Supersonic Impact of Metallic Microparticles

Mostafa Hassani-Gangaraj[1], David Veysset[2,3], Keith A. Nelson[2,3], Christopher A. Schuh[1*]

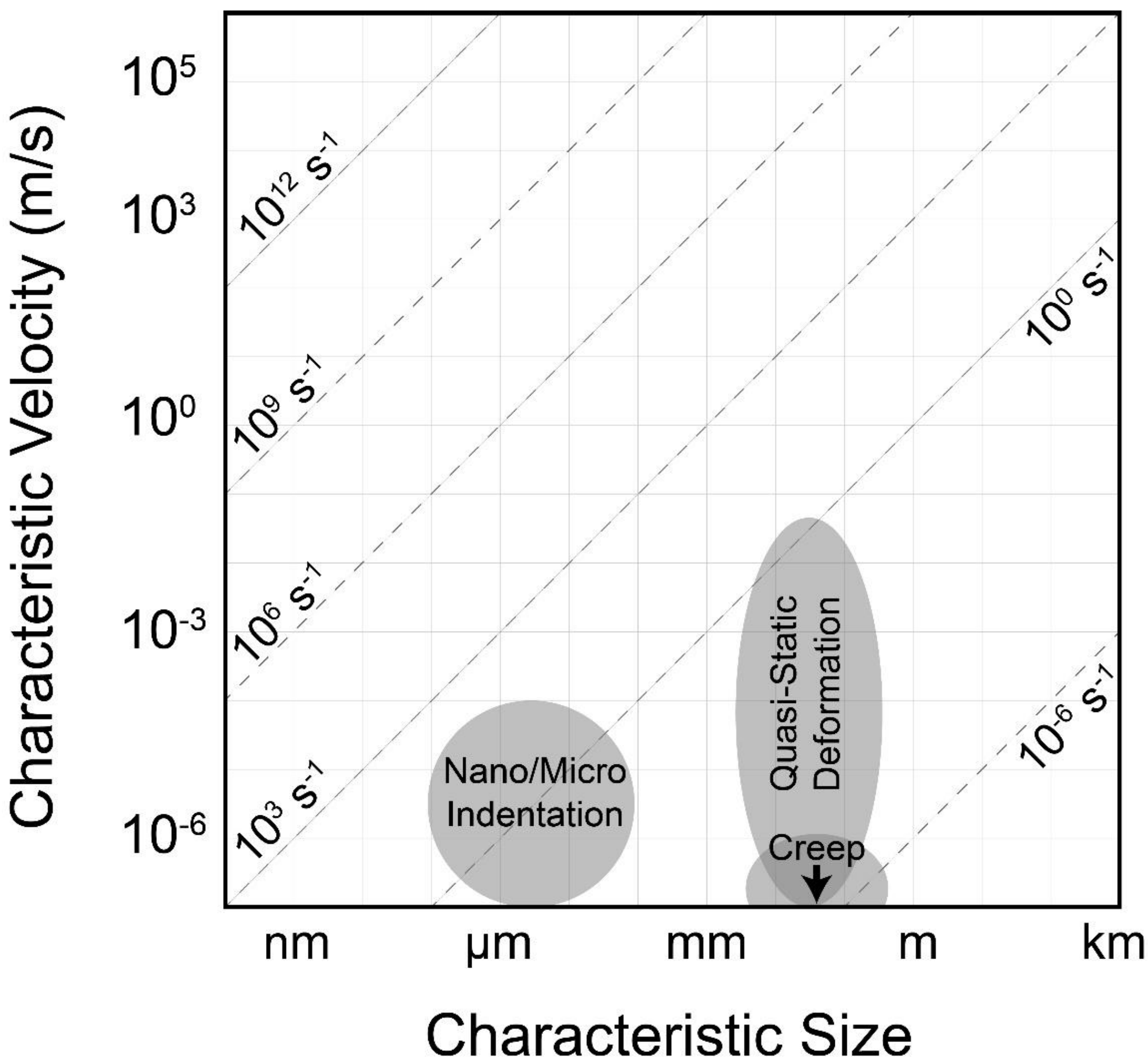
[1]Department of Materials Science and Engineering, MIT, Cambridge, Massachusetts 02139, USA
[2]Institute for Soldier Nanotechnologies, MIT, Cambridge, Massachusetts 02139, USA
[3]Department of Chemistry, MIT, Cambridge, Massachusetts 02139, USA

ICHSF, May 2018

Email: mhassani@mit.edu

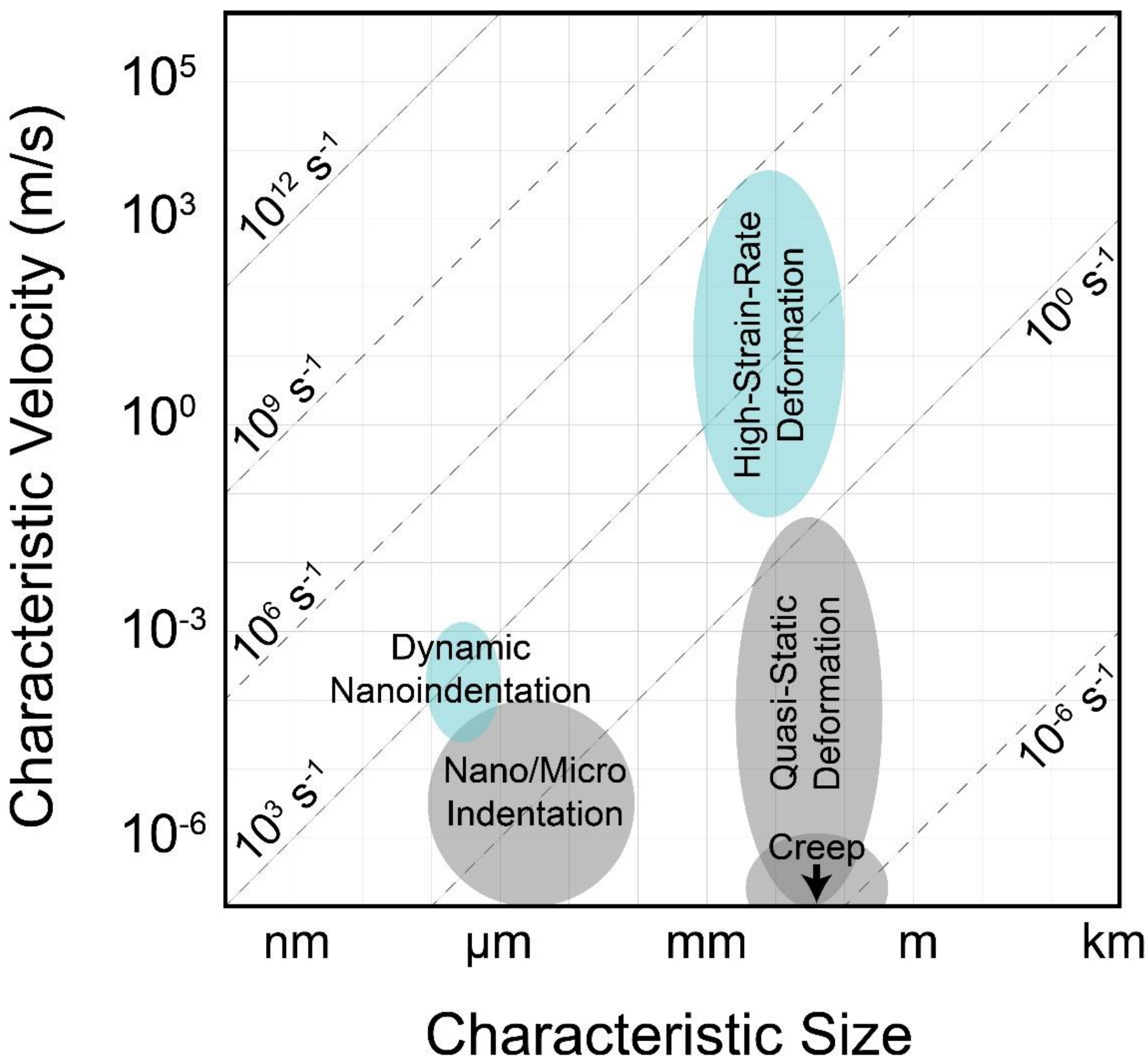
Strain Rate Space

$$\dot{\varepsilon} = \frac{V}{d}$$



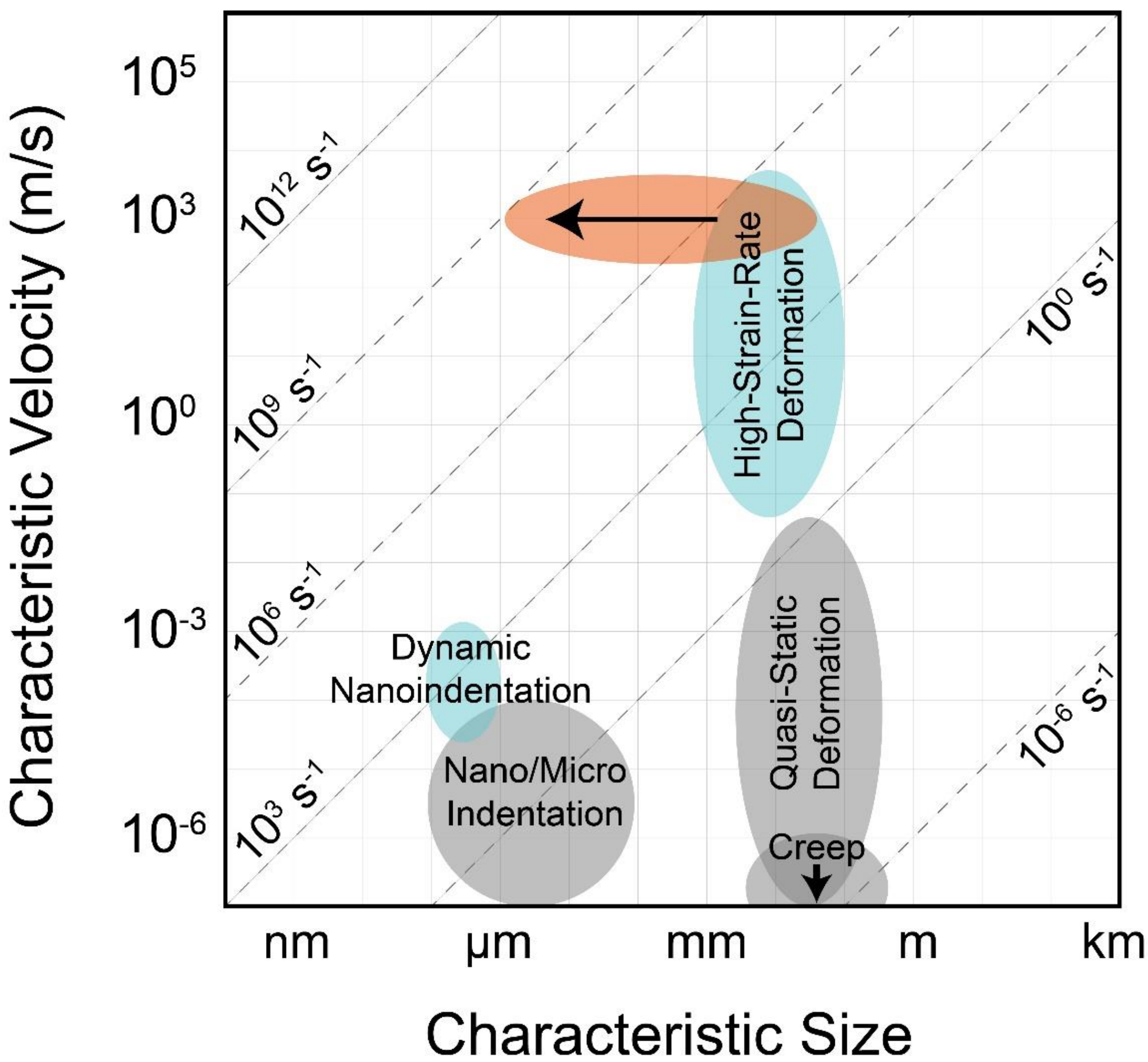
Strain Rate Space

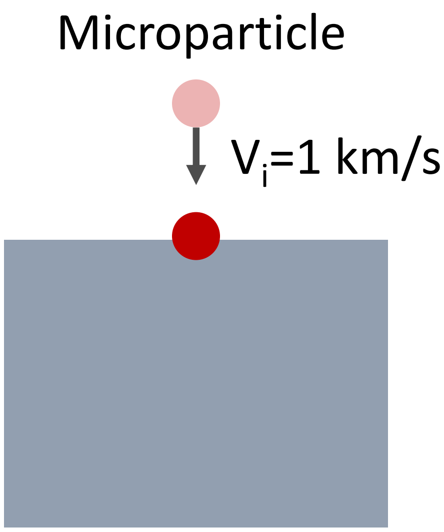
$$\dot{\varepsilon} = \frac{V}{d}$$



Microparticle Impact?

$$\dot{\varepsilon} = \frac{V}{d}$$





Microparticle Impact?

I. Smaller Scales, i.e., Higher Rates

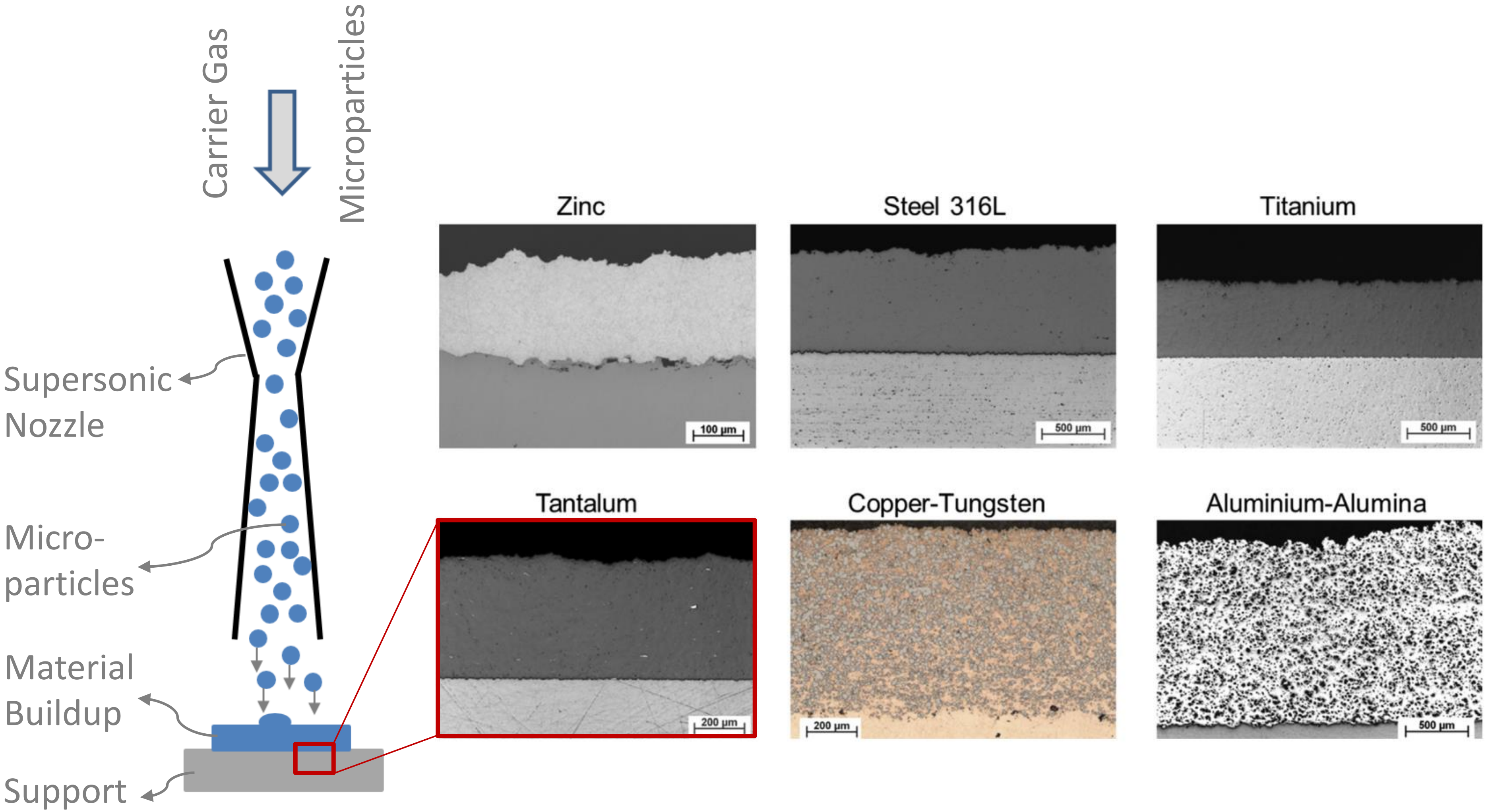
Microparticle Impact?

I. Smaller Scales, i.e., Higher Rates

II. Impact for Manufacturing

GE Research, 2013

Cold Spray

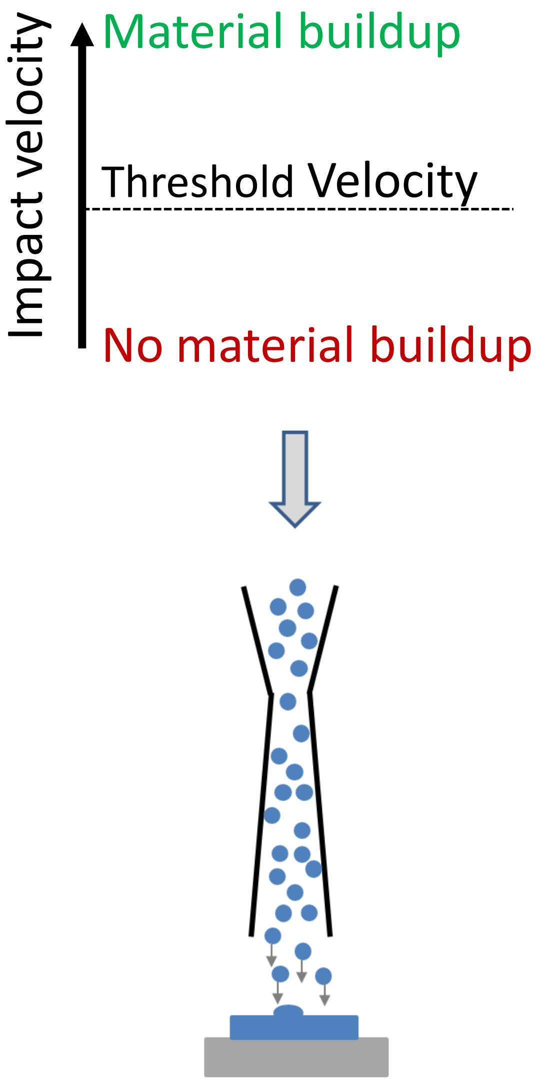


Assadi et al. Acta Mat (2016); Champagne et al. Surface Engineering (2014); Moridi et al. Surface Engineering (2014).

Cold Spray

Courtesy of Vic Champagne, ARL

Call for *in-situ* studies



Challenge 1.
No direct measurement of V_{cr}

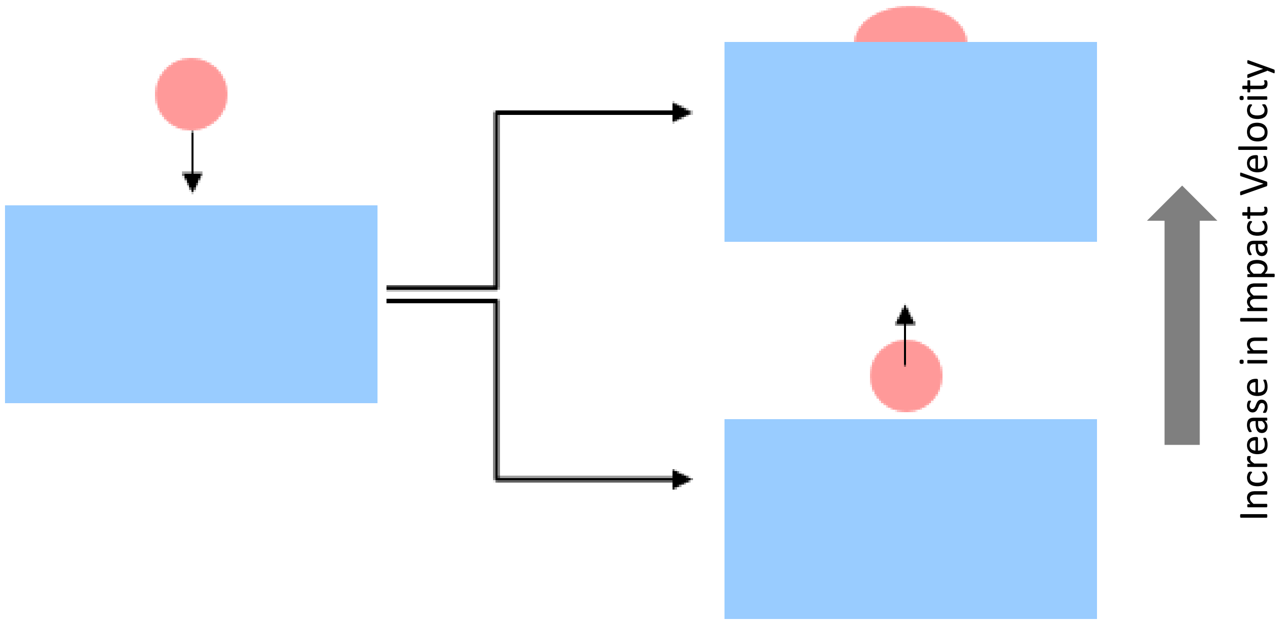
Only in-direct estimations based on deposition efficiency and fluid dynamics

Challenge 2.
No consensus on bonding mechanisms

Adiabatic shear localization
Mechanical Interlocking
Localized melting
Diffusion
…

Assadi et all. Acta Matter 2003; Grujicic et al. Mat Design 2004; Guetta et al. J Thermal Spray Tech 2009; Bae et al. Acta Mat 2009; Champagne et al. J Thermal Spray Tech 2015; Ko et all. Matter Letter 2016.

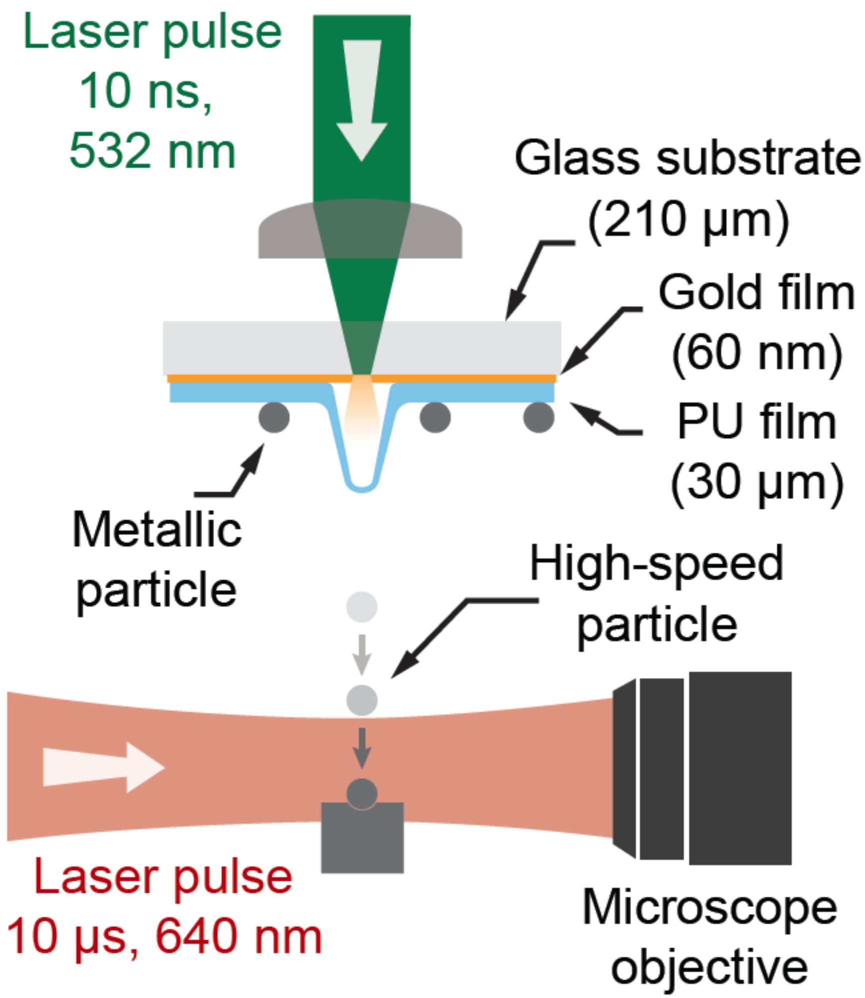
Unit Process: Single Particle Impact



Particle size: 5-50 **μm**
Impact Velocity: 400-1000 **m/s**
Characteristic time: ~100 **ns**

100 million fps

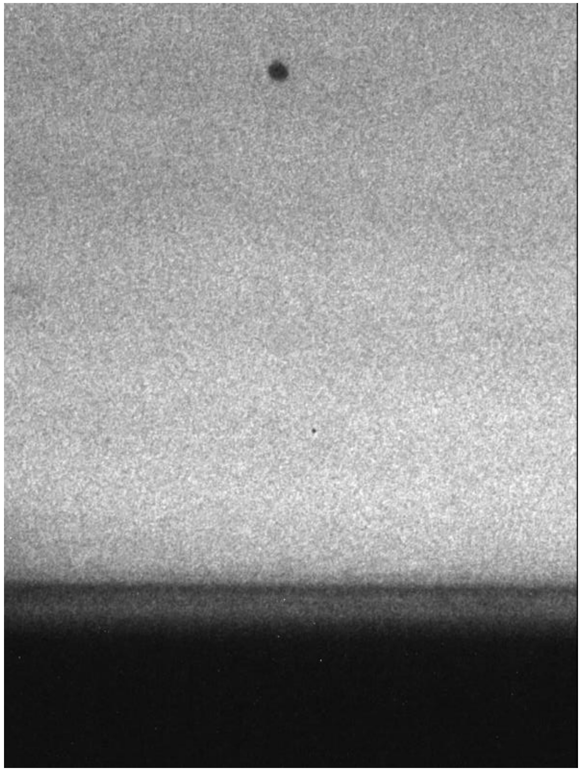
In-situ studies of single microparticle impact

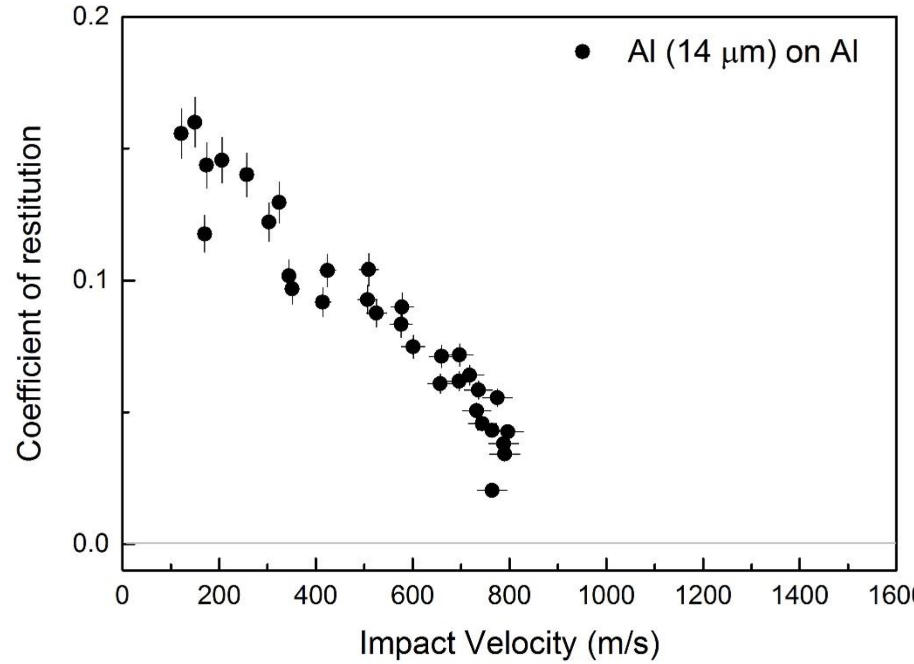


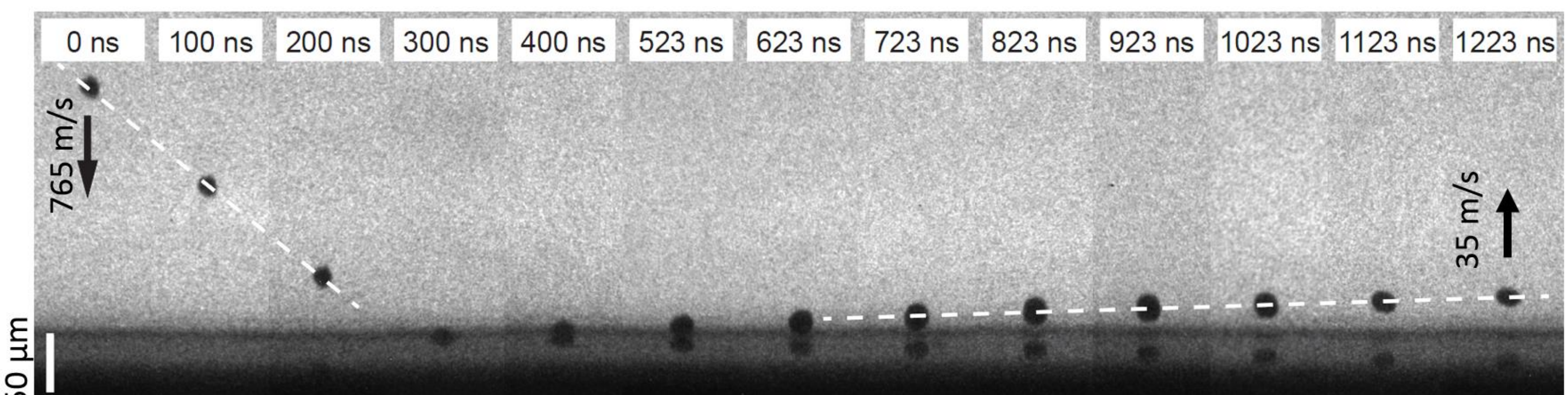
Hassani-Gangaraj et al. Physical Review Letters (2017); Hassani-Gangaraj et al. Scripta Materialia (2018); Veysset at al. Sci. Rep. (2016)

Rebound

Al on Al



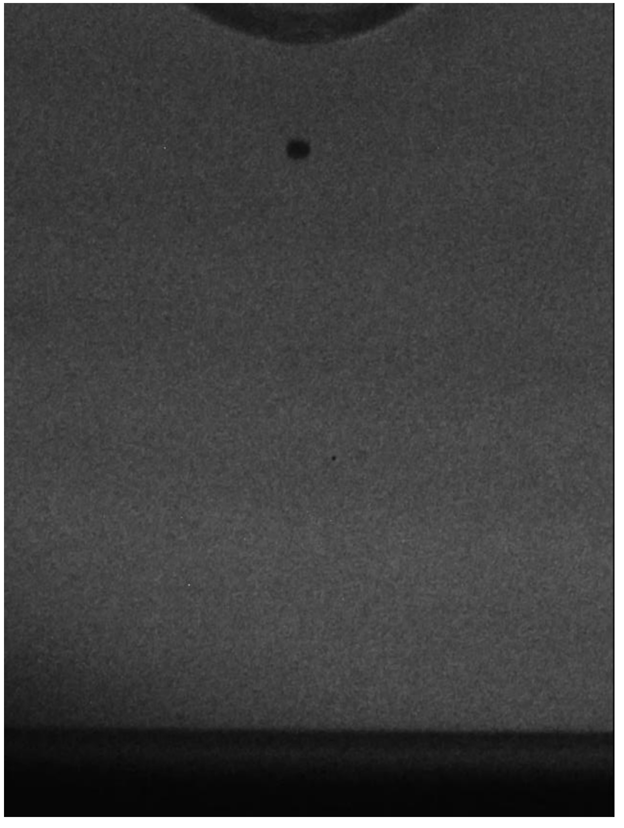


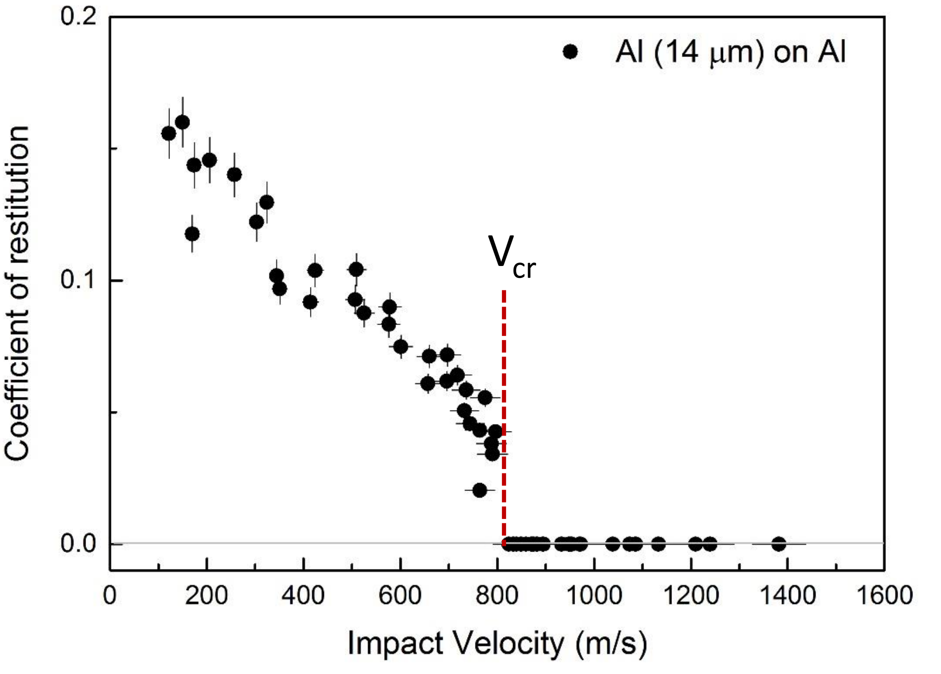


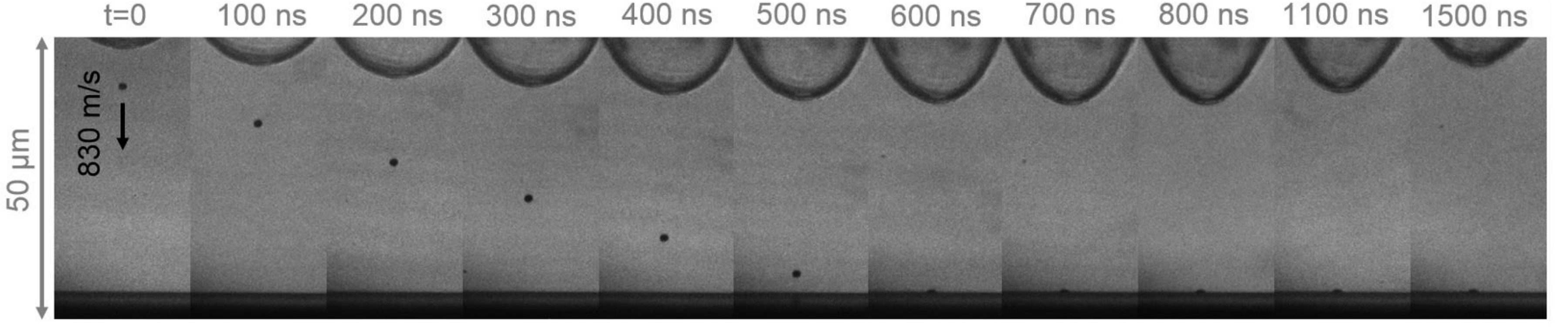
Hassani-Gangaraj et al. Scripta Materialia 145 (2018) 9–13.

Adhesion

Al on Al

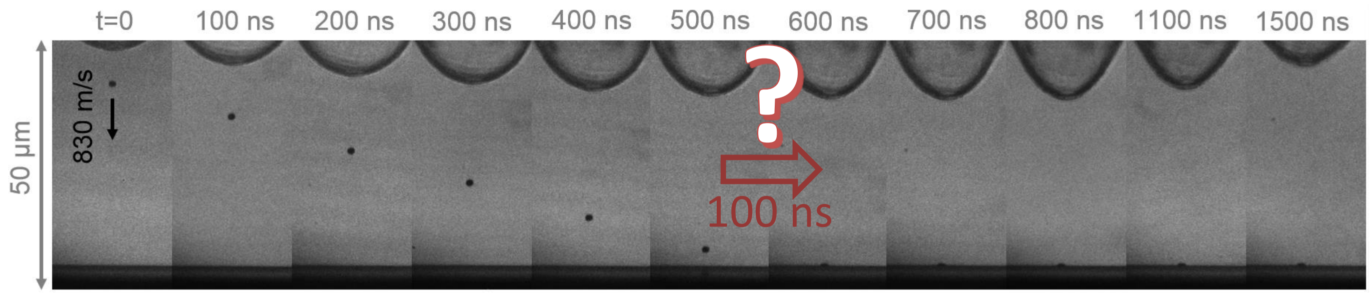






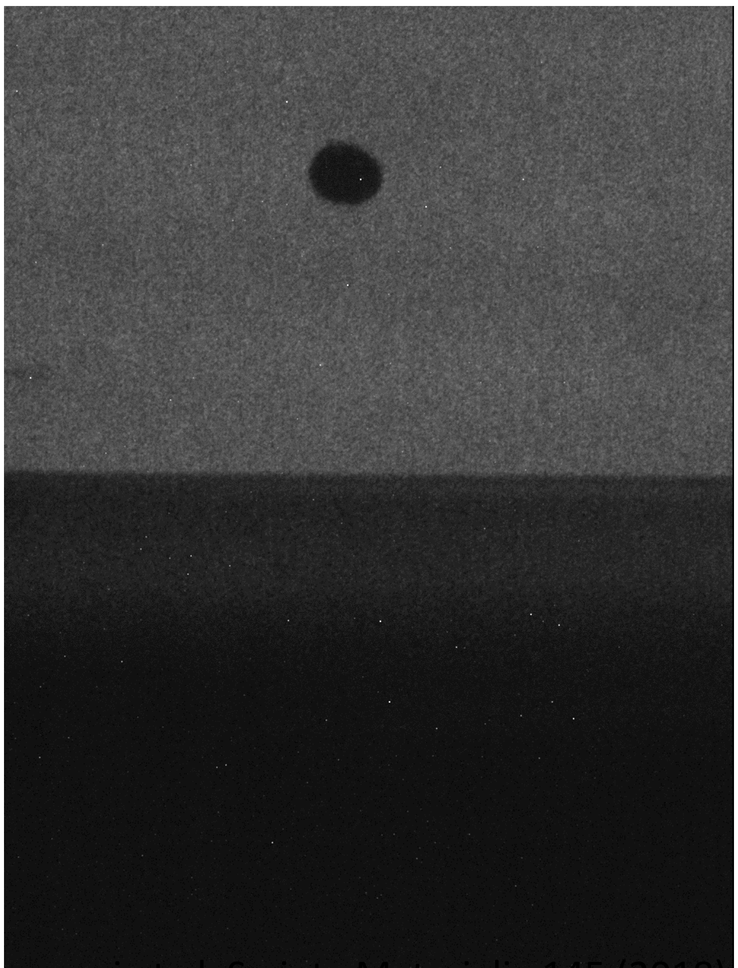
Hassani-Gangaraj et al. Scripta Materialia 145 (2018) 9–13.

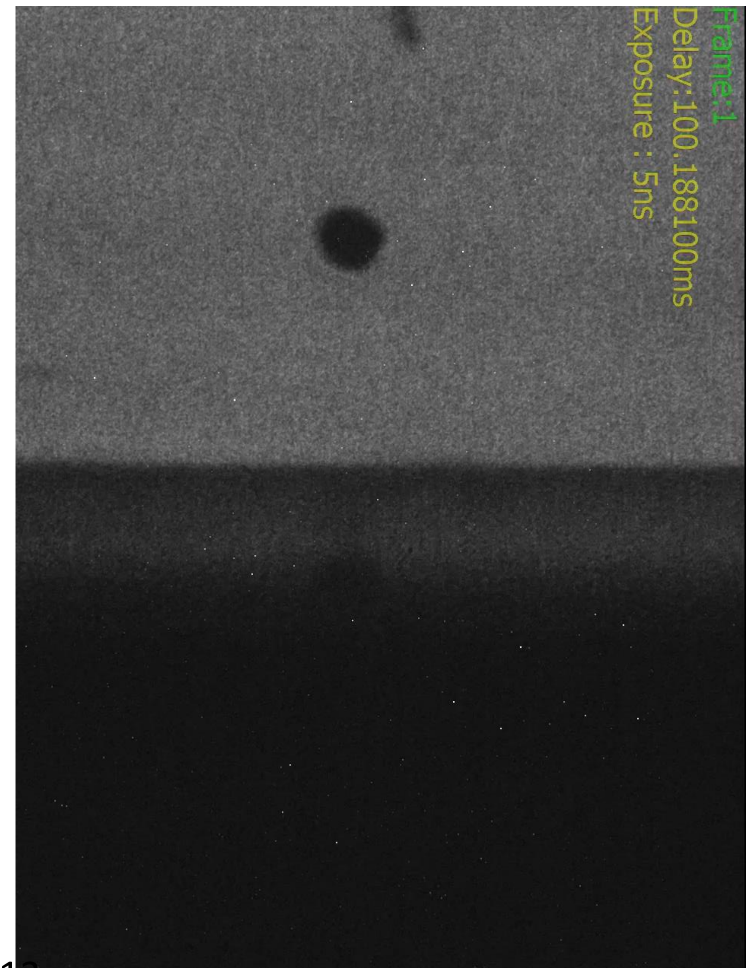
The Moment of Bonding



Al
45 µm
605 m/s

Inter-
frame
time:
20 ns



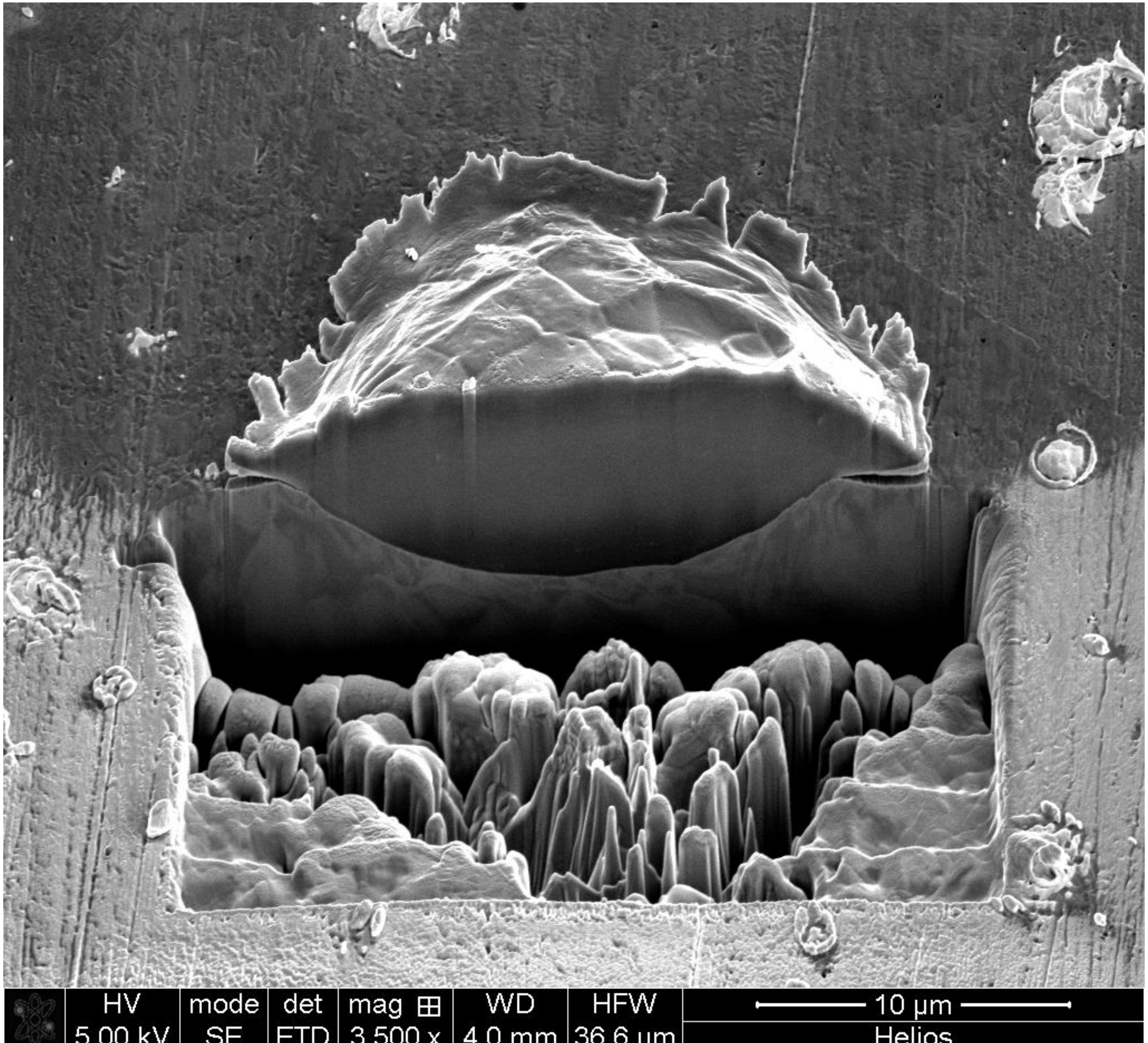


Al
45 µm
805 m/s

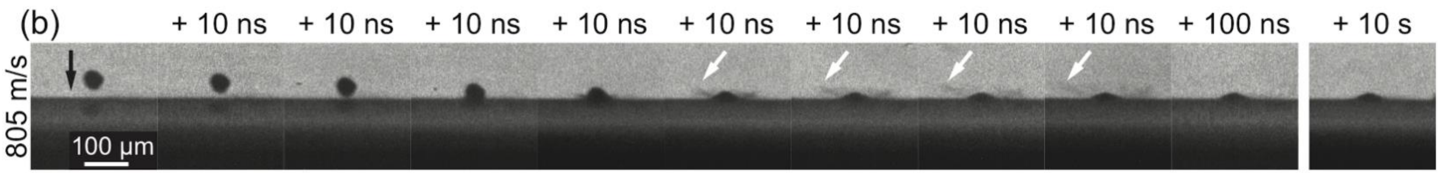
Inter-
frame
time:
10 ns

Hassani-Gangaraj et al. Scripta Materialia 145 (2018) 9–13.

Post-mortem

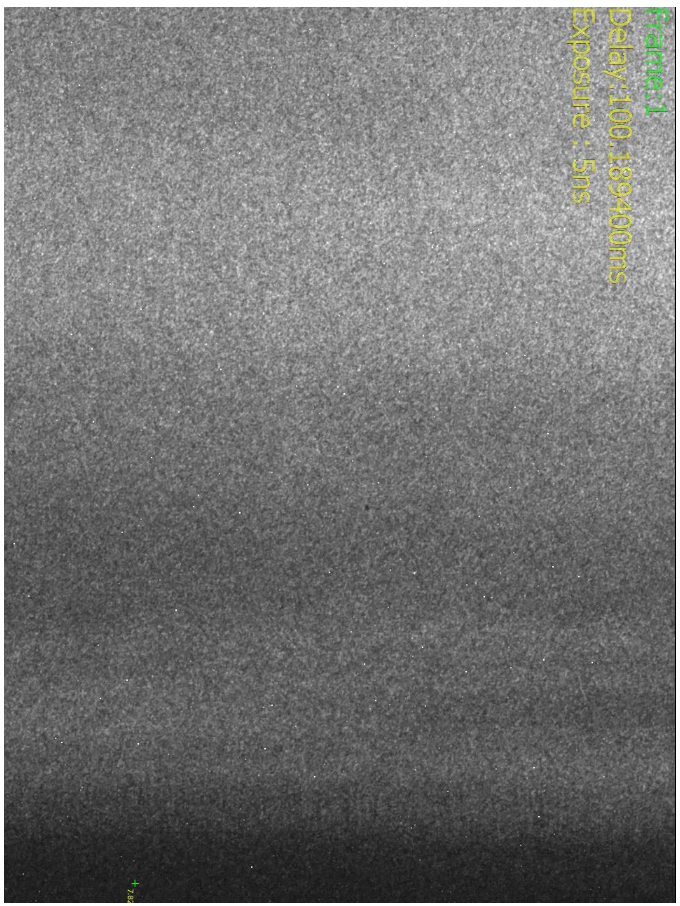

HV
5.00 kV
mode
SE
det
ETD
mag ⊞
3 500 x
WD
4.0 mm
HFW
36.6 µm
10 µm
Helios

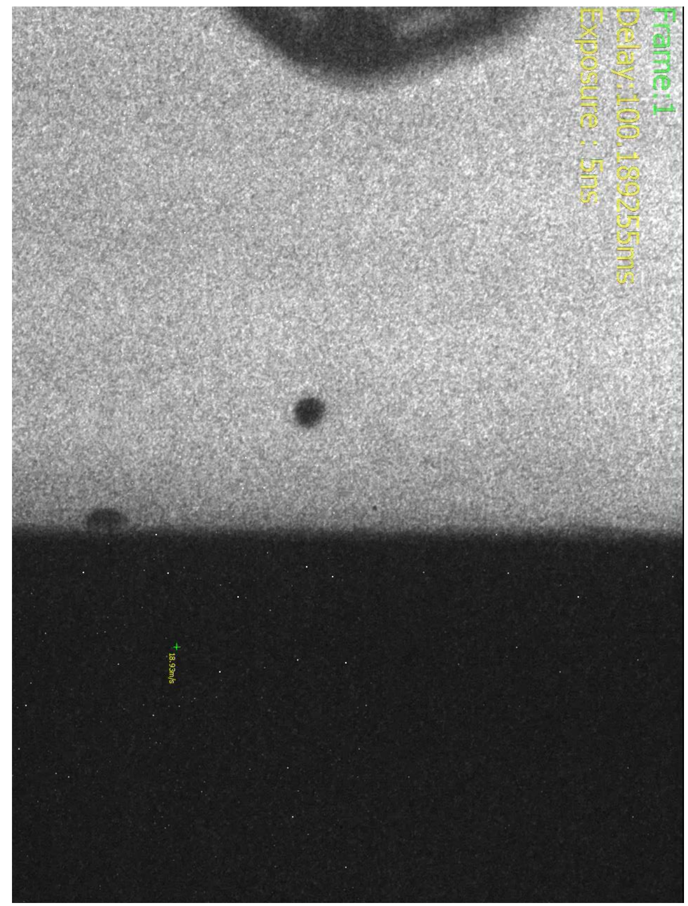
Ejecta; Base Metal or Oxide?



Bonding Moment for Gold

115 m/s





310 m/s

Adiabatic Shear Instability

The origin of jetting?

⇕

Jetting leads to Bonding.

⇕

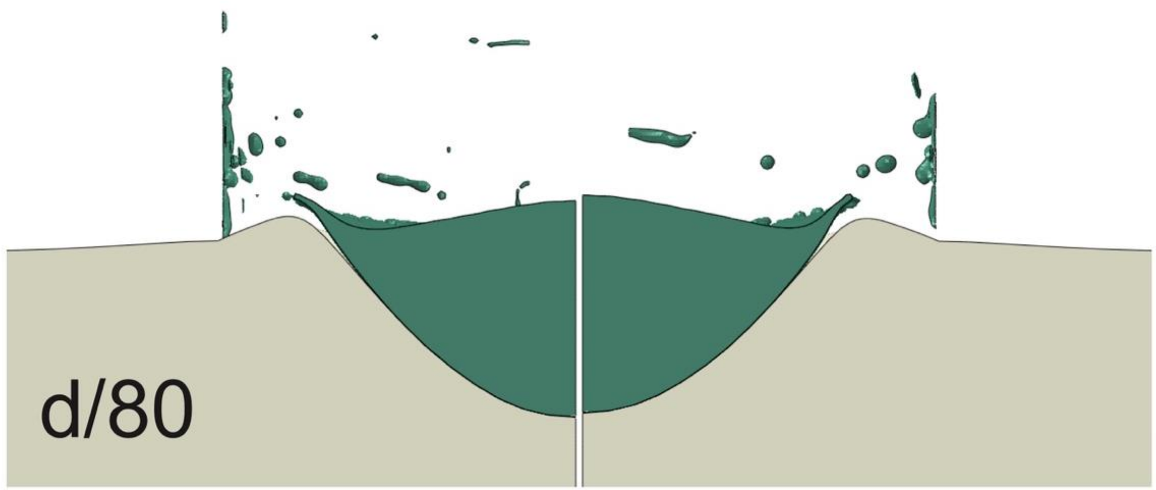
Develop a mechanistic prediction of V_{cr} for bonding

Origin of jetting/bonding: Adiabatic Instability?

- Cu Particle/Substrate
- V_{cr}=550 m/s

Johnson-Cook Plasticity

$$\sigma_y = \left[A + B\varepsilon_p^n\right]\left[1 + C ln \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^m\right]$$



With Thermal Softening

Without Thermal Softening

Hassani-Gangaraj et al. (2018), *submitted to Acta Mat.*

The origin of jetting? — Adiabatic Shear Instability ✗

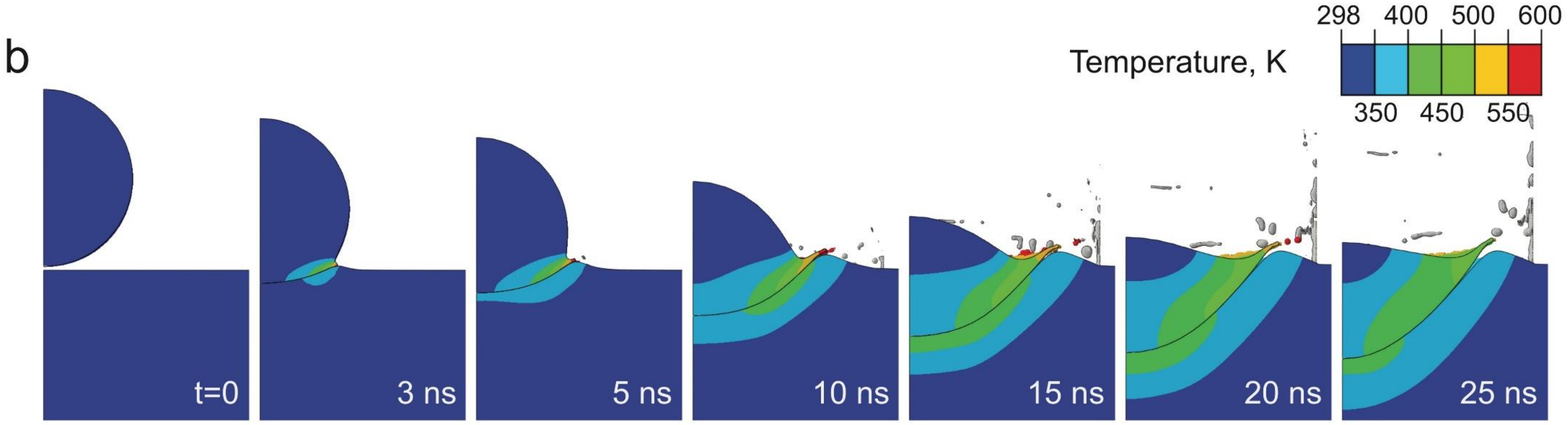
⇕

Jetting leads to Bonding.

⇕

Develop a mechanistic prediction of V_{cr} for bonding

Localized Melting?



Cu, Vi=550 m/s

Hassani-Gangaraj et al. (2018),
submitted to Acta Mat.

The origin of jetting?

- Adiabatic Shear Instability ✗
- Localized Melting ✗

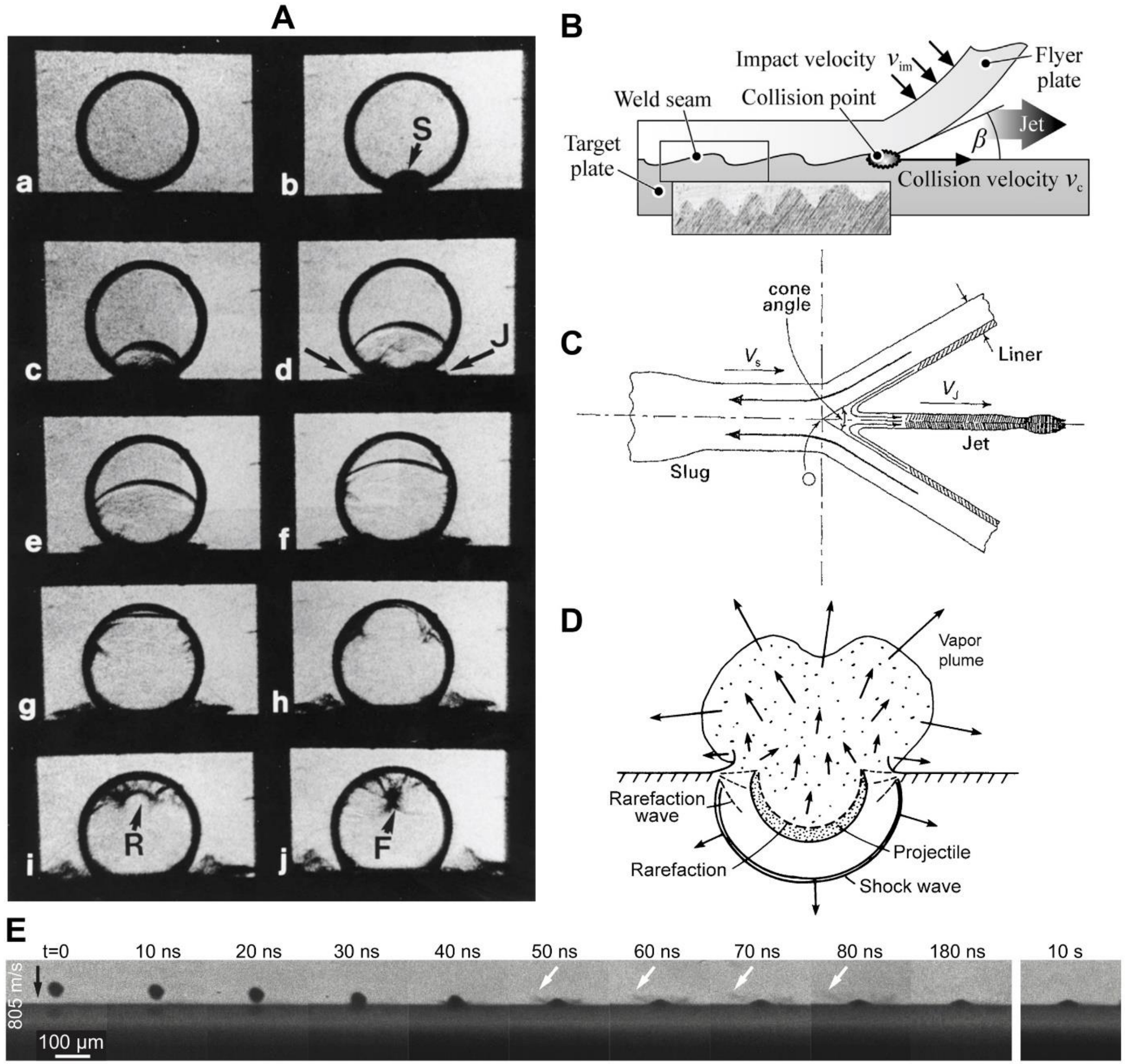
⇕

Jetting leads to Bonding.

⇕

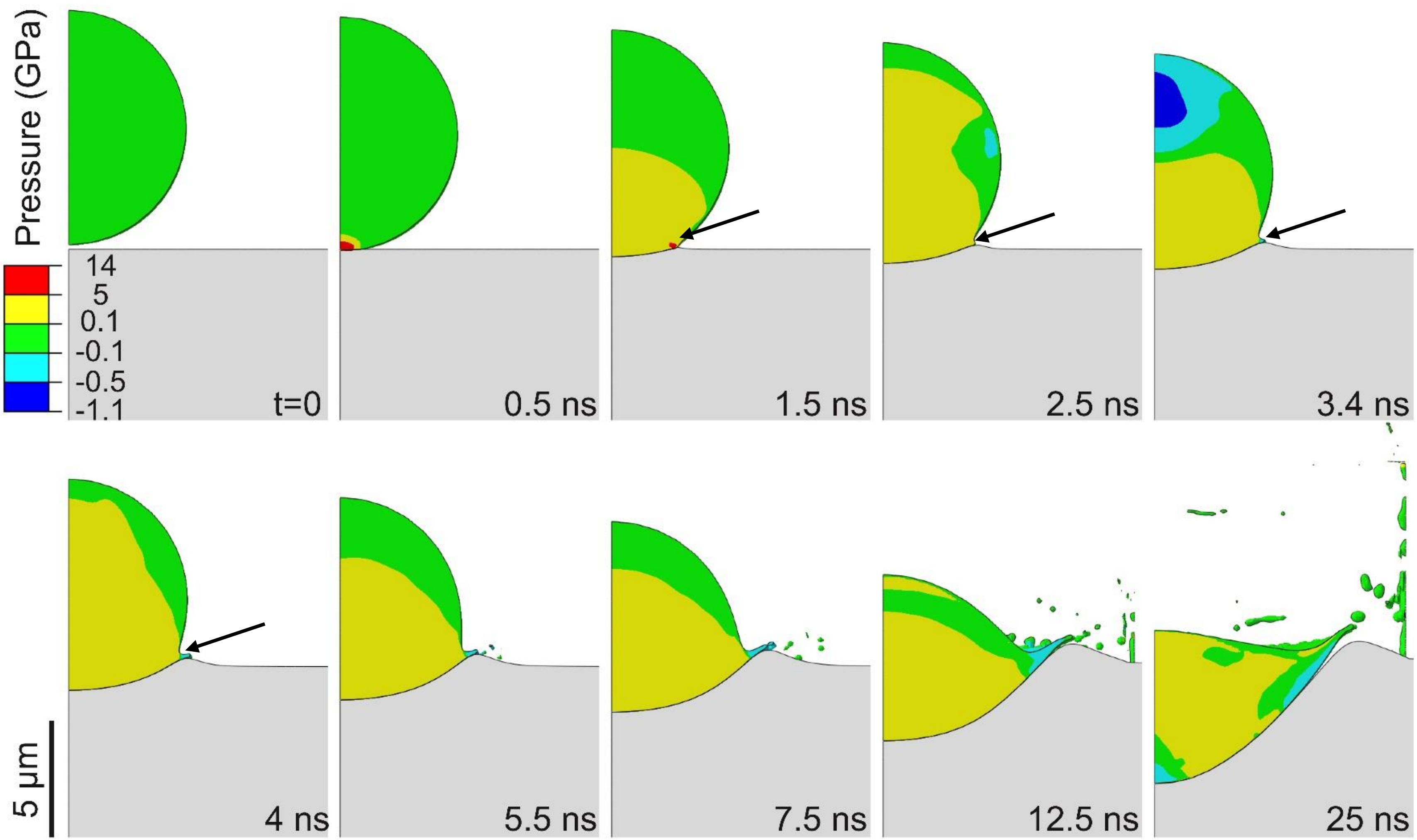
Develop a mechanistic prediction of V_{cr} for bonding

Jetting, a hydrodynamic phenomenon



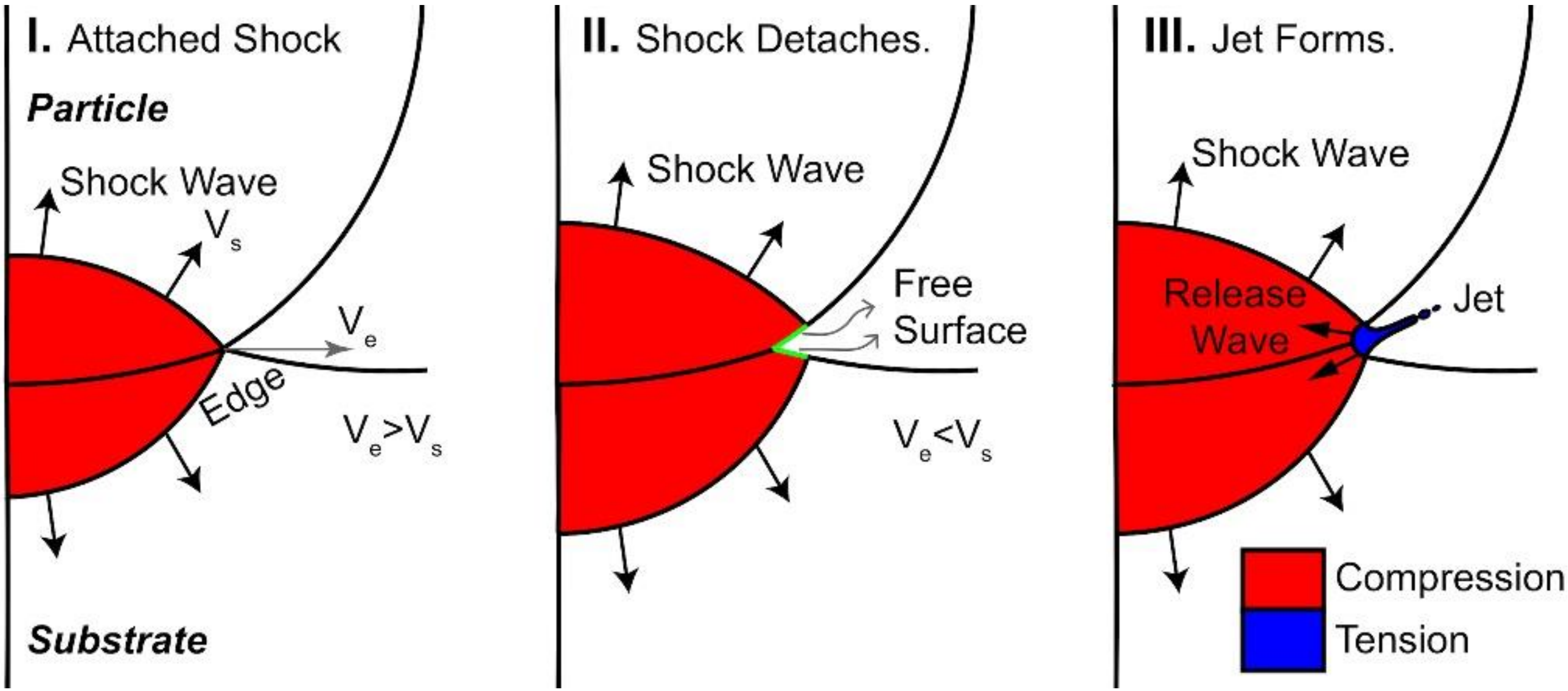
Hahn et al. J. Mater. Process. Technol. (2016); Murr et al. J. Mater. Sci. (1995); Field at al. Wear (2012); Glass et al. Springer (2012)

Hydrodynamic Origin of Jetting



Hassani-Gangaraj et al. (2018), *submitted to Acta Mat.*

Material ejection/fragmentation



Hassani-Gangaraj et al. (2018), submitted to Acta Mat.

The origin of jetting? — Adiabatic Shear Instability ✗

Localized Melting ✗

Hydrodynamic Effects ✓

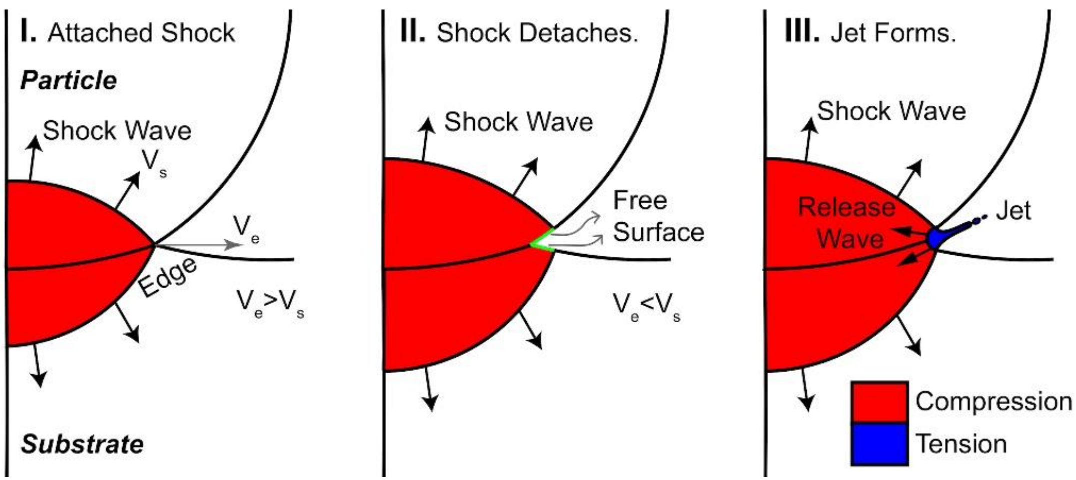
⇕

Jetting leads to Bonding.

⇕

Develop a mechanistic prediction of V_{cr} for bonding

Material ejection/fragmentation



$$P^- = P_{spall}$$

$$P^- = kP \qquad P_{spall} = \alpha B$$

$$k \times \left\{ \frac{1}{2} \left(\rho C_0 V_{cr} + s \frac{\rho V_{cr}^2}{2} \right) \right\} = \alpha B$$

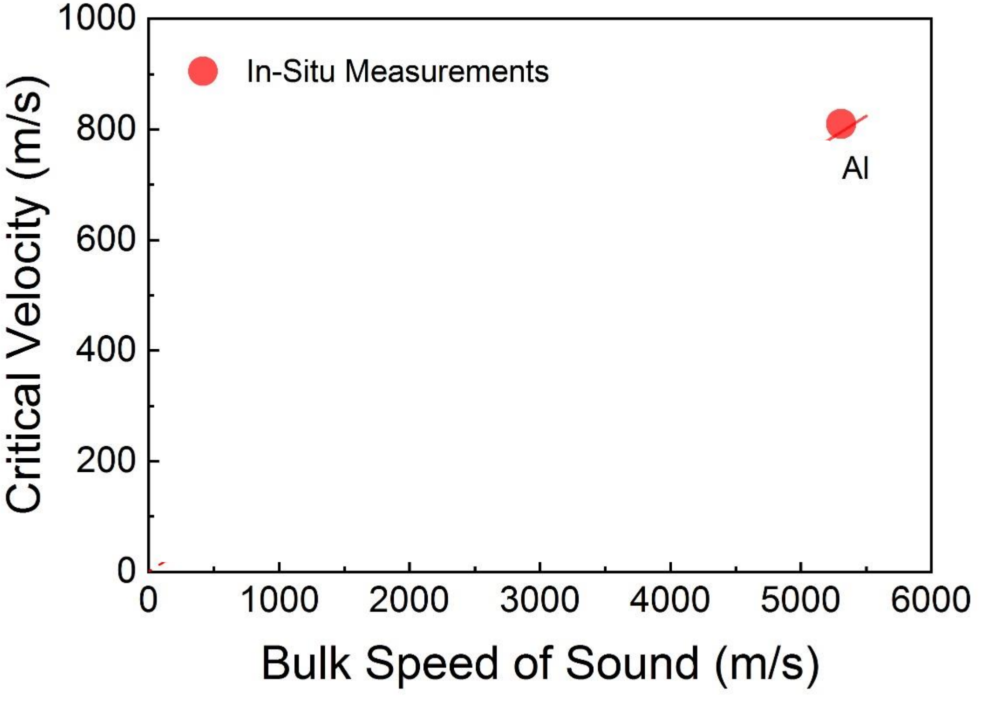
$$V_{cr} = \left(\frac{\sqrt{1 + \frac{4s\alpha}{k}} - 1}{s} \right) \times \sqrt{\frac{B}{\rho}}$$

$$V_{cr} = c \times C_0$$

Hassani-Gangaraj et al. (2018), submitted to Acta Mat.

V_{cr} and C_0

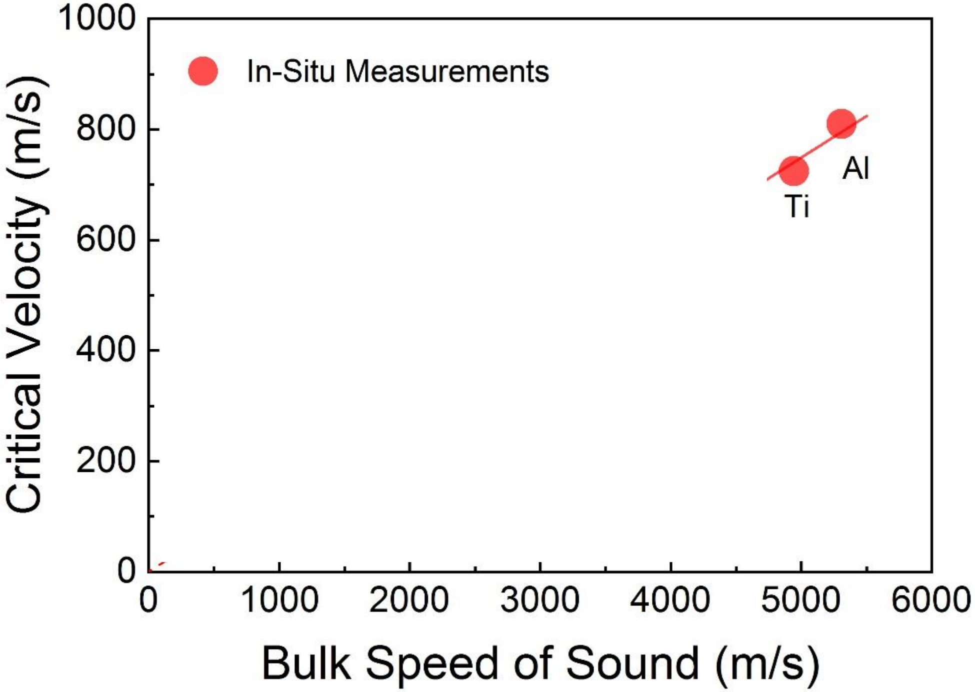
$$V_{cr} = c \times C_0 \qquad c \approx 0.15$$

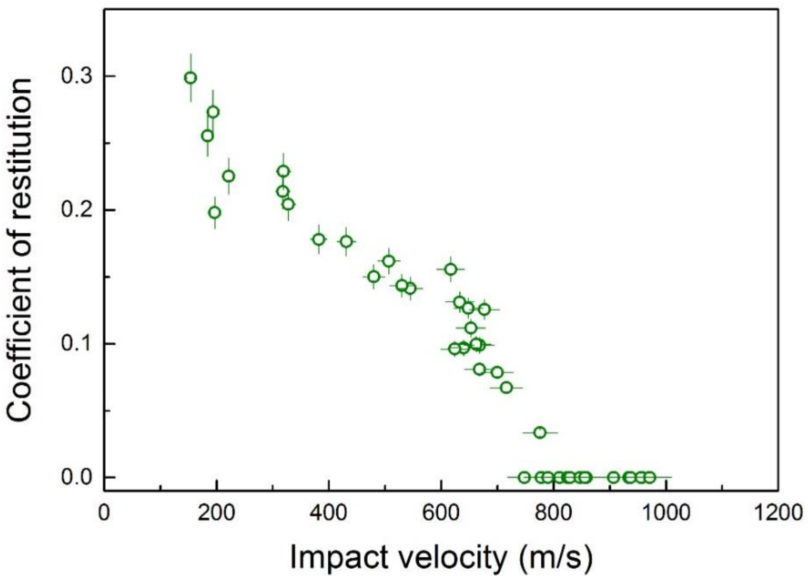


Hassani-Gangaraj et al. (2018), submitted to Scripta Mat.

Ti on Ti

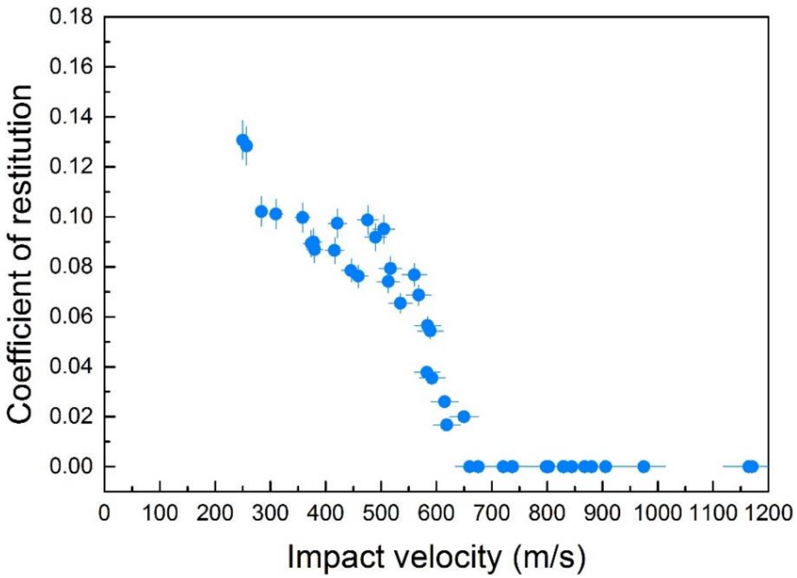
$$V_{cr} \approx 0.15 \times C_0$$



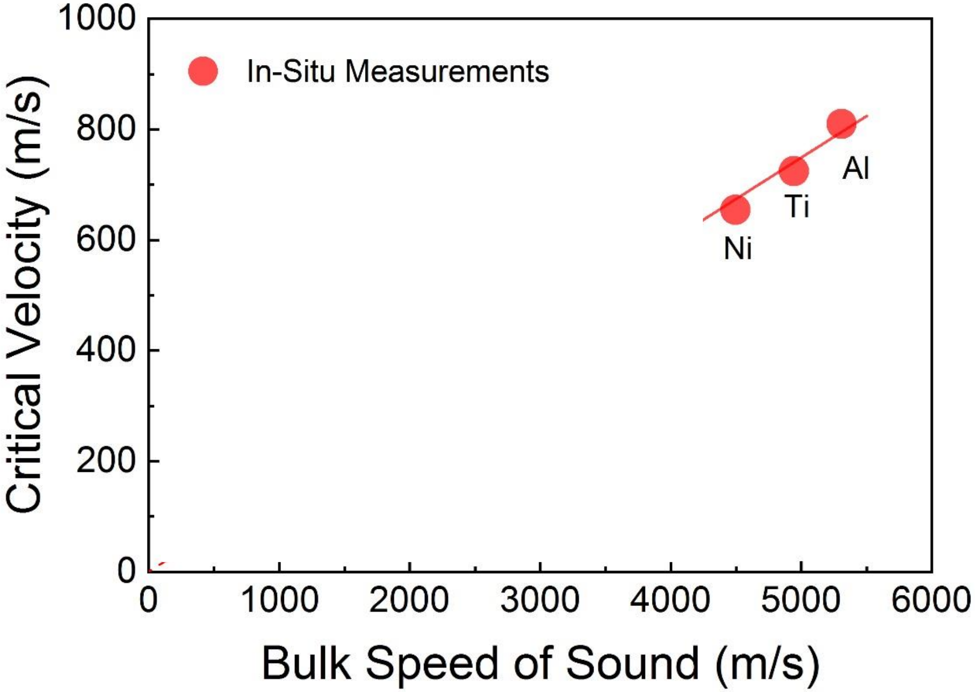


Hassani-Gangaraj et al. Scripta Materialia 145 (2018) 9–13.
Hassani-Gangaraj et al. Submitted to Acta Materialia.

Ni on Ni



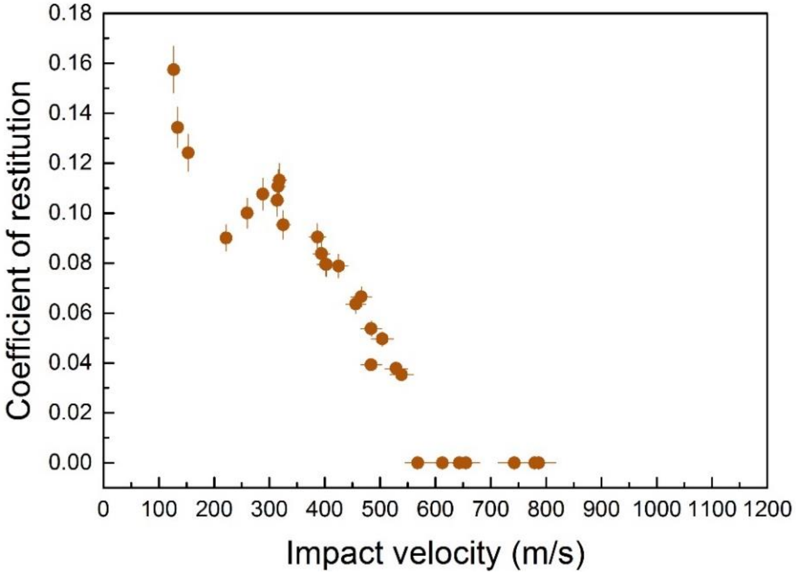
$V_{cr} \approx 0.15 \times C_0$

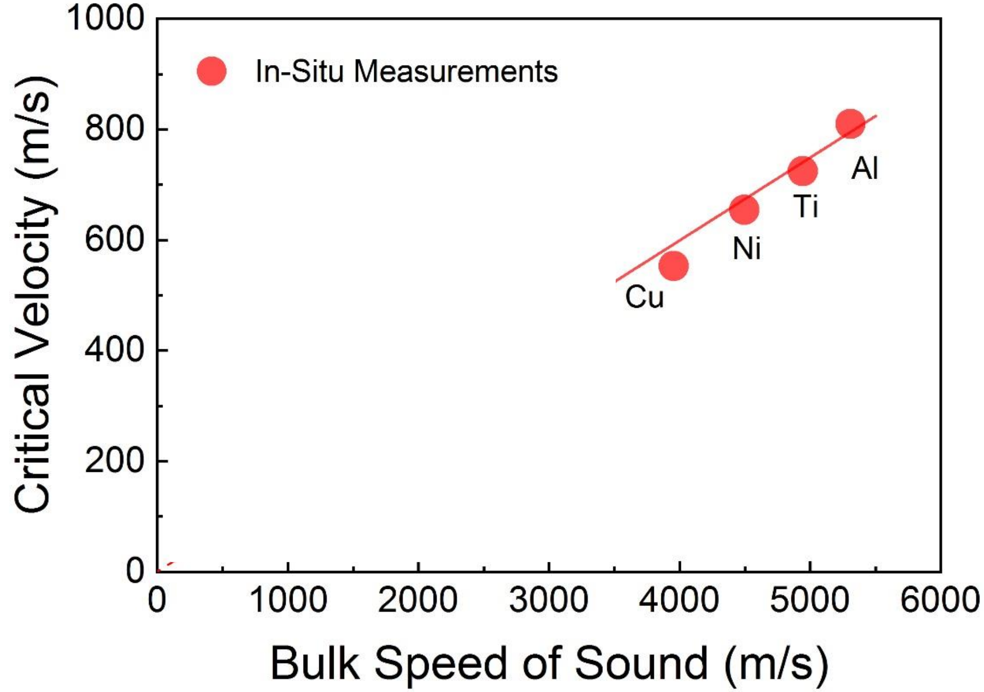


Hassani-Gangaraj et al. Scripta Materialia 145 (2018) 9–13.
Hassani-Gangaraj et al. Submitted to Acta Materialia.

Cu on Cu

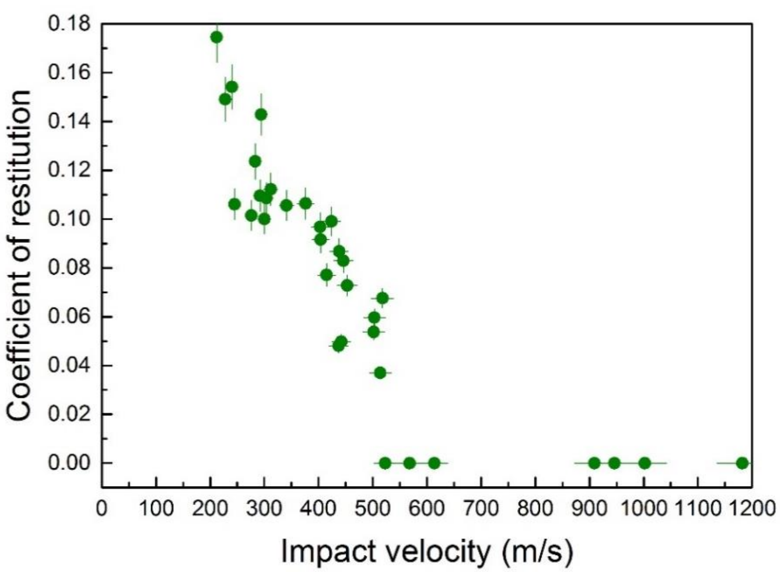
$V_{cr} \approx 0.15 \times C_0$



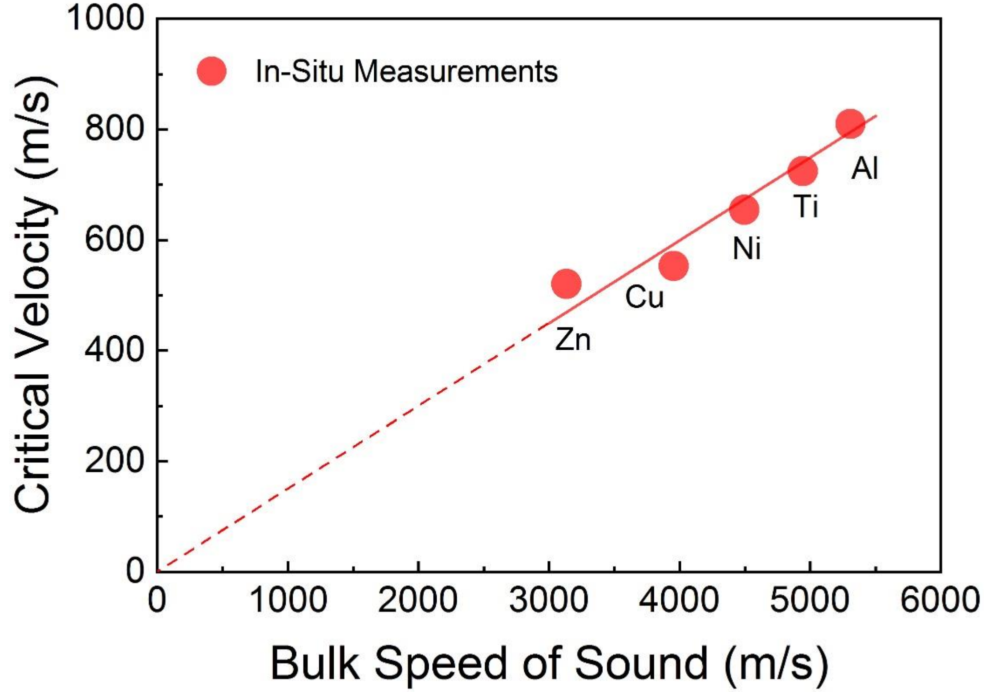


Hassani-Gangaraj et al. Scripta Materialia 145 (2018) 9–13.
Hassani-Gangaraj et al. Submitted to Acta Materialia.

Zn on Zn

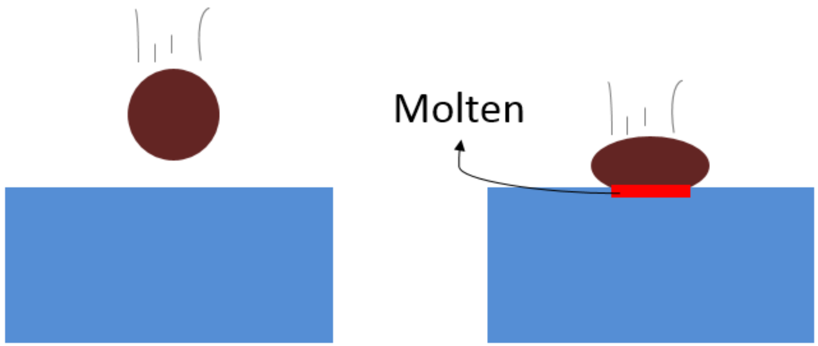


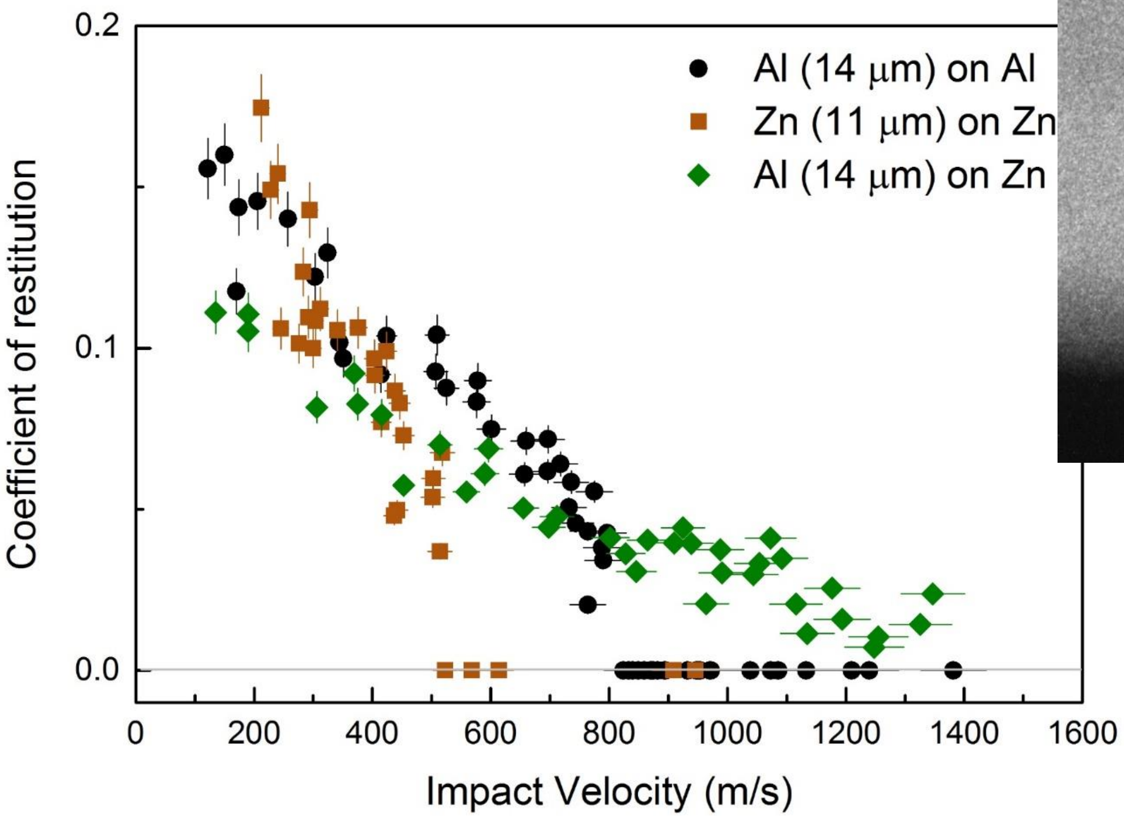
$$V_{cr} \approx 0.15 \times C_0$$

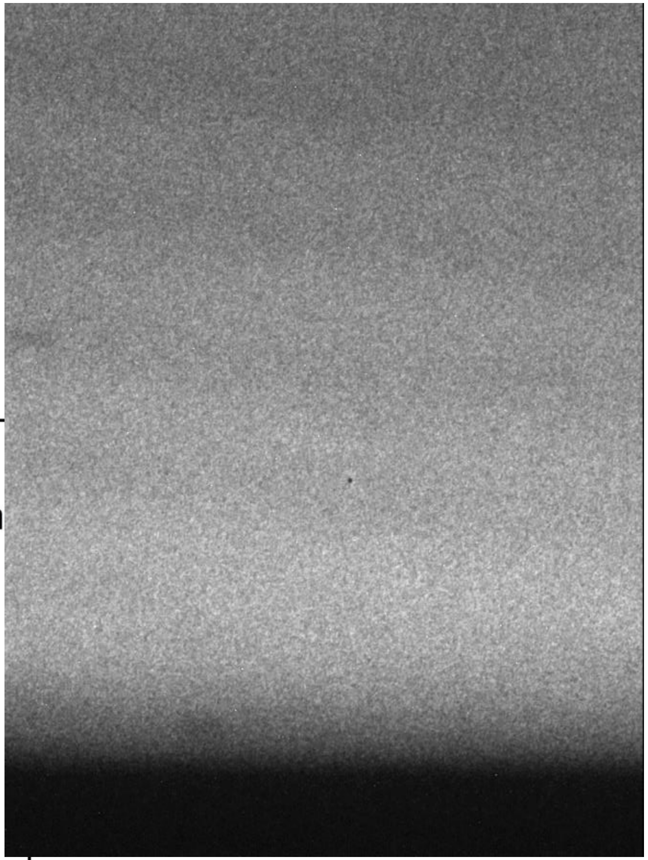


Hassani-Gangaraj et al. Scripta Materialia 145 (2018) 9–13.
Hassani-Gangaraj et al. Submitted to Acta Materialia.

Melting Promotes Bonding?



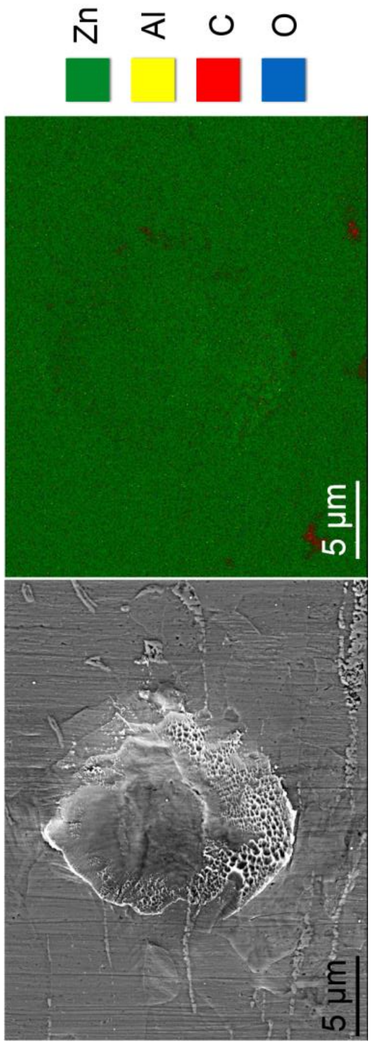


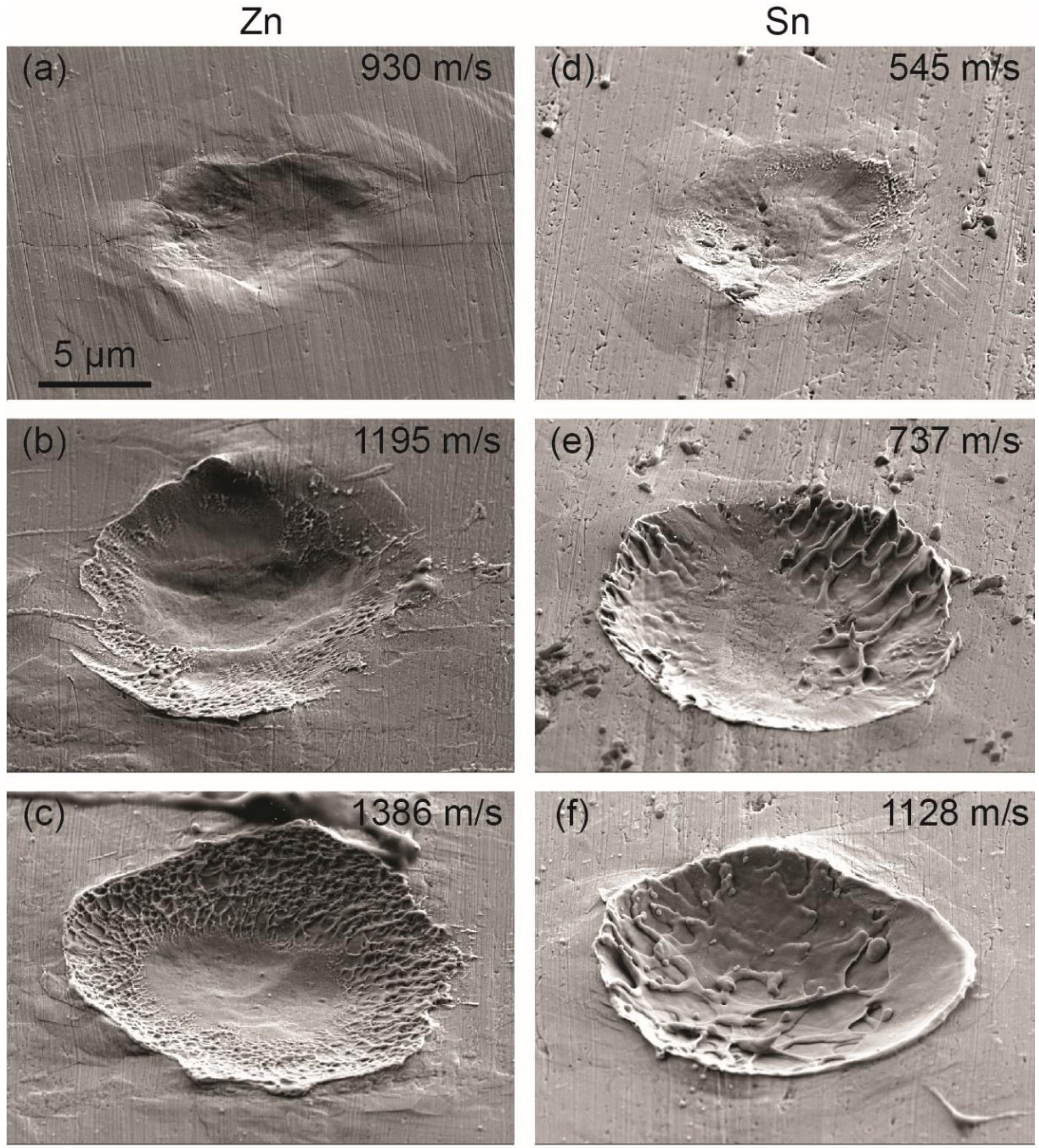


Al on Zn
1070 m/s

Hassani-Gangaraj et al. Phys. Rev. Lett. 119 (2017) 175701.

Melting emerges …





Hassani-Gangaraj et al. Phys. Rev. Lett. 119 (2017) 175701.

Time

residence time

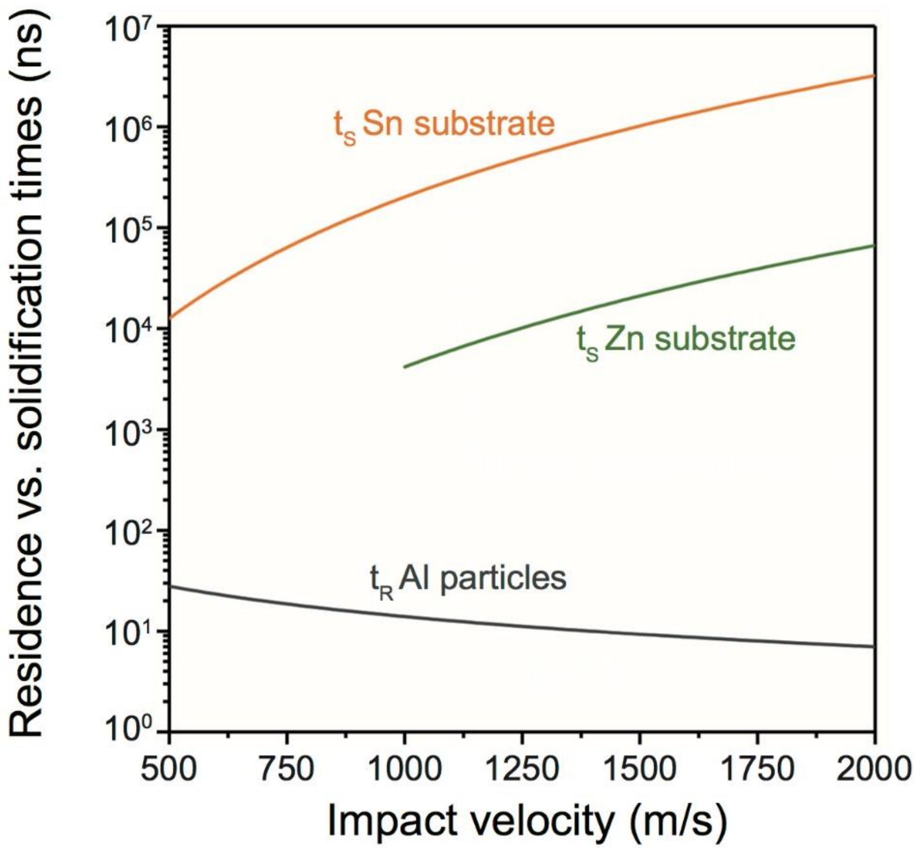
$$t_r = \frac{d}{V_i}$$

d: particle size
V_i: impact velocity

solidification time

$$t_s = \left[\frac{H_f}{(T_m - T_0)}\right]^2 \left[\frac{\rho_s \pi}{4KC}\right] \left(\frac{v_{melt}}{A}\right)^2$$

$$\frac{\rho_s v_{melt}}{m_p} = k\left(\frac{V_i^2}{E_m}\right)^{3\mu/2}$$

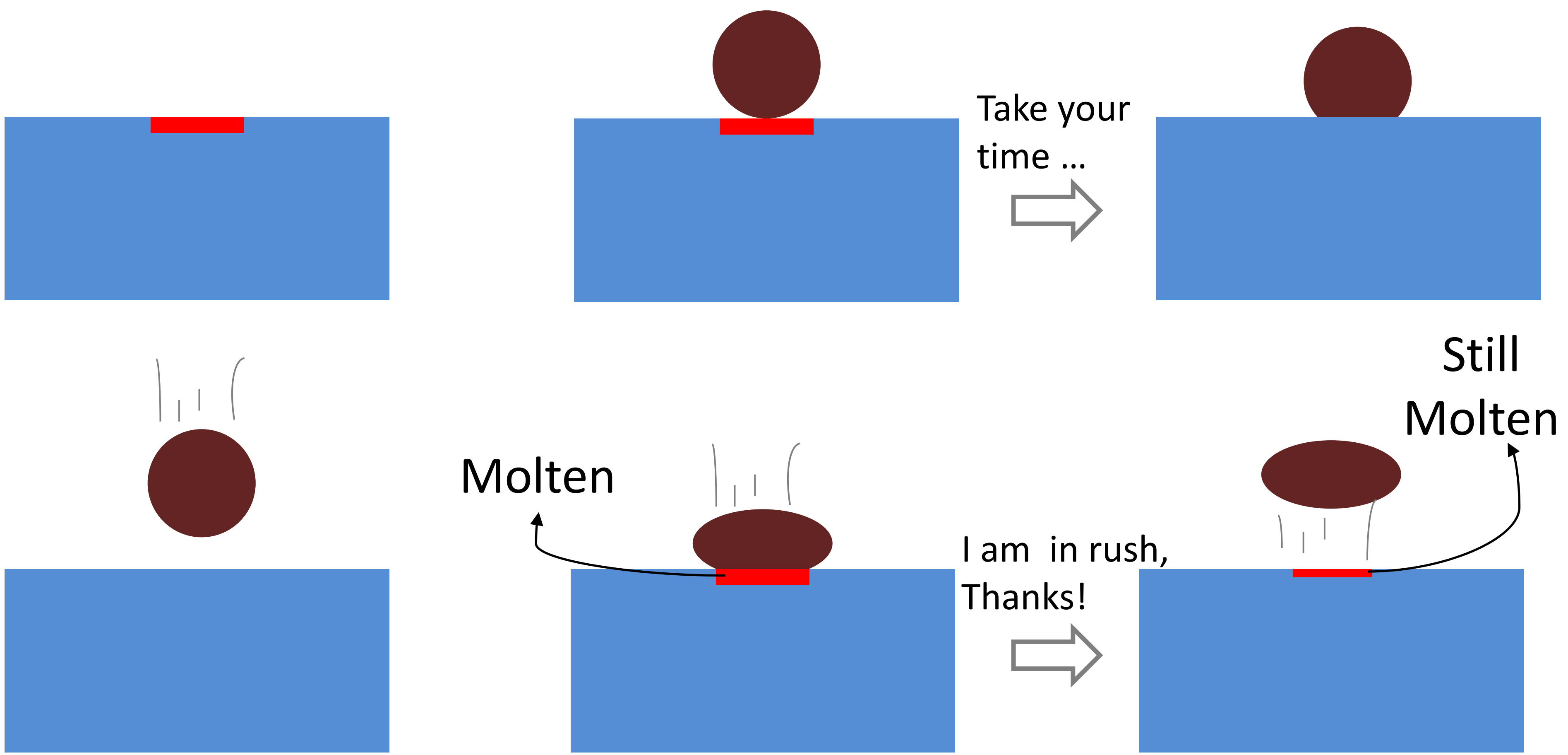


H_f: heat of fusion
T_m: melting temperature
T_0: initial temperature
ρ: density
K: thermal conductivity
C: specific heat
v_{melt}: melt volume
A: melt area
E_m: Shock energy at melting onset

Hassani-Gangaraj et al.
Phys. Rev. Lett. 119 (2017) 175701.

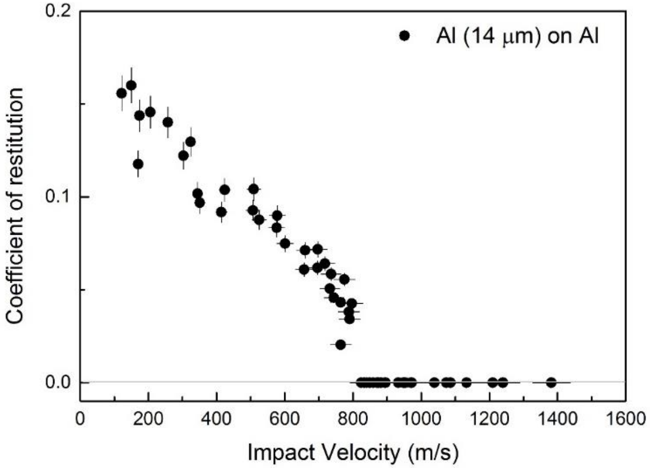
Melting and Rebound?

residence time vs. solidification time

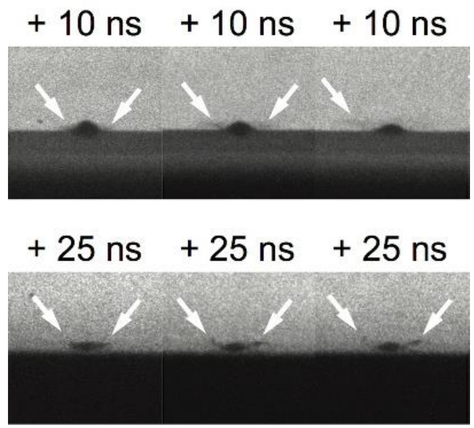


Hassani-Gangaraj et al. Phys. Rev. Lett. 119 (2017) 175701.

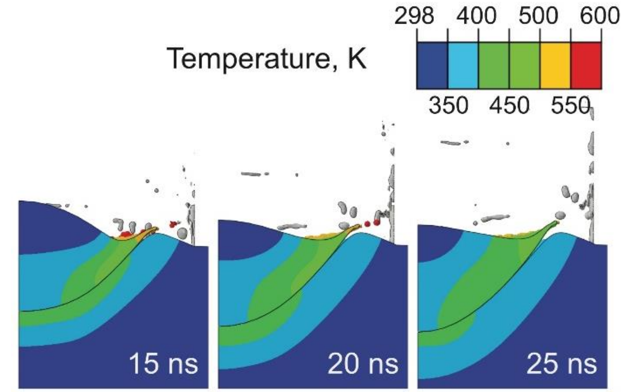
Summary



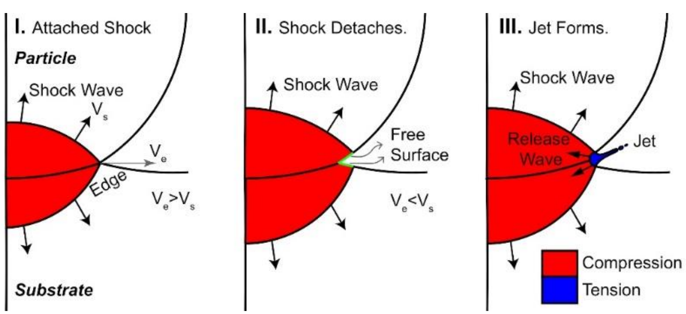
Direct measurements of V_{cr}



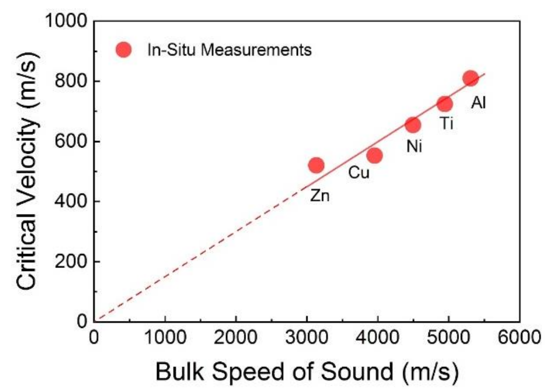
Material ejection/fragmentation upon bonding



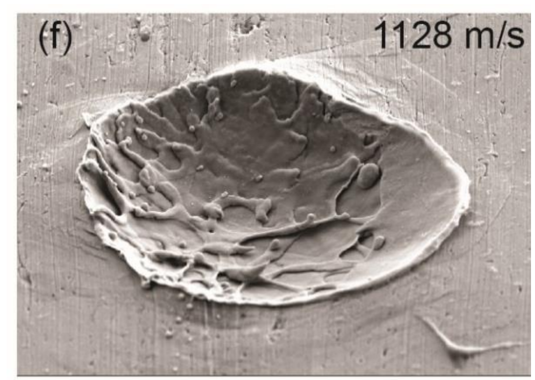
No melting at the critical velocity.



Hydrodynamics origin of jetting.



$V_{cr} = c \times C_0$



Localized melting can hinder boning.

Acknowledgement

Hassani-Gangaraj et al. “Melting can hinder impact-induced adhesion” ***Physical Review Letters.*** 119 (2017) 175701

Hassani-Gangaraj et al. “In-situ observations of single micro-particle impact bonding” **Scripta Materialia.** 145 (2018) 9.

Videos available in the supplementary materials.

Email: mhassani@mit.edu