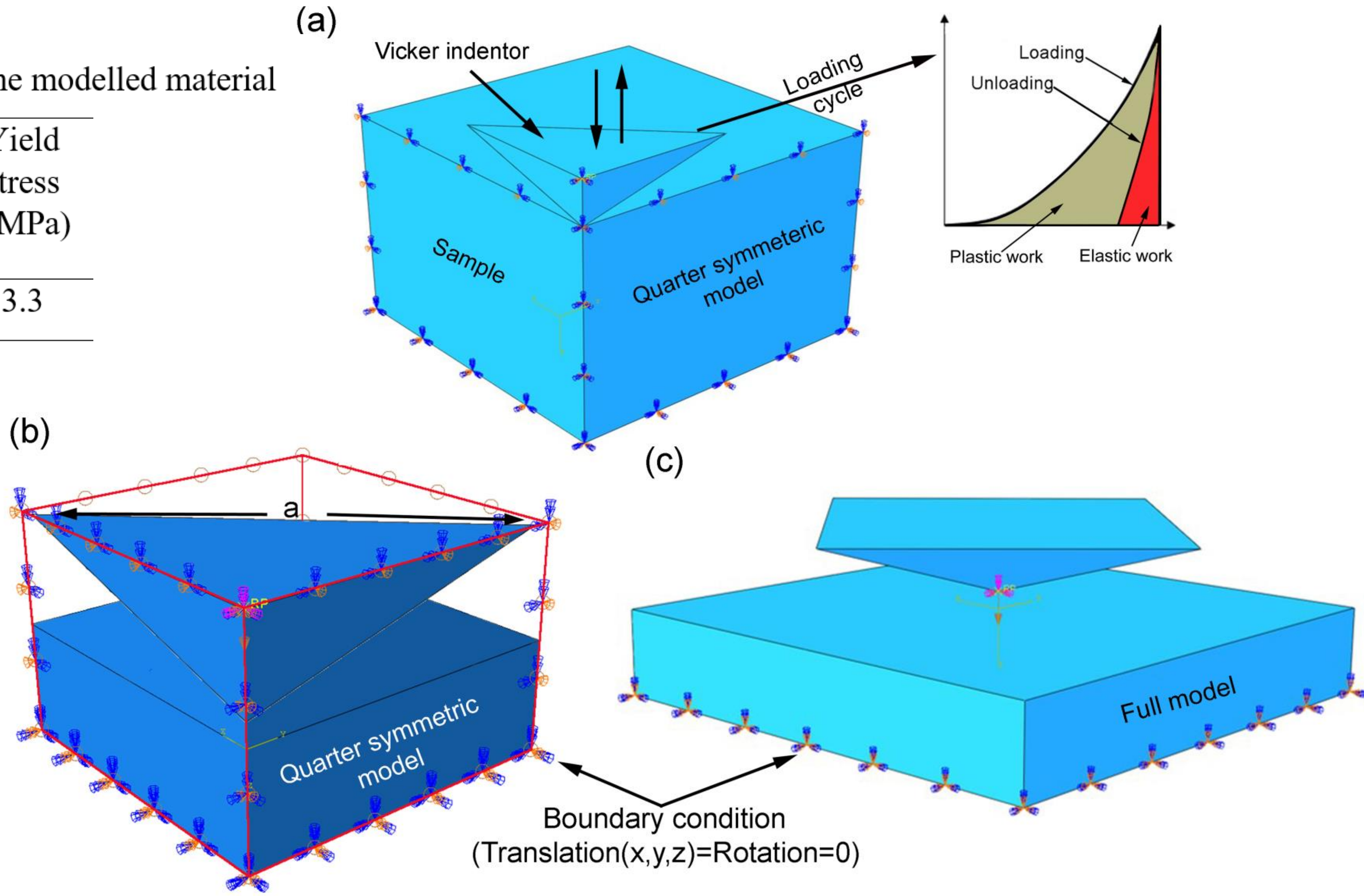
Hassani, M. et al., 2020

Simulation setup

Table 1. Mechanical and thermal properties of the modelled material

Density (kg/m^3)	Thermal conductivity (W/(m·K))	Elastic modulus (GPa)	Poison's ratio	Yield stress (MPa)
8.96e3	386	115	0.34	33.3



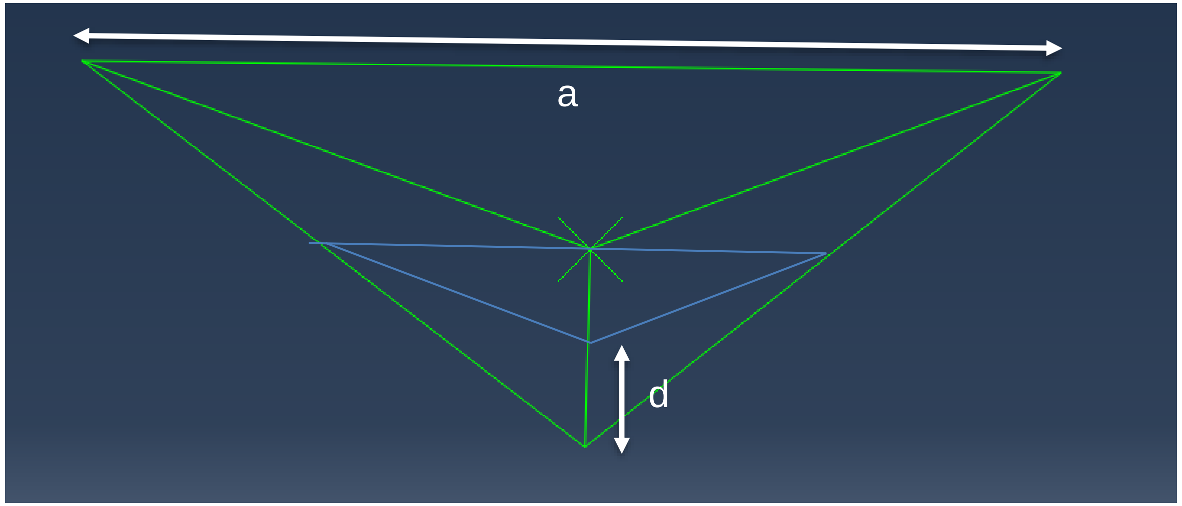


Boundary condition
(Translation(x,y,z)=Rotation=0)

Y. Mao et al., Scripta, (submitted), 2021

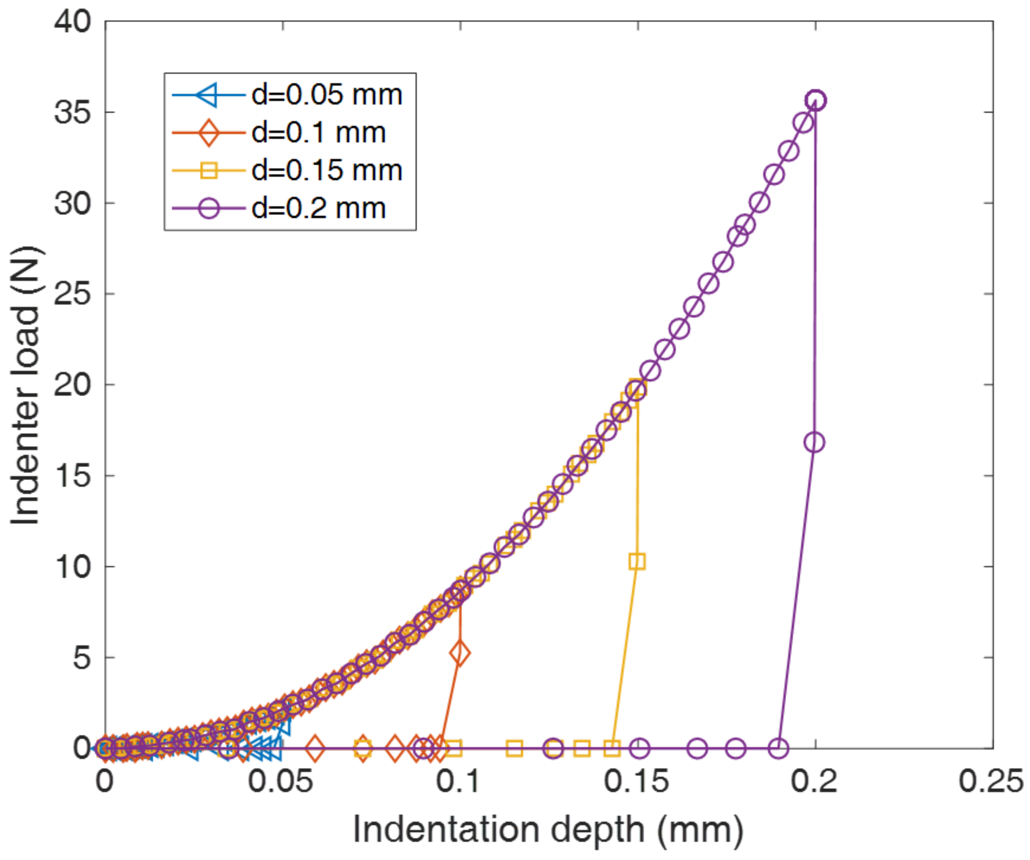
Calculations

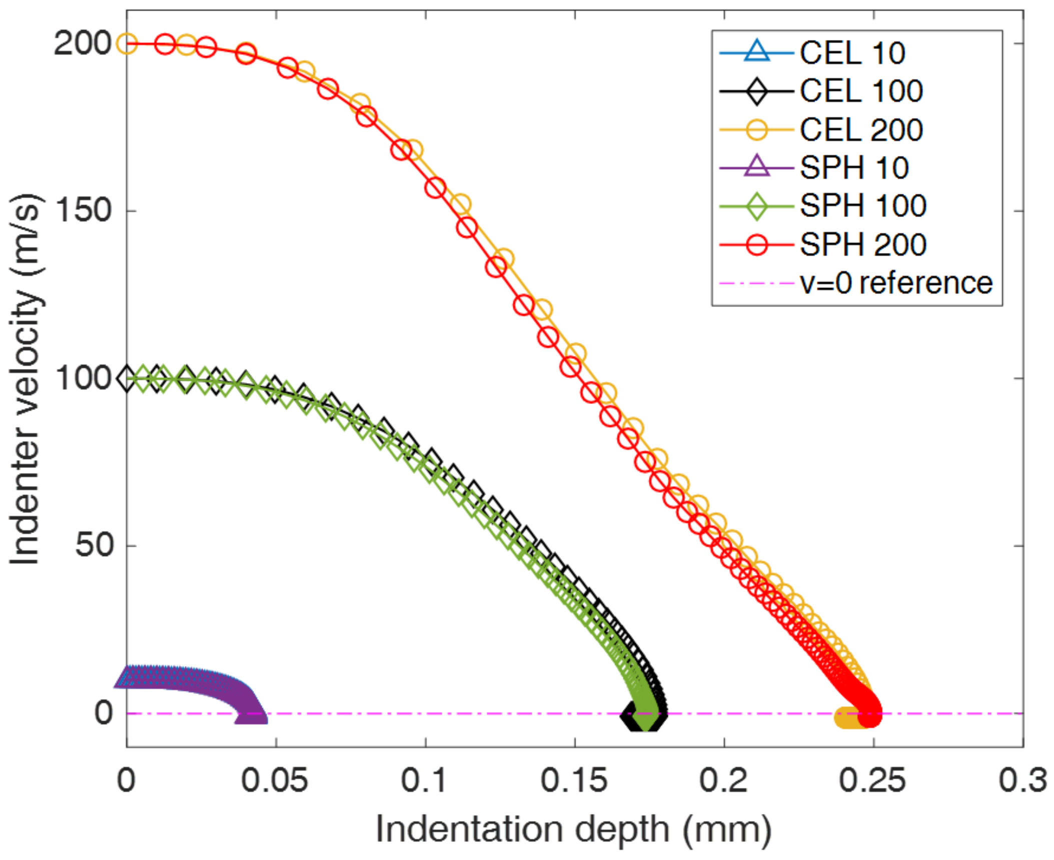
- $H_d = \frac{\int F_{load} dx - \int F_{unload} dx}{V_{indentation}}$, for static indentation
- $H_d = \frac{0.5 \cdot m_i \cdot (v_i^2 - v_r^2)}{V_{indentation}}$, for dynamic projectile
- $R_H = \frac{H_d}{\sigma_0}$



a (mm)	0.02	0.2	2
vi (m/s)	50	10	50
	100	50	100
		100	
	200	150	200
		200	

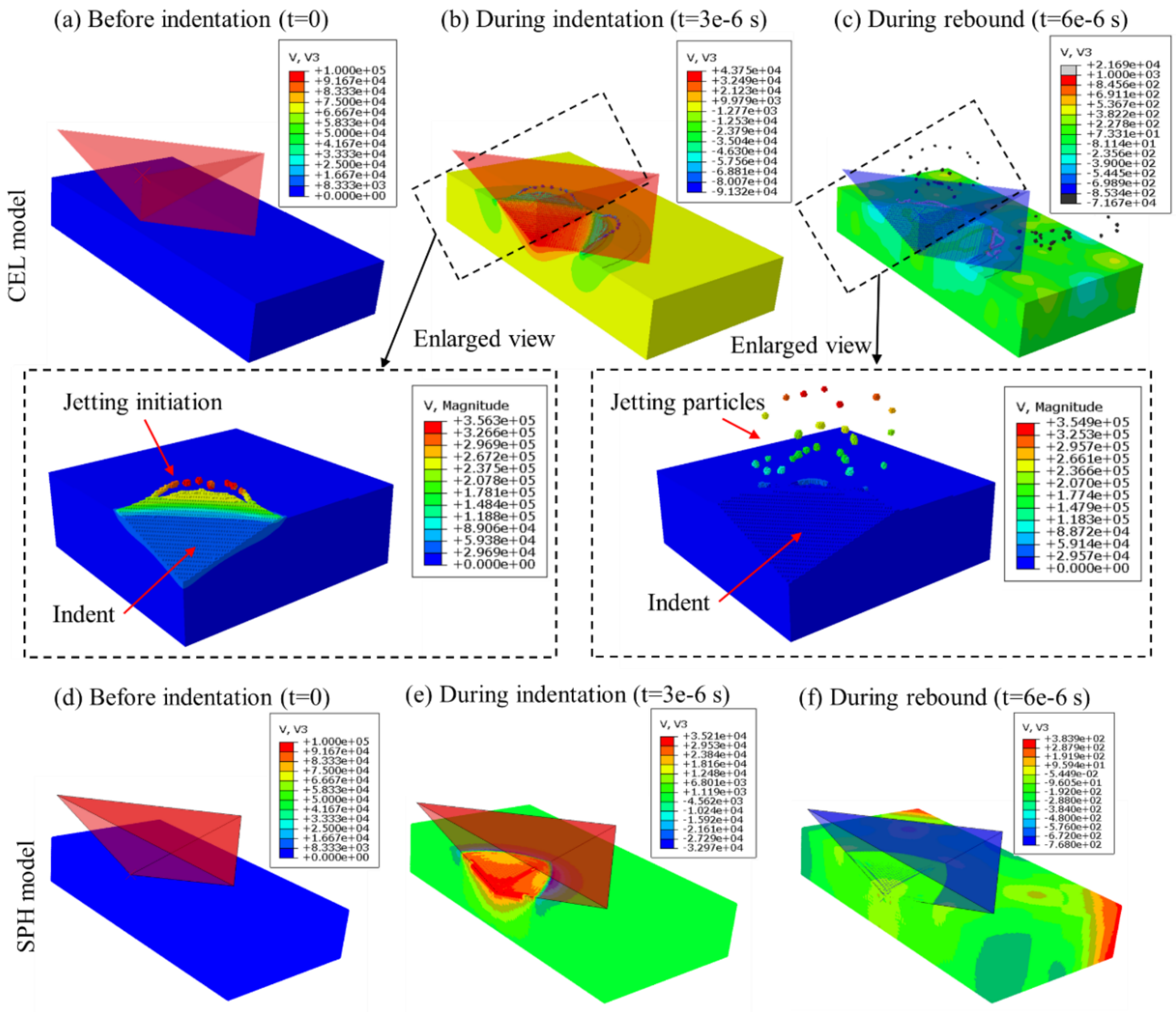
Results: static indentation and dynamic projetile





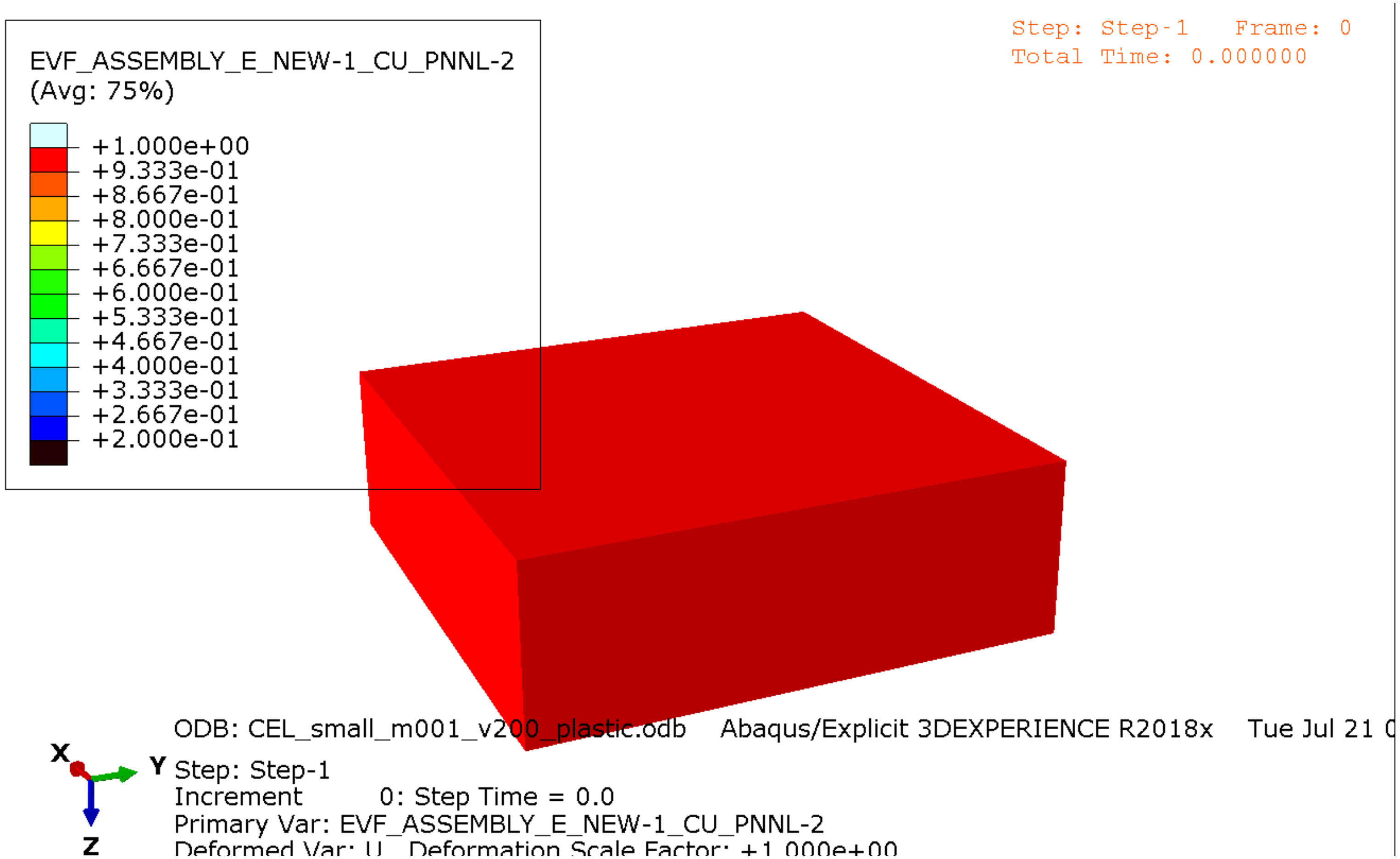
Mao et al (submitted, 2021)

Results: CEL vs SPH



Mao et al (submitted, 2021)

CEL shows jetting



EVF_ASSEMBLY_E_NEW-1_CU_PNNL-2
(Avg: 75%)

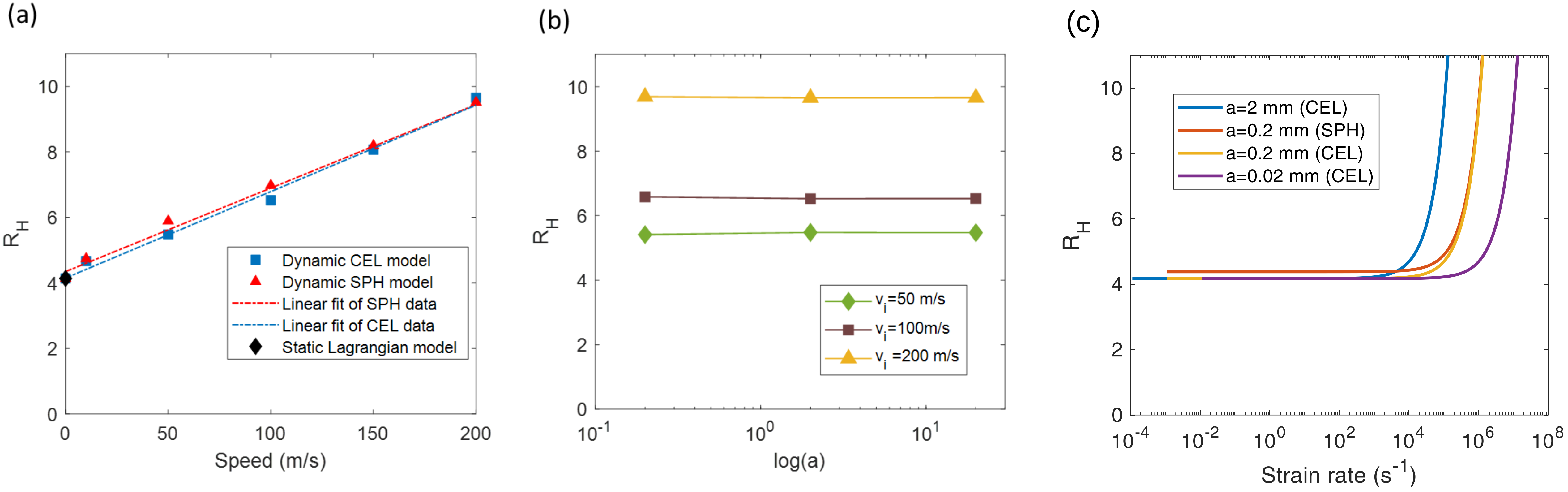
Step: Step-1   Frame: 0
Total Time: 0.000000

ODB: CEL_small_m001_v200_plastic.odb   Abaqus/Explicit 3DEXPERIENCE R2018x   Tue Jul 21

Step: Step-1
Increment   0: Step Time = 0.0
Primary Var: EVF_ASSEMBLY_E_NEW-1_CU_PNNL-2
Deformed Var: U   Deformation Scale Factor: +1.000e+00

Vi=200 m/s

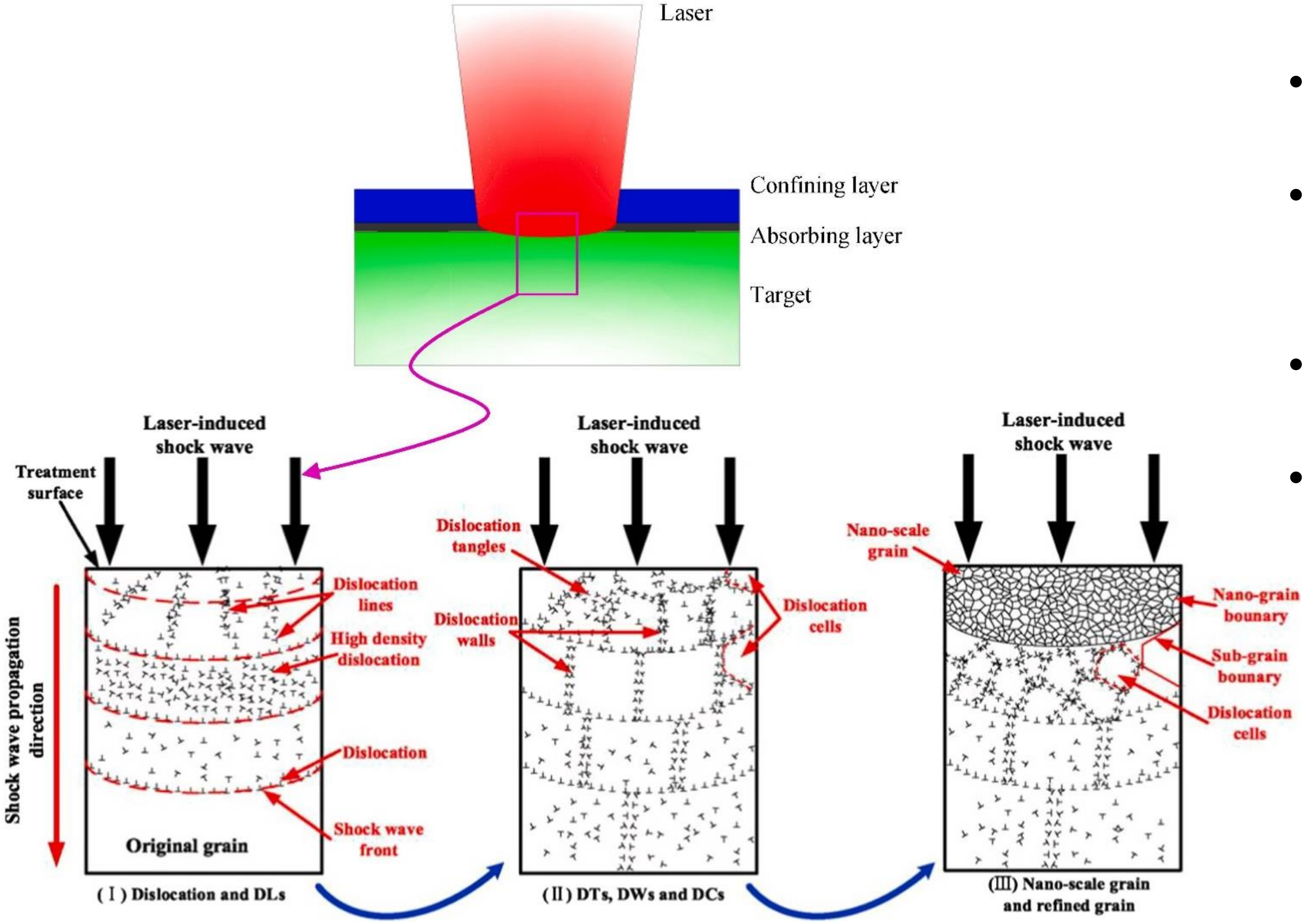
Dynamic hardness: roles of strain rate vs speed



- Dynamic hardness increases with <u>impact speed</u> instead of <u>strain rate</u>

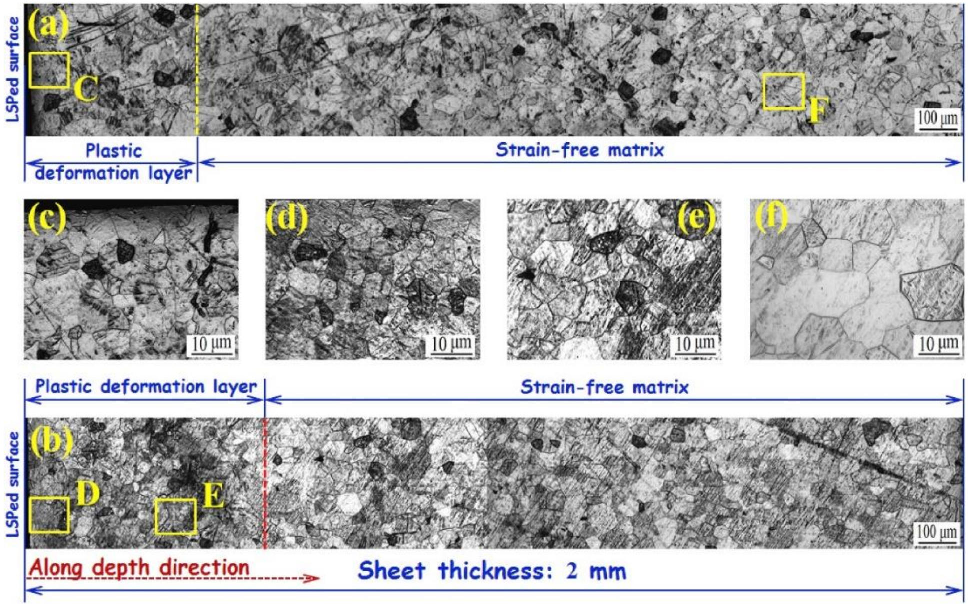
Mao et al (submitted, 2021)

Shock-hardening in laser shock peening (LSP)



Wang et al. (2020)

- LSP: Shock pressure of 15-20 GPa (Wang et al., 2020) under uniaxial strain state.
- v_i =750m/s generates 16.7 GPa impact between the alumina particle and Cu plate (Hugoniot calculation)
- The shock front induces grain refinement, causing hardening.
- This process <u>may not involve strain-rate hardening</u>.



Lu et al. (2017)

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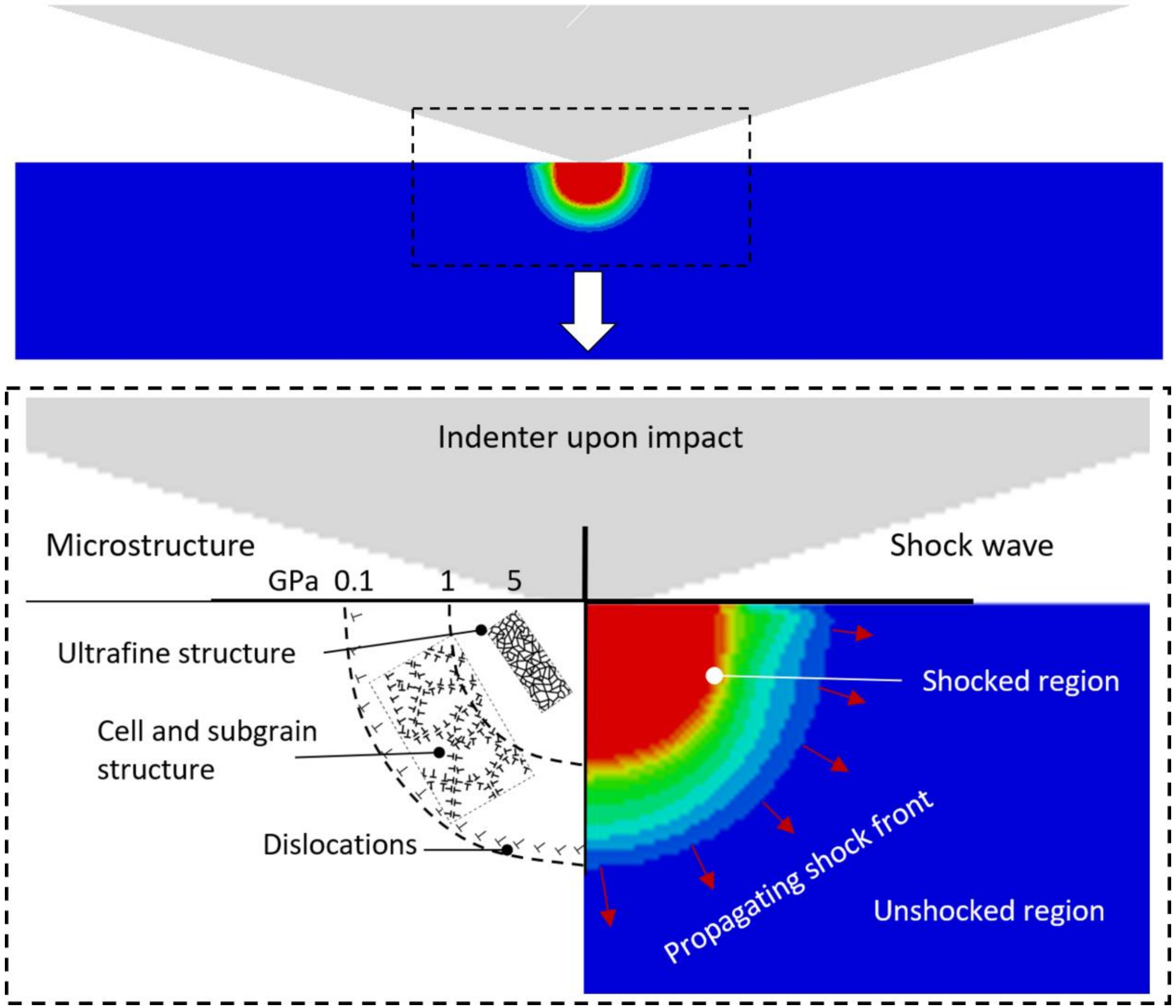
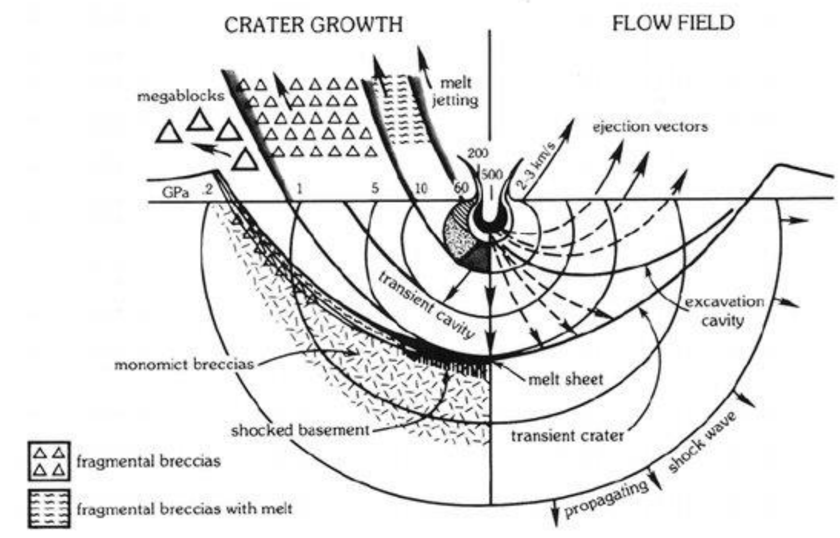
Shock propagation



Mao et al (submitted, 2021)

- Shock front moves much faster than the particle or indentation-driven displacement. (v_s=4.72 km/s, for ceramic-copper impact v_i=750 m/s)
- A discrete uniaxial-strain interface is created between the shocked and unchoked regions.
- Dislocations are generated from elastic distortion and pinched out at the shock front.
- Significant microstructural hardening ahead of the larger displacements required to accommodate the indenter.



Stöffler et al. (2007)

Summary and future work

- Without rate-hardening model, a clear linear speed effect with no size effect on dynamic energetic hardness is observed.
- Shock effects can induce unique microstructures and significant hardening.
- Shock hardening has different origins and phenomenology than strain rate hardening. A complete model needs to be established:
  - a quantitative model to show the effects of density and modulus on the slope of the H-vi curve.
  - an analytical model to understand the origin of the behavior