Quantitative Studies of Supersonic Microparticle Impacts on Metals

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Keith Nelson

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Hye-Sook Park, Jesse Pino, Alison Saunders, and Camelia Stan (LLNL)

Financial Support: DOE BES (work on hydrodynamic effects, extreme phenomena)
ARL Cold Spray Team (work on oxides in cold spray)
LLNL (work on impact melting)

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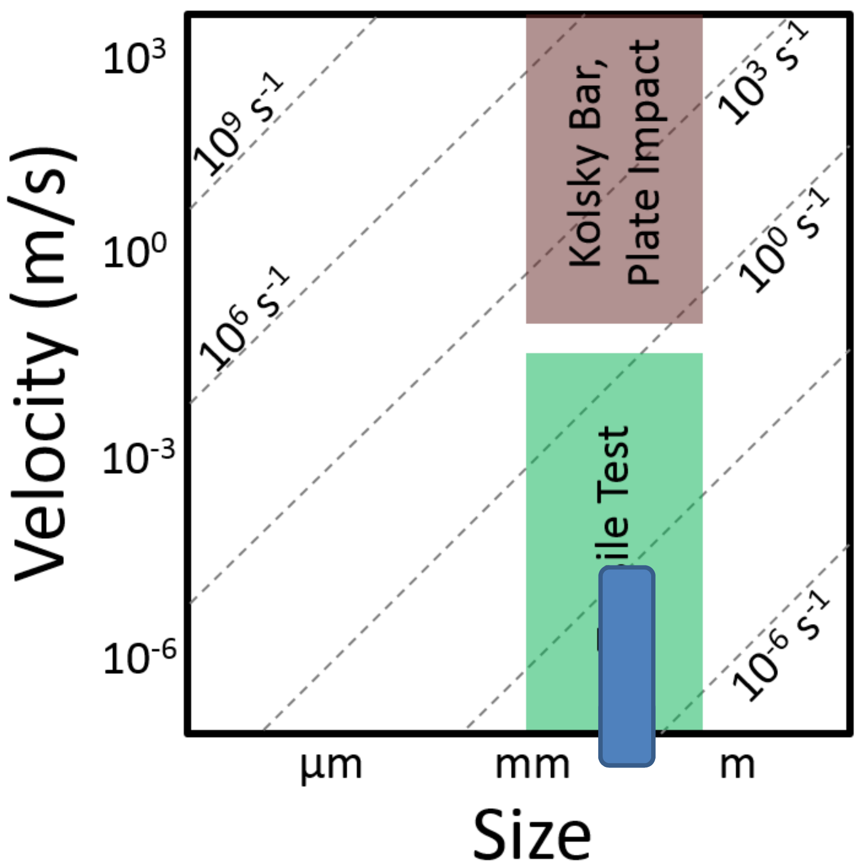
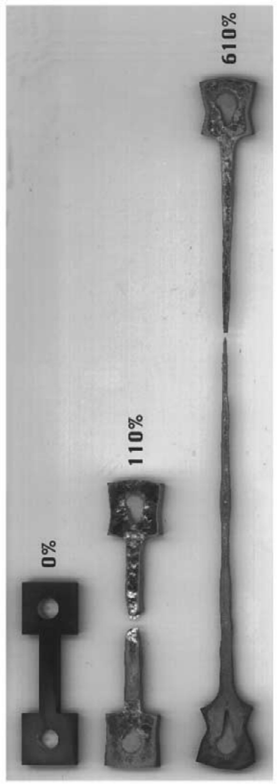
A personal journey of impatience

$\dot{\varepsilon} \sim V/d$

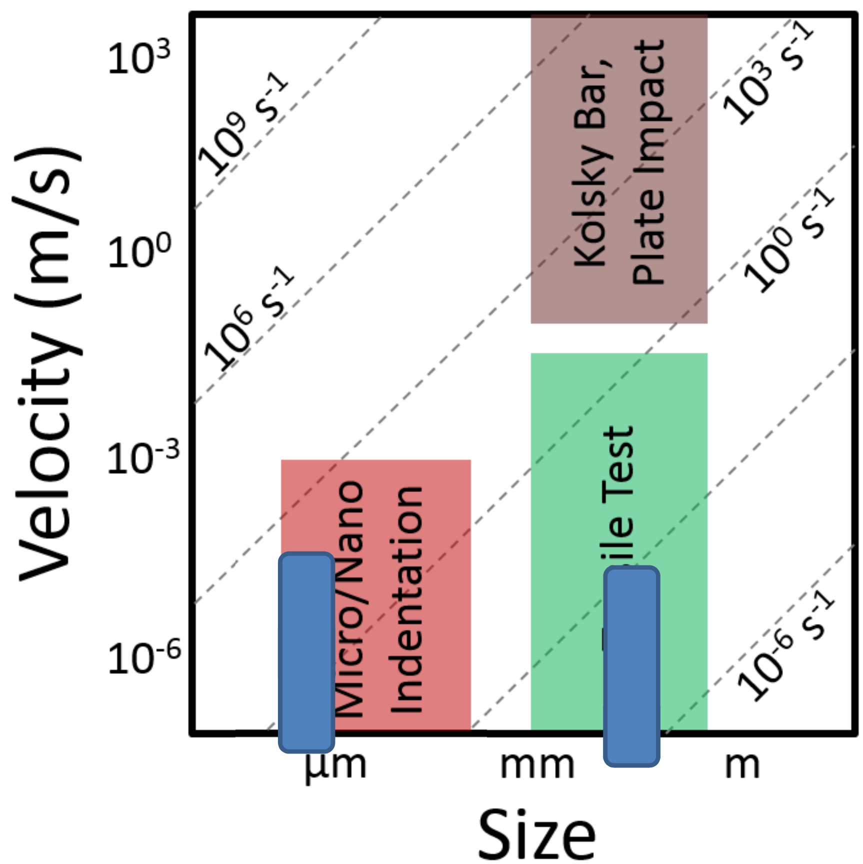


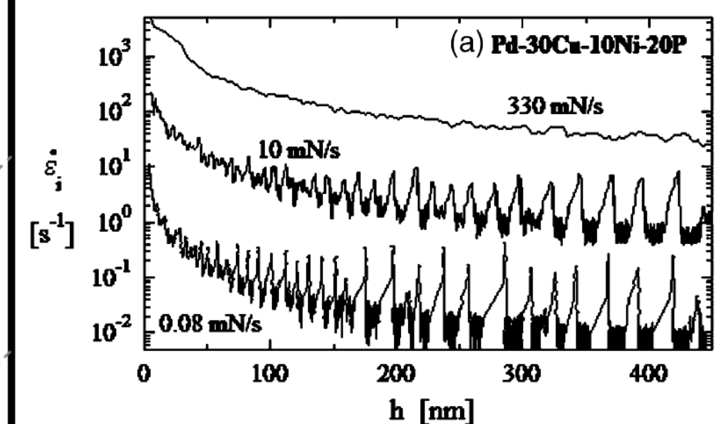


Acta Mater 1998

A personal journey of impatience

$\dot{\varepsilon} \sim V/d$

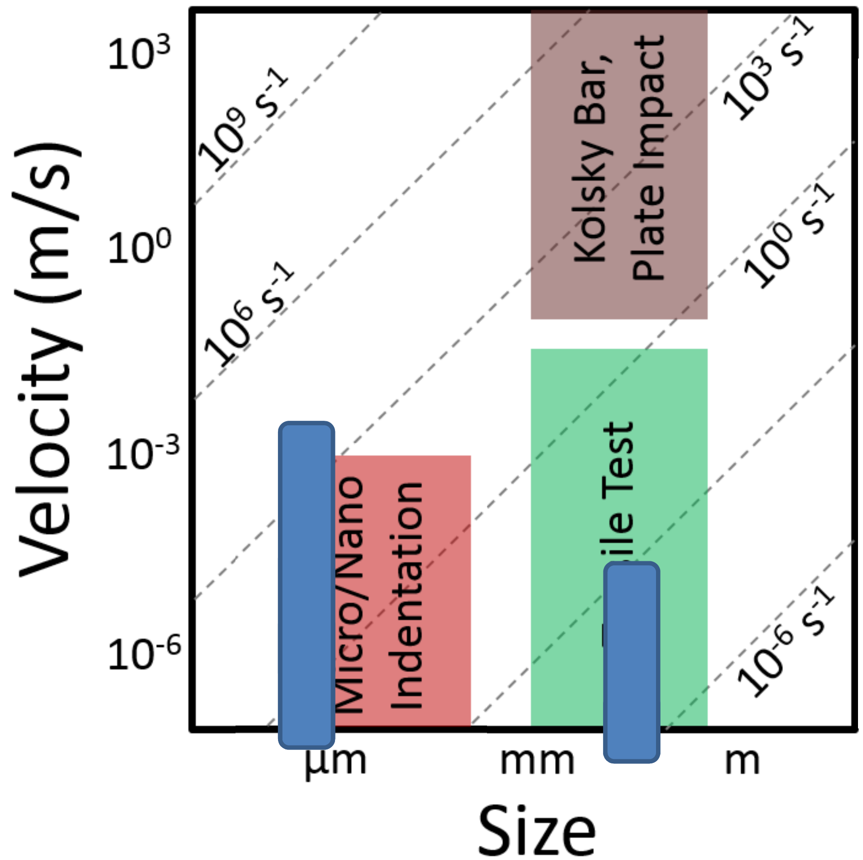


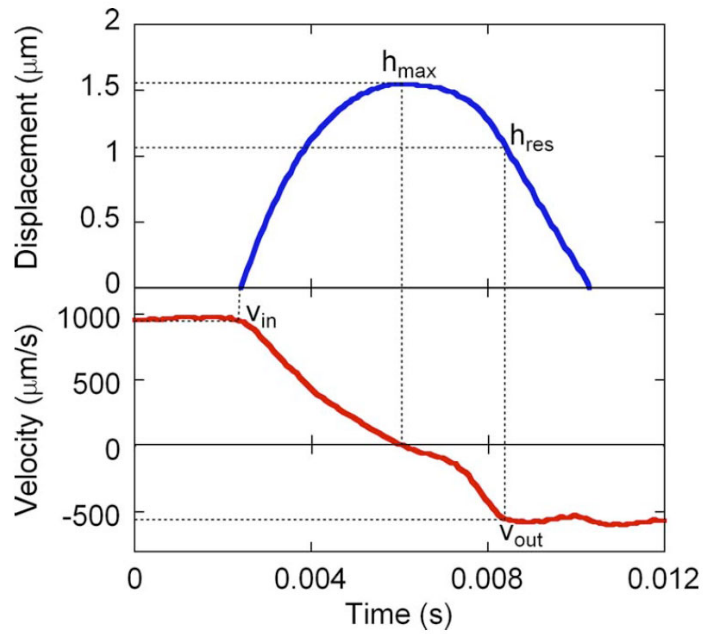


Acta Mater 2003

A personal journey of impatience

$\dot{\varepsilon} \sim \mathrm{V/d}$

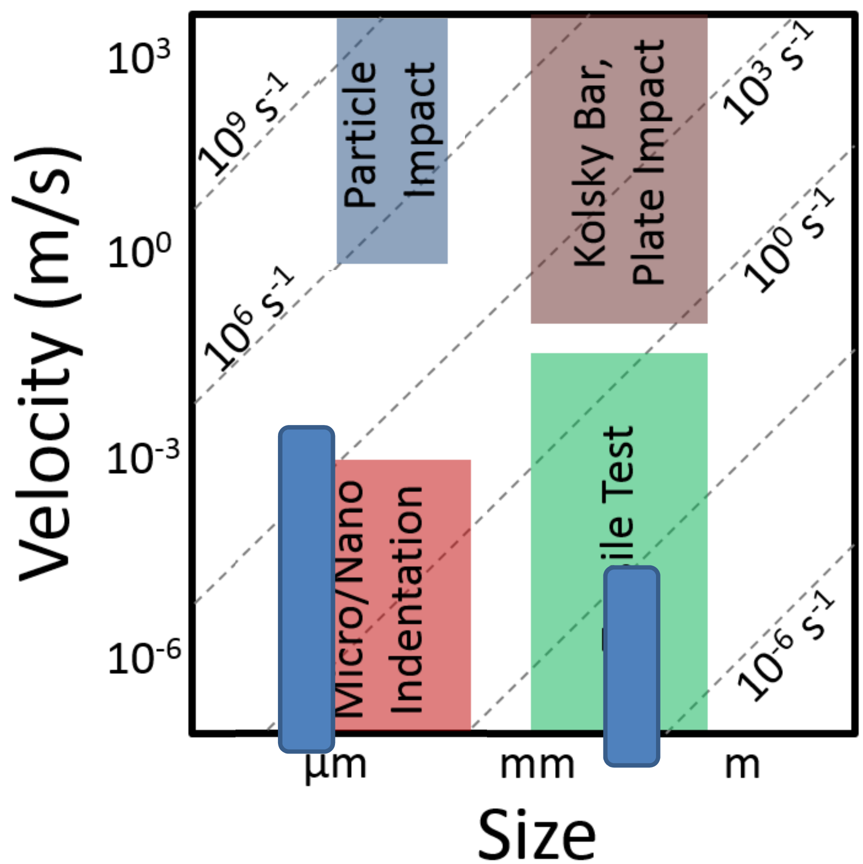


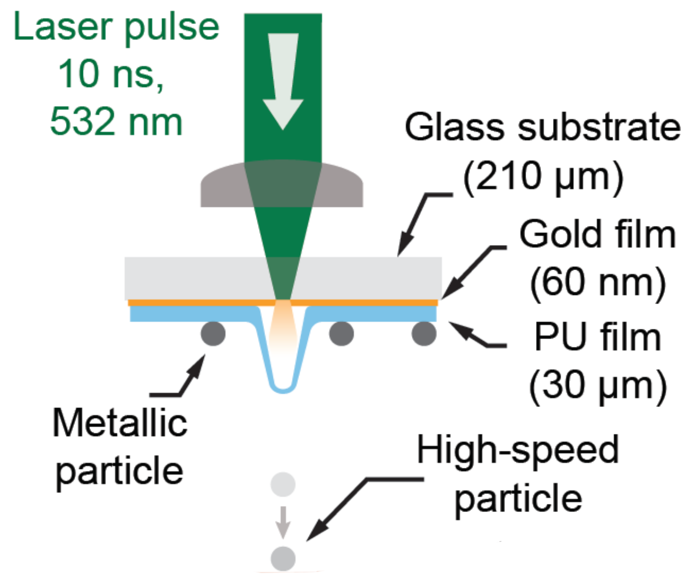


APL 2008

A personal journey of impatience

$\dot{\varepsilon} \sim V/d$

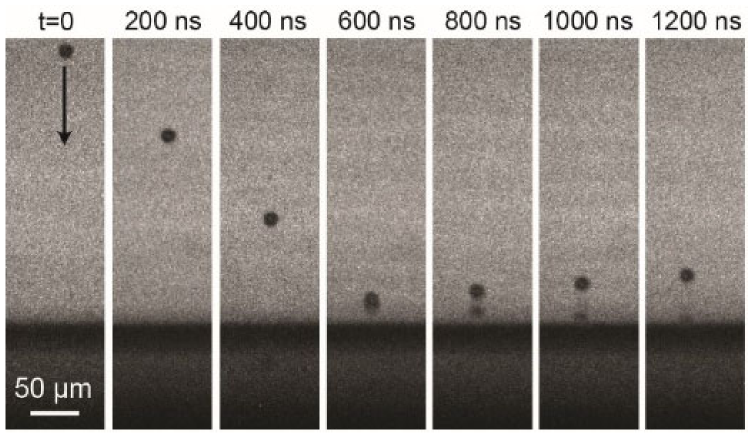




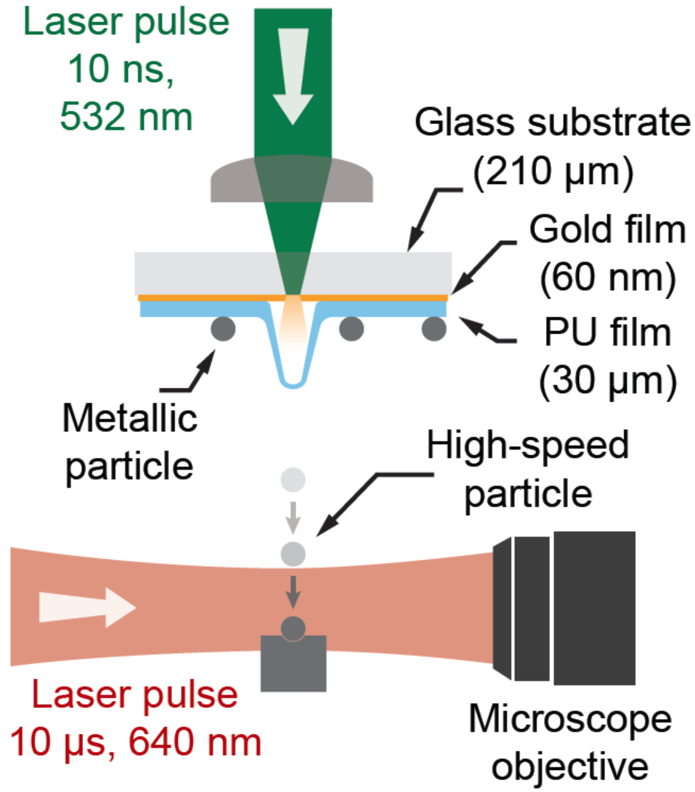
16 frames with interframe as short as 3 ns

Laser-induced particle impact test (LIPIT)

Alumina particle on Copper substrate



M. Hassani, D. Veysset, K.A. Nelson, and C.A. Schuh, Scr. Mater. **177**, 198 (2020).



16 frames with interframe as short as 3 ns

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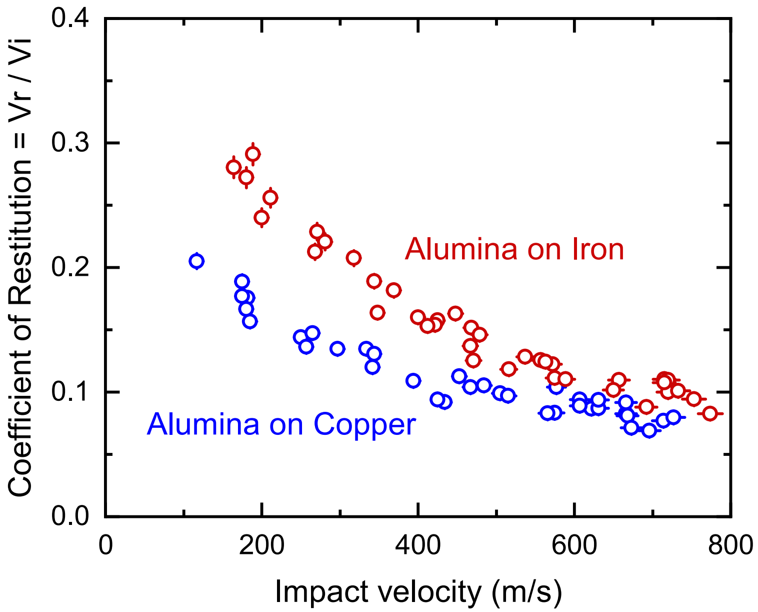
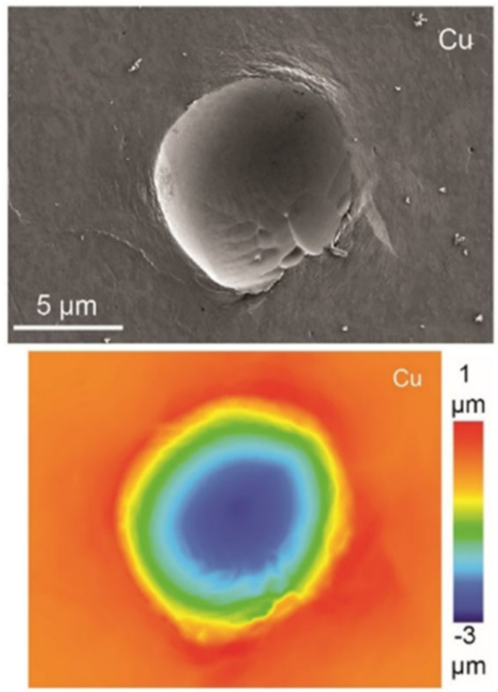
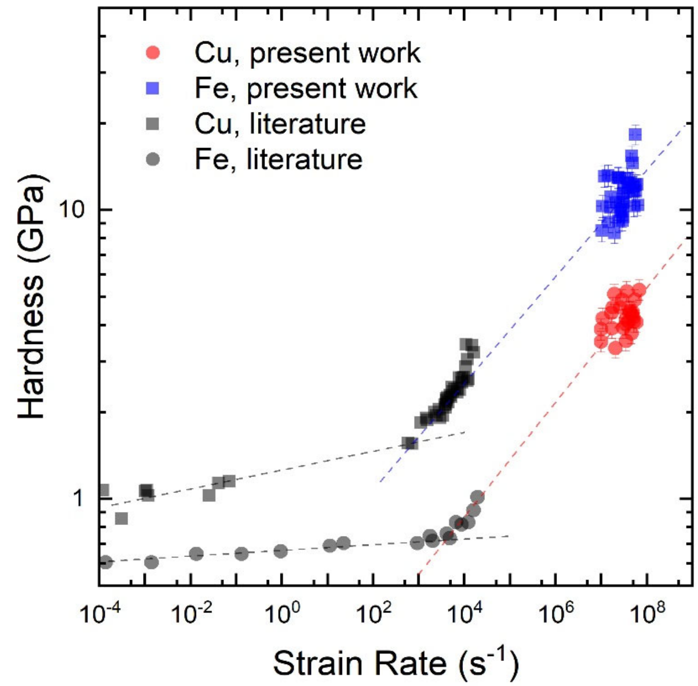
High strain rate metal hardness

$$Hardness \equiv \frac{load}{contact\ area} = \frac{plastic\ work}{V_{indent}}$$







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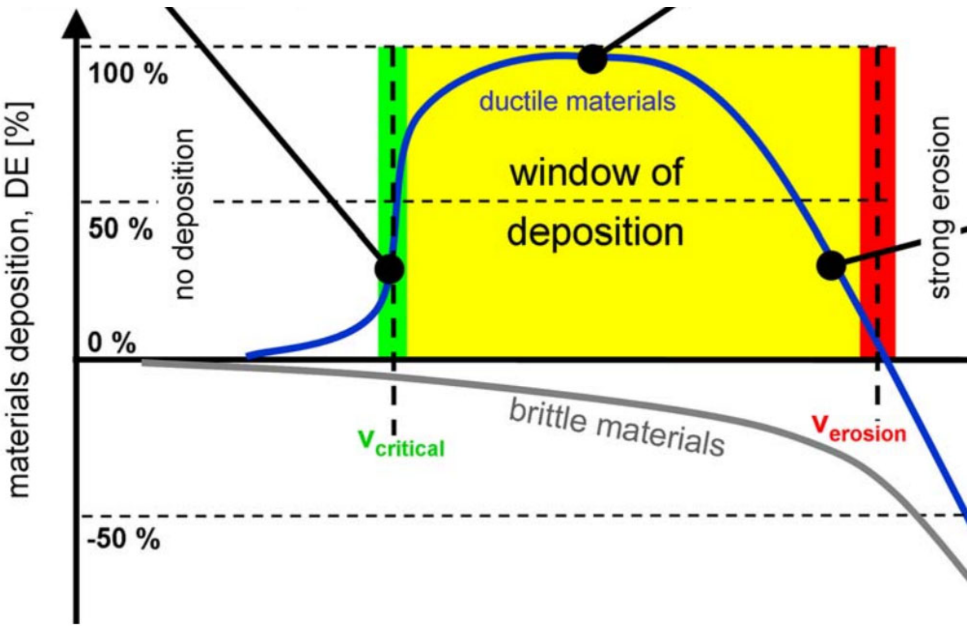
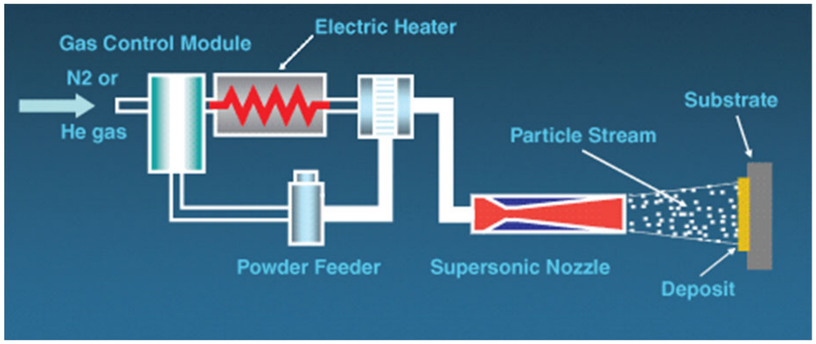
M. Hassani, D. Veysset, K.A. Nelson, and C.A. Schuh, Scr. Mater. **177**, 198 (2020).

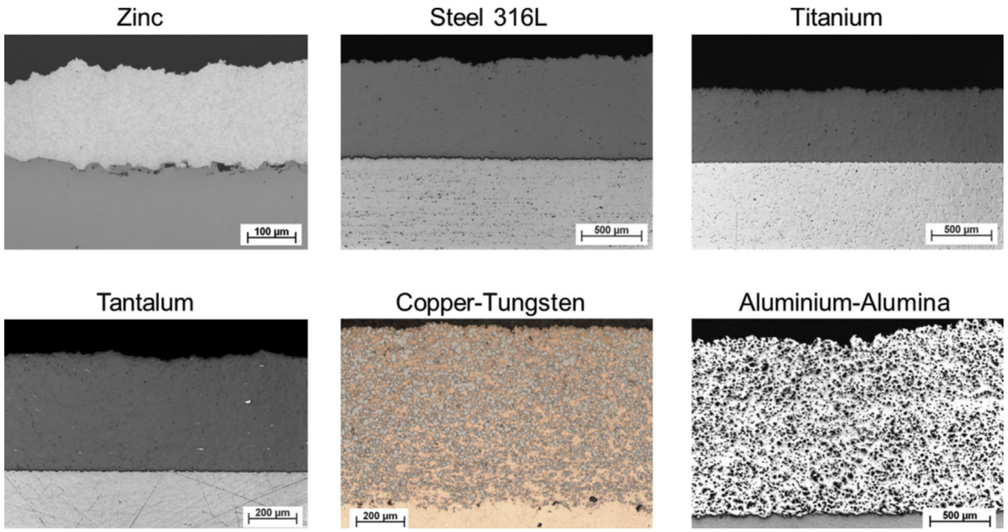
Kinetic Deposition or Cold Spray



Schmidt et al., J. Thermal Spray Tech., v18 (2009) p799



ARL, Cold Spray Action Team, V. Champagne



Assadi et al. Acta Mat 2016

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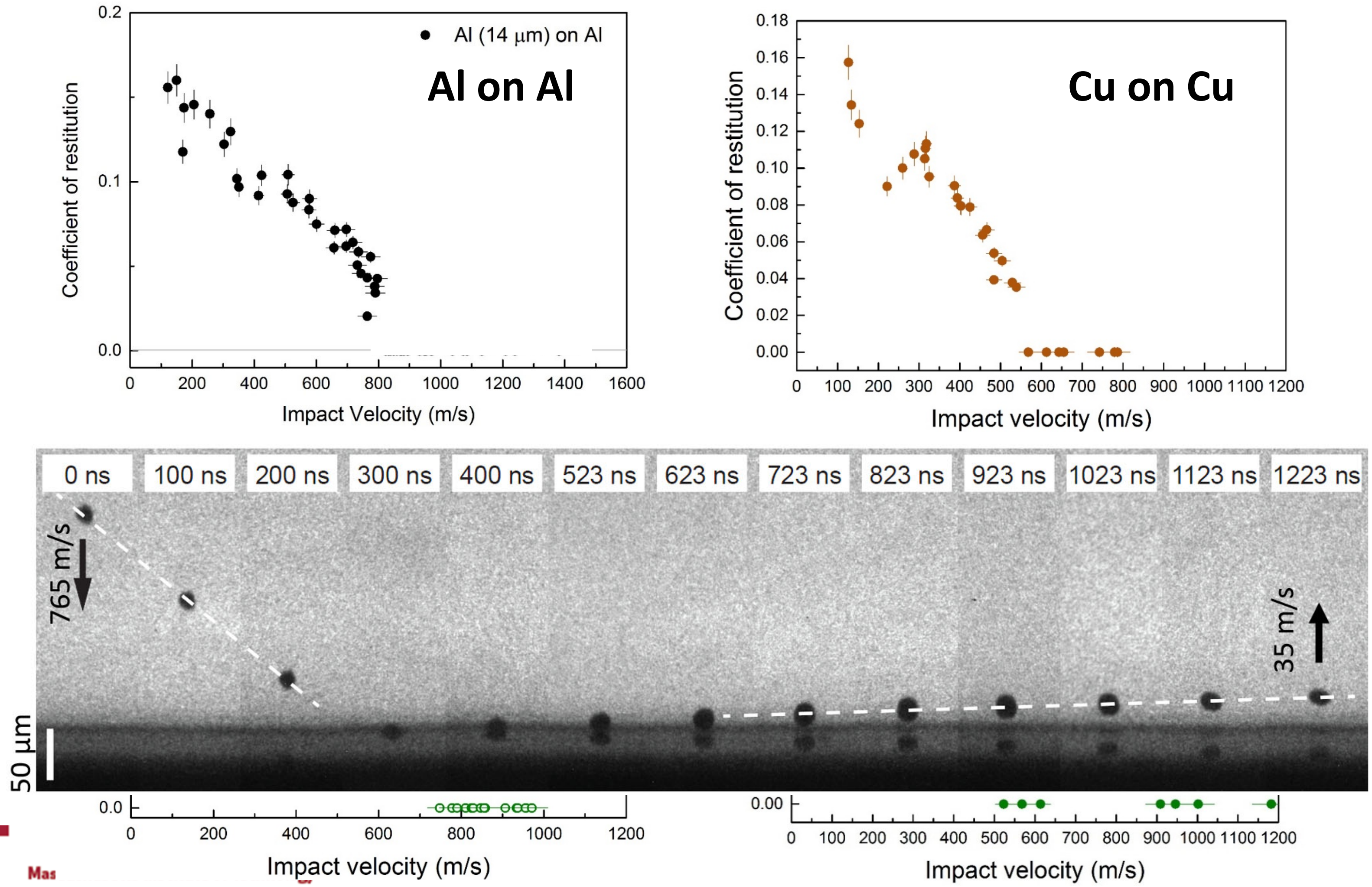
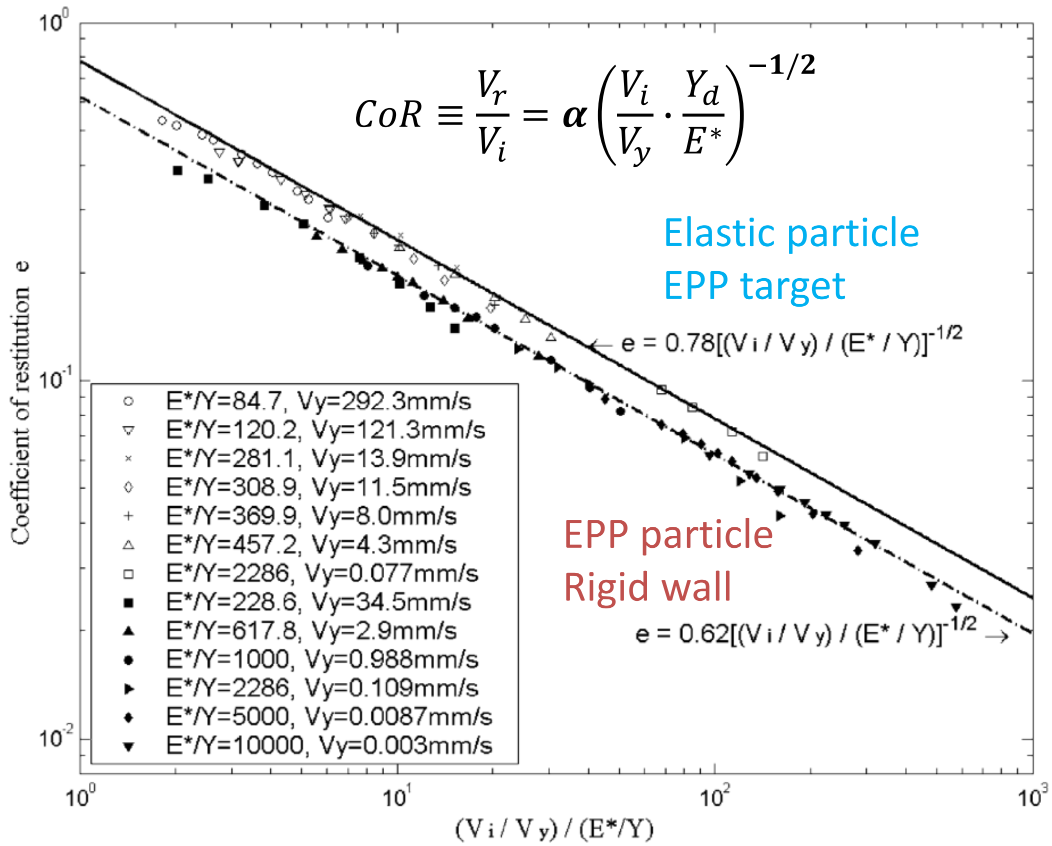
Matched metal impacts



Elastic-perfectly plastic impact model: Wu et al.

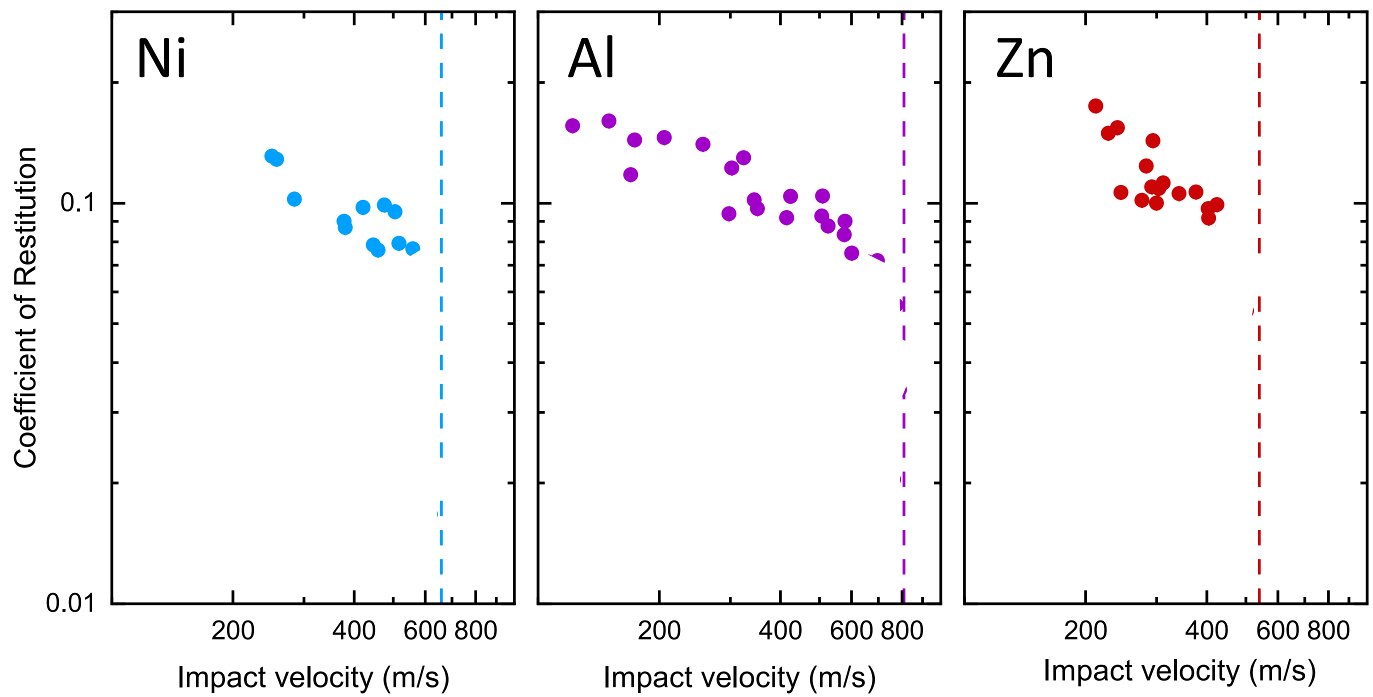


- $\boldsymbol{CoR \propto V_i^{-1/2}}$
- Relevant material properties: $\boldsymbol{\rho, E, \nu, Y_d}$
- $\boldsymbol{\alpha}$ dependent on which body deforms

C. Wu, L. Li, and C. Thornton, Int. J. Impact Eng. **28**, 929 (2003).

Power law behavior and Divergent behavior

$$CoR = \alpha\left(\frac{V_y}{V_i}\cdot\frac{E^*}{\boldsymbol{Y_d}}\right)^{-1/2}$$



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Y. Sun, D. Veysset, K.A. Nelson, and C.A. Schuh, J. Appl. Mech. **87**, 1 (2020).

Power law behavior and Divergent behavior

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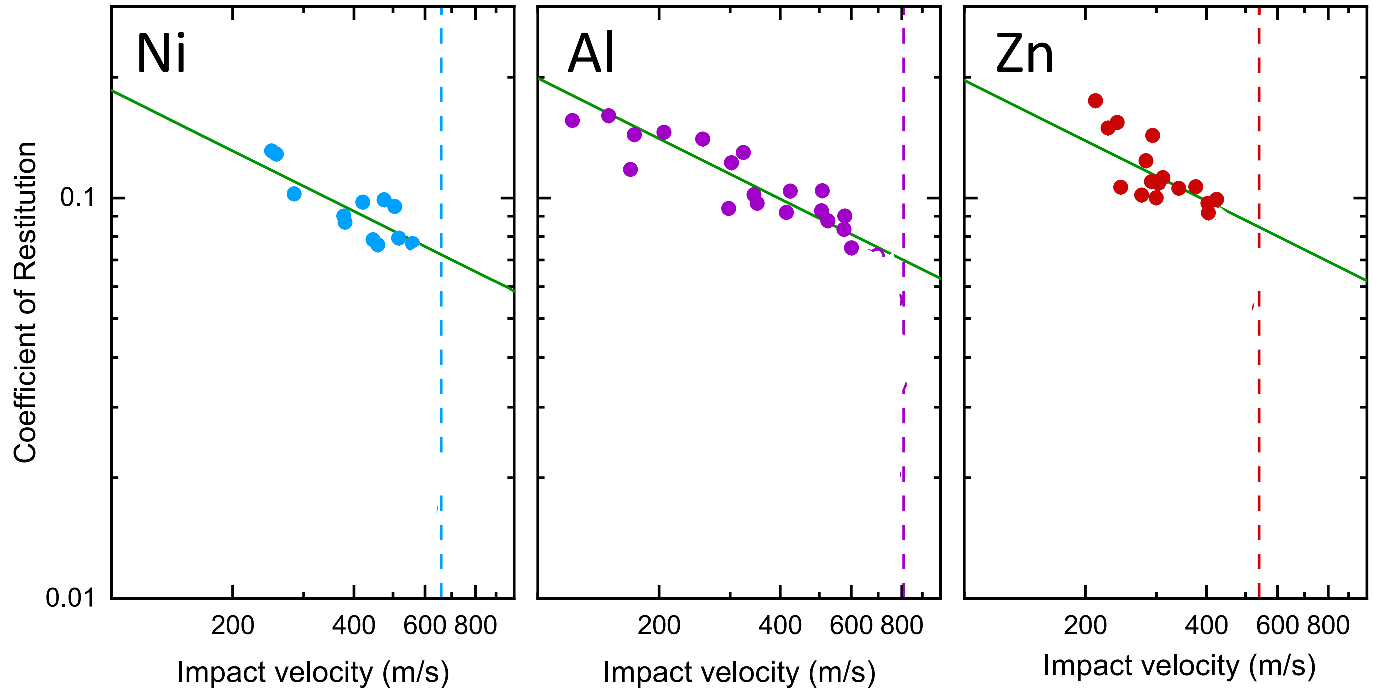

Material	Copper	Nickel	Aluminum	Zinc
Dynamic yield strength (MPa)	450 ± 45	800 ± 32	290 ± 10	470 ± 21

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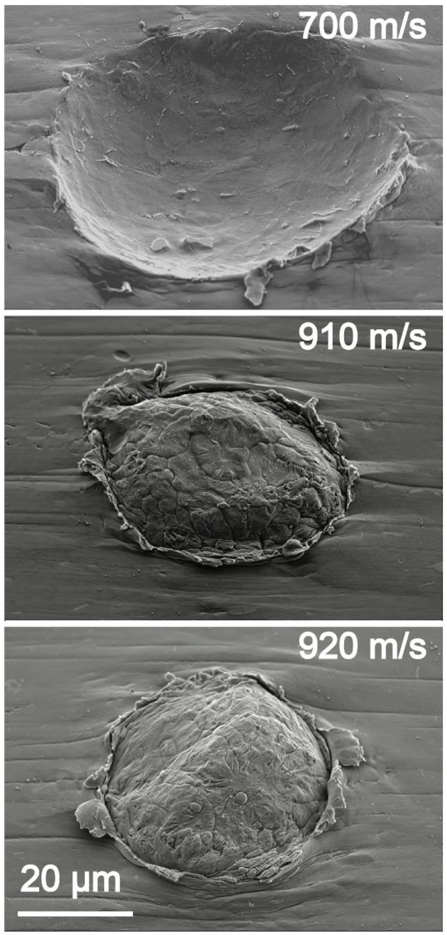
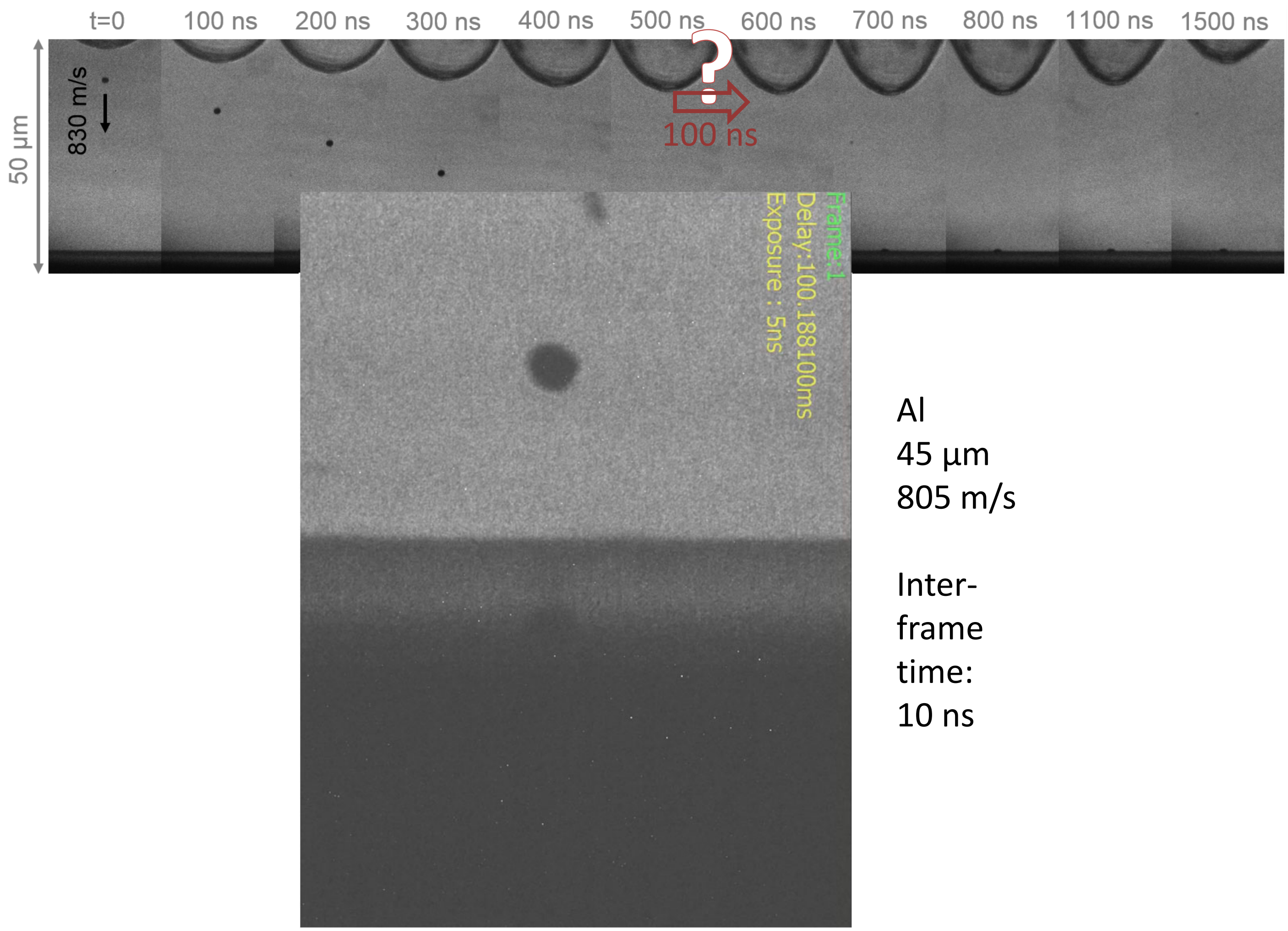
Y. Sun, D. Veysset, K.A. Nelson, and C.A. Schuh, J. Appl. Mech. **87**, 1 (2020).

What new phenomenon sets on around the adhesion transition?

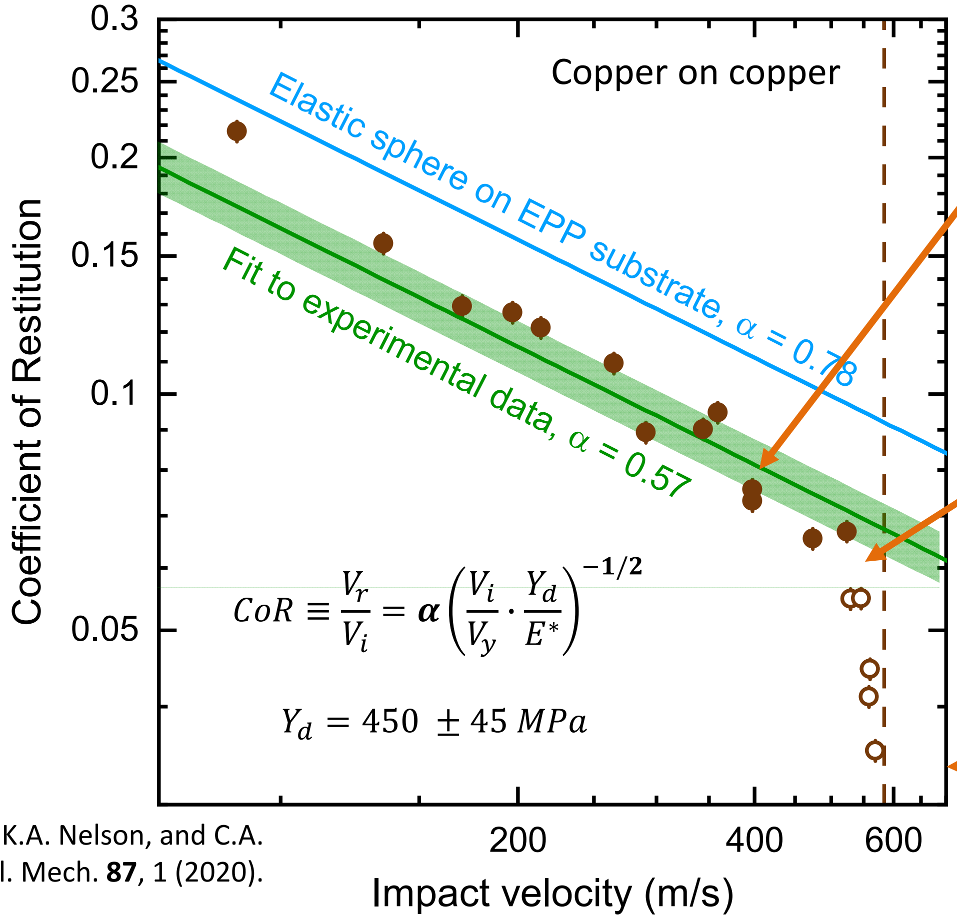


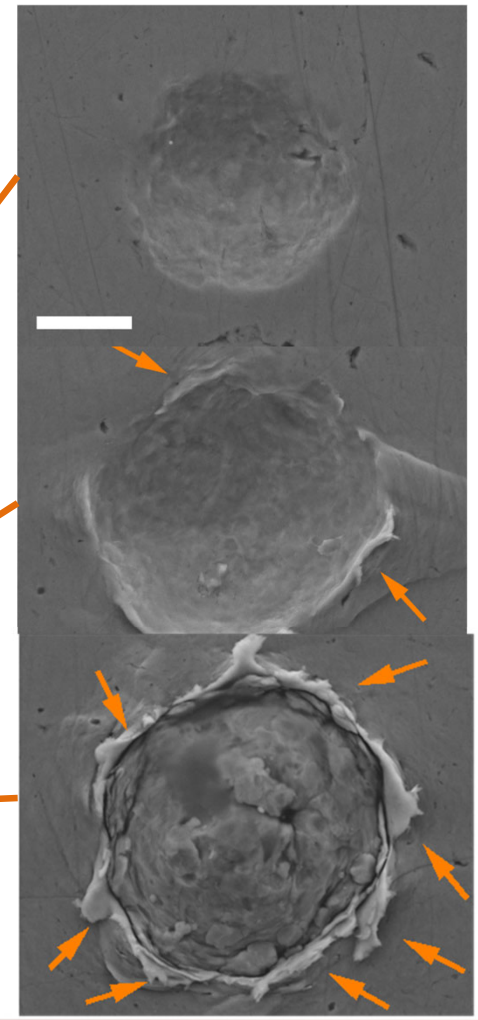


Al
45 µm
805 m/s

Inter-
frame
time:
10 ns

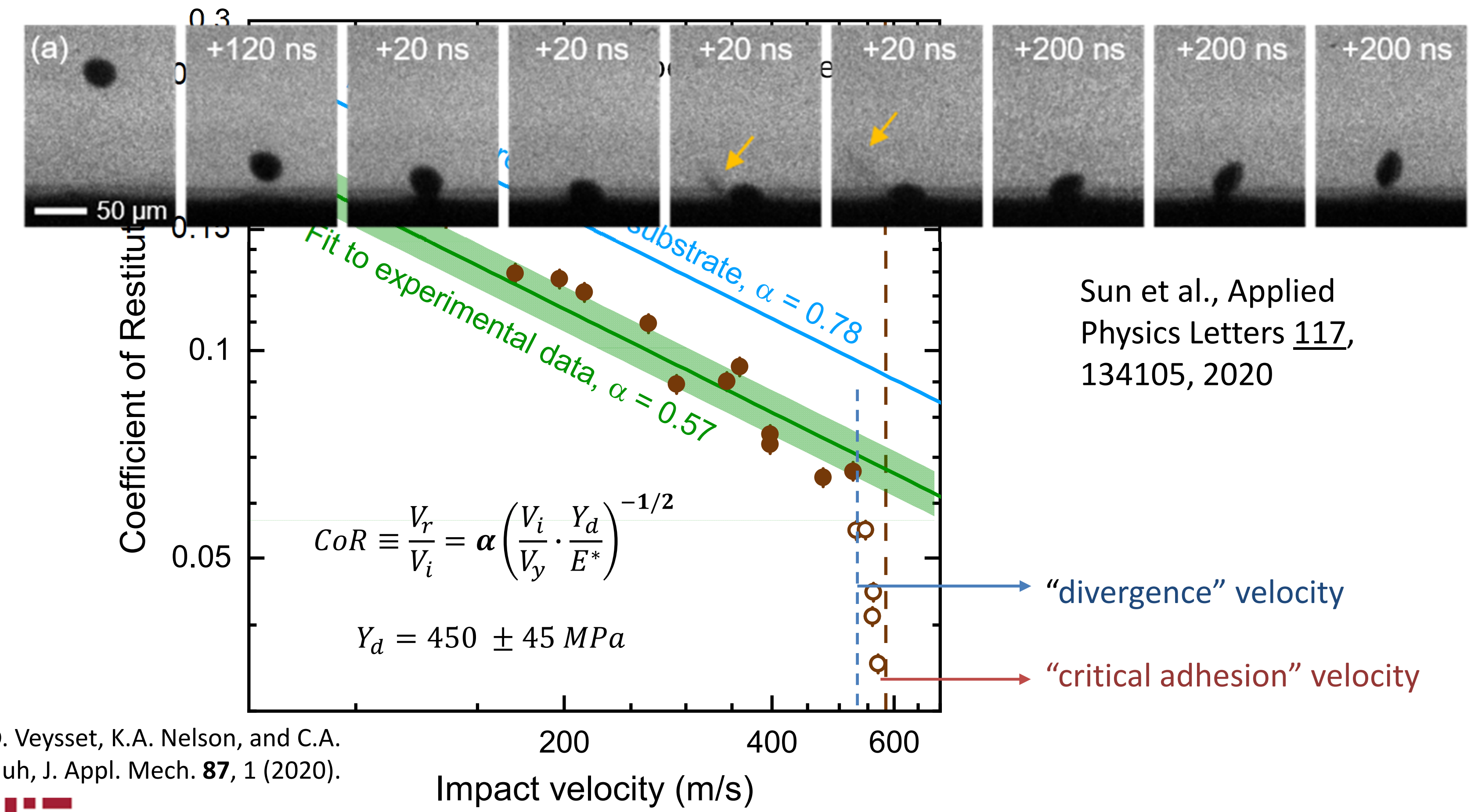
"Jetting" is the new phenomenon associated with adhesion





Y. Sun, D. Veysset, K.A. Nelson, and C.A. Schuh, J. Appl. Mech. **87**, 1 (2020).

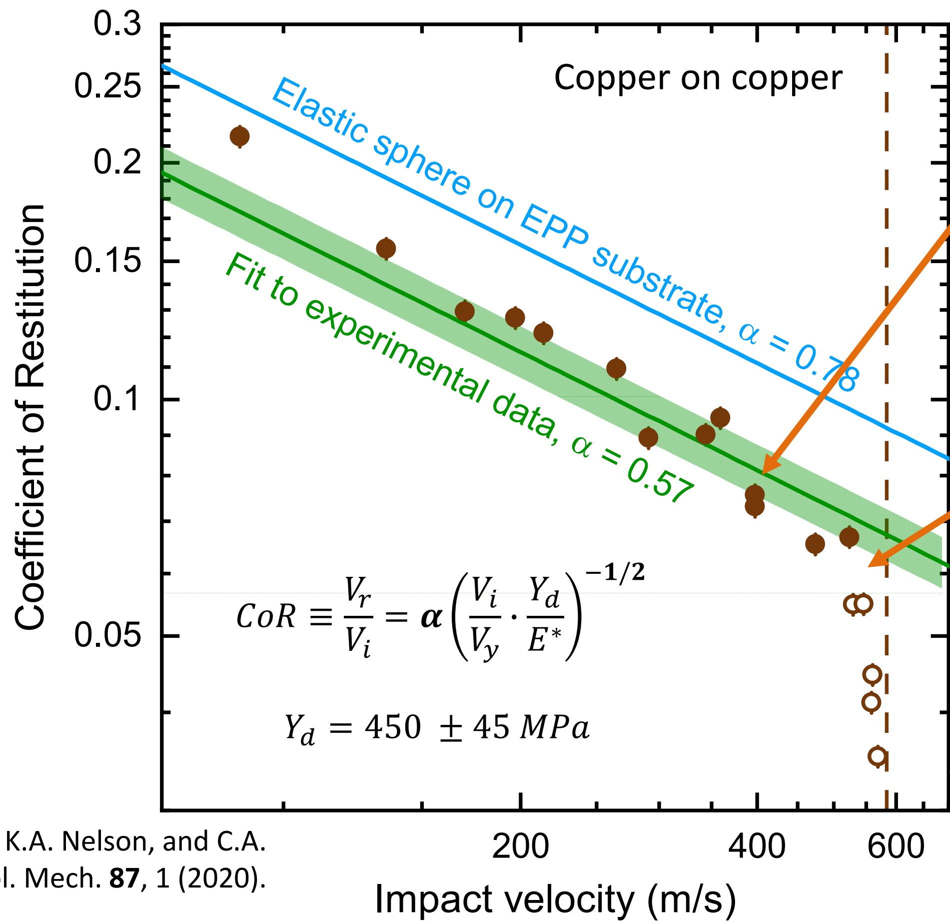
Jet formation is the new phenomenon associated with adhesion

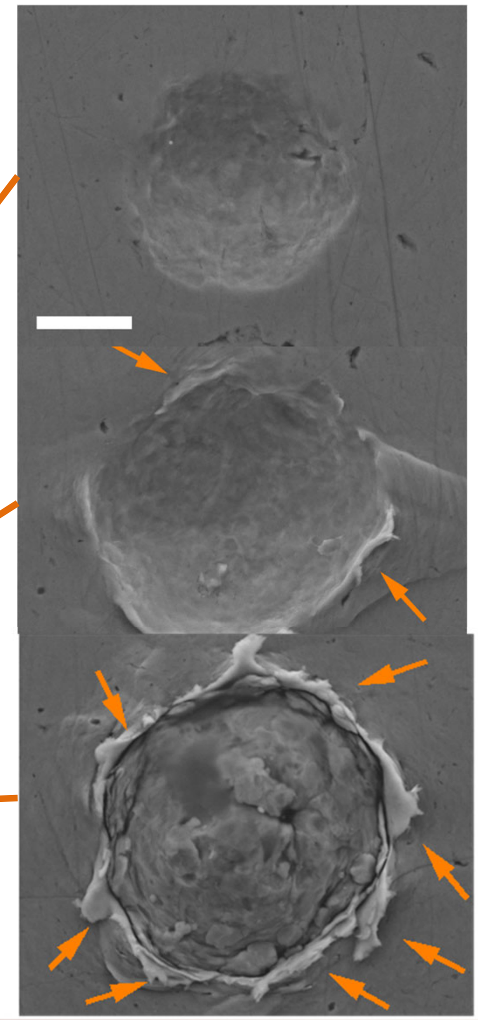


Sun et al., Applied Physics Letters <u>117</u>, 134105, 2020

Y. Sun, D. Veysset, K.A. Nelson, and C.A. Schuh, J. Appl. Mech. **87**, 1 (2020).

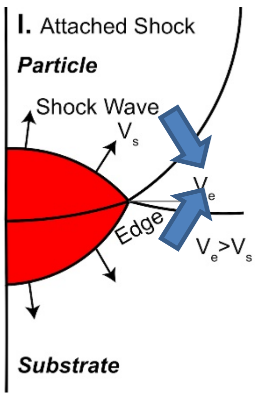
By the way: no evidence of melting here…



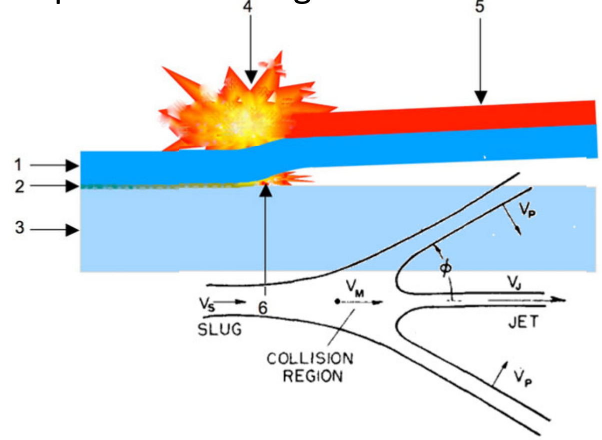


Y. Sun, D. Veysset, K.A. Nelson, and C.A. Schuh, J. Appl. Mech. **87**, 1 (2020).

Convergent shock on the microscale

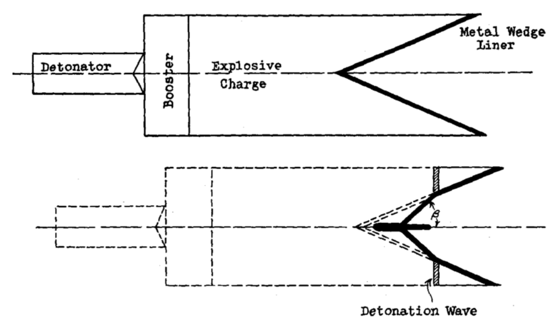


Explosion Welding



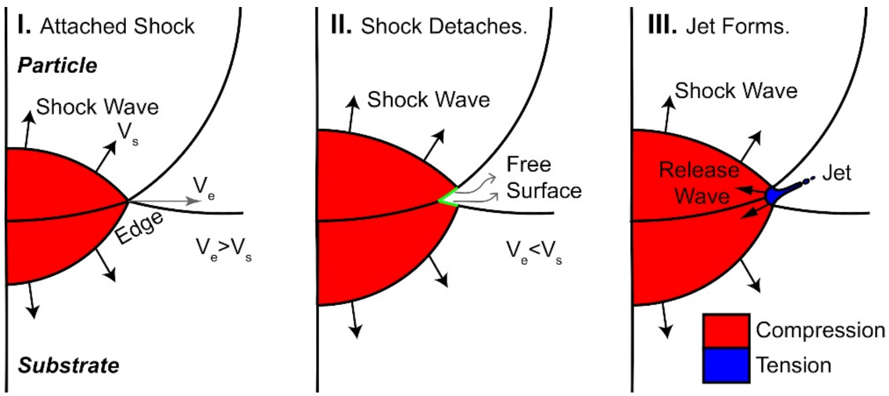
Walsh et al. J Applied Physics 1953;
Meyer "Dynamic Behavior of Materials" 1994.

Shaped Charges



Birkhoff et al. J Applied Physics 1948

How to test this theory?



$$P^{-} = dynamic\ strength$$

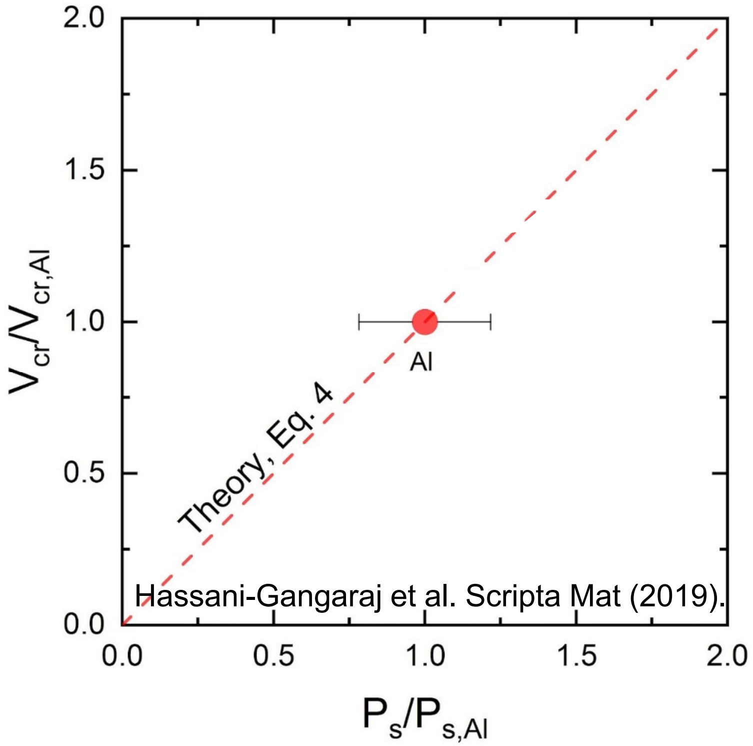
$$k \times \left\{ \frac{1}{2} \left(\rho C_0 V_{cr} + s \frac{\rho V_{cr}^2}{2} \right) \right\} = dynamic\ strength$$

$$\frac{V_{cr}}{C_0} = \left(\frac{\sqrt{1 + \frac{4 s P_s}{kB}} - 1}{s} \right)$$

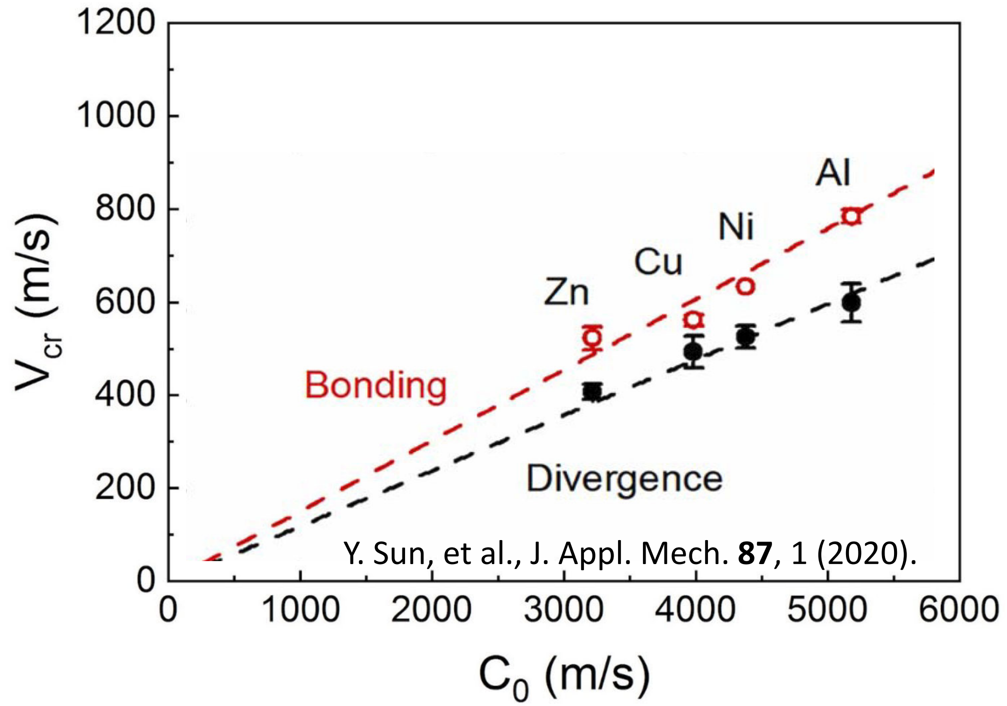
$$\frac{V_{cr}}{C_0} \approx \frac{2}{k} \times \frac{P_s}{B}$$

Validation of the hydrodynamic jet theory: $\frac{V_{cr}}{C_0} \approx \frac{2}{k} \times \frac{P_s}{B}$

1. Alloys isolate the **strength** dependence

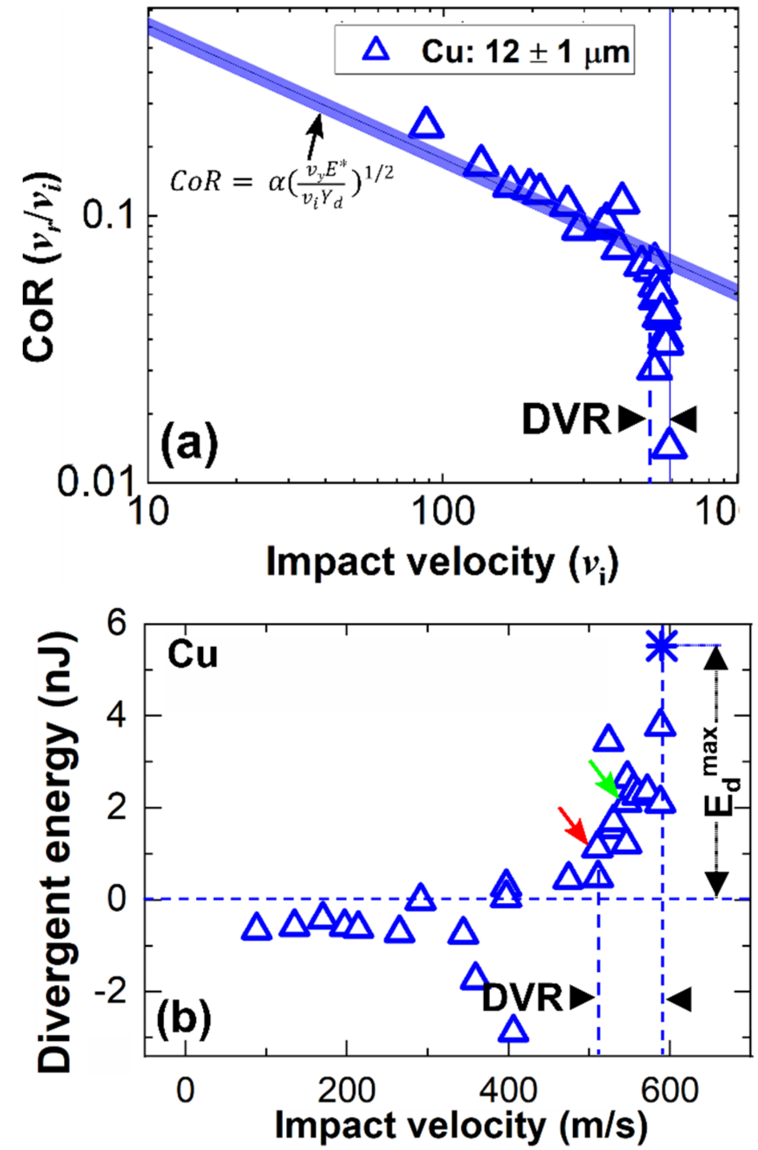


2. Pure metals isolate the **speed of sound** dependence



Where does the energy go?

- Oxide rupture?



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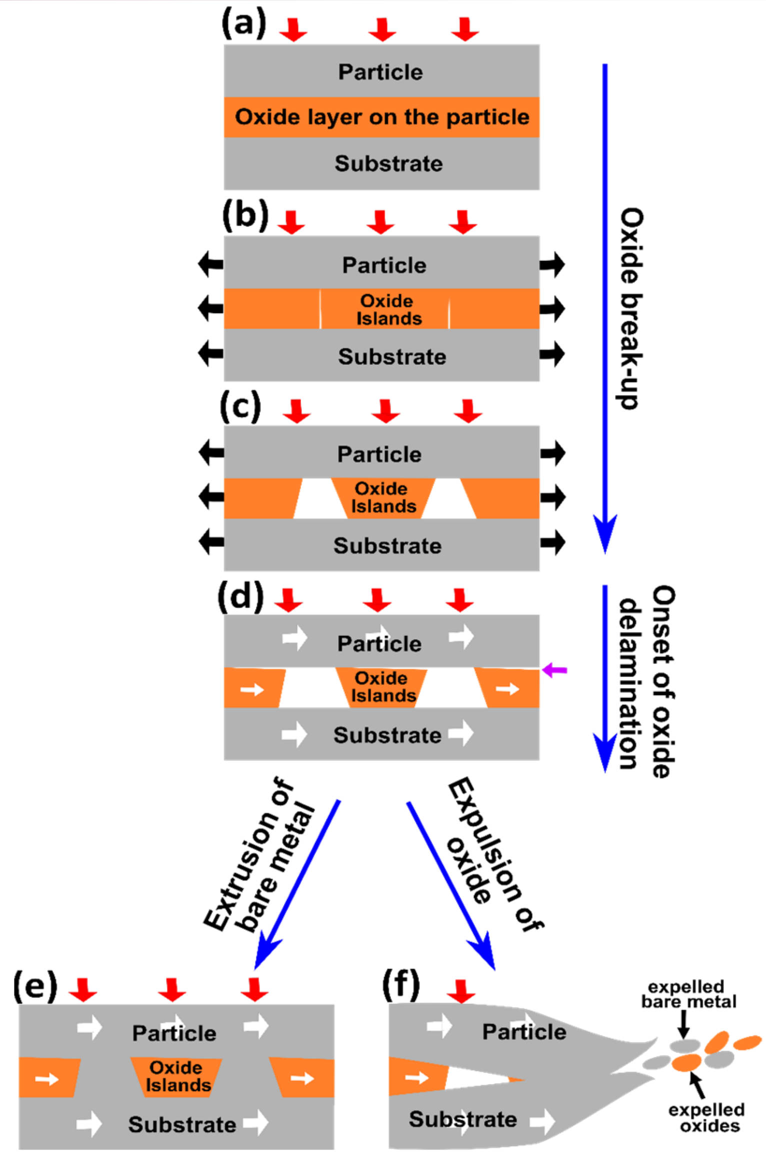
Where does the energy go?

- Oxide rupture?



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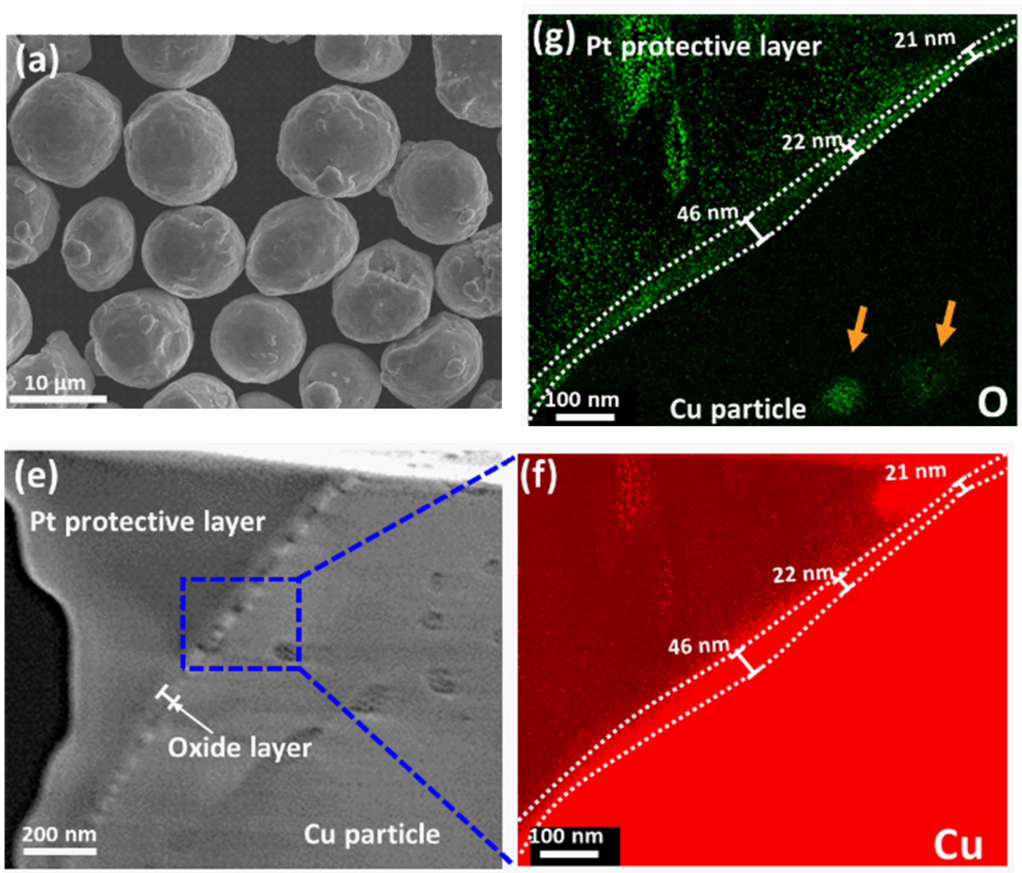
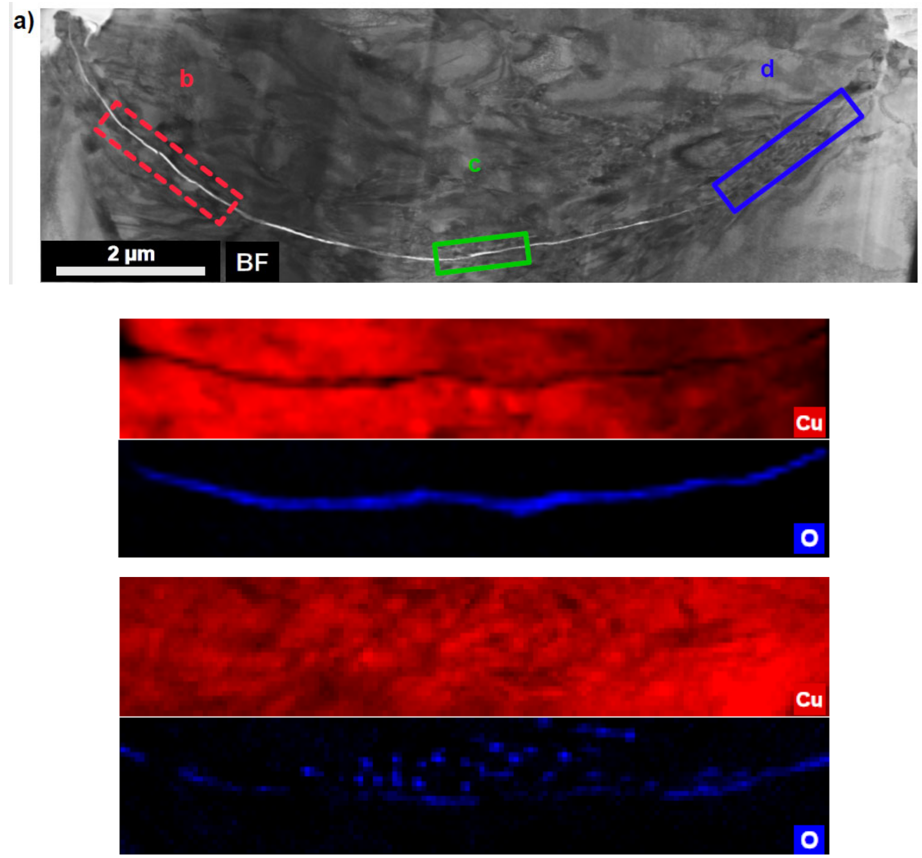
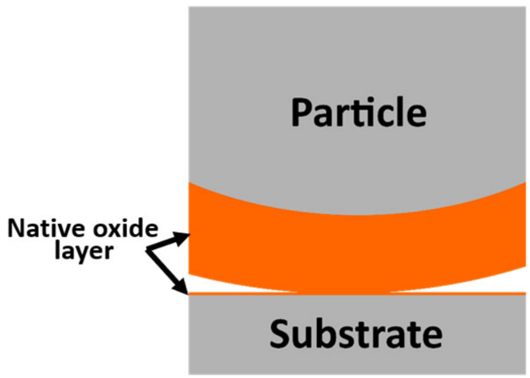
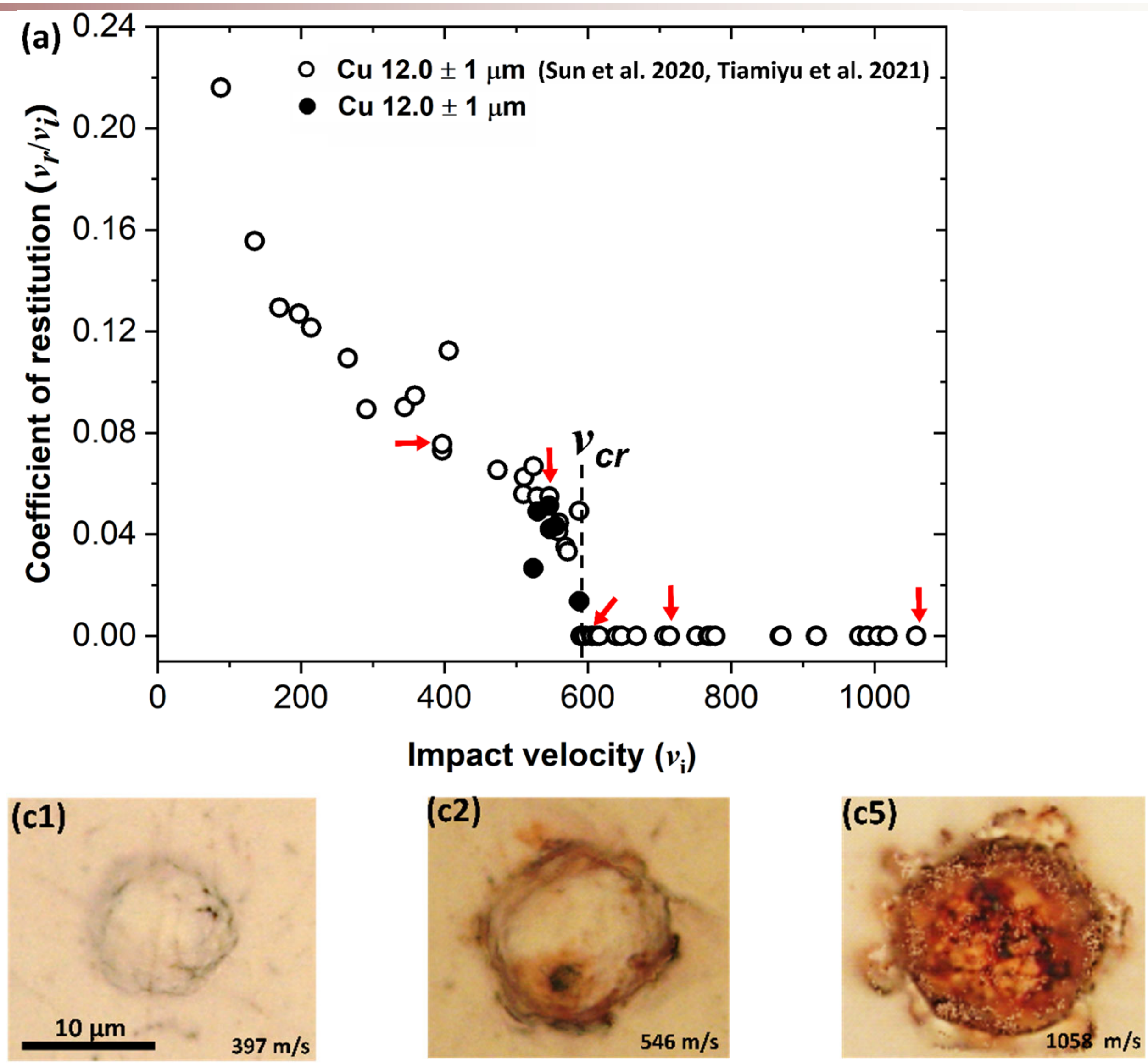
Breaking the oxide achieves metallic bonding

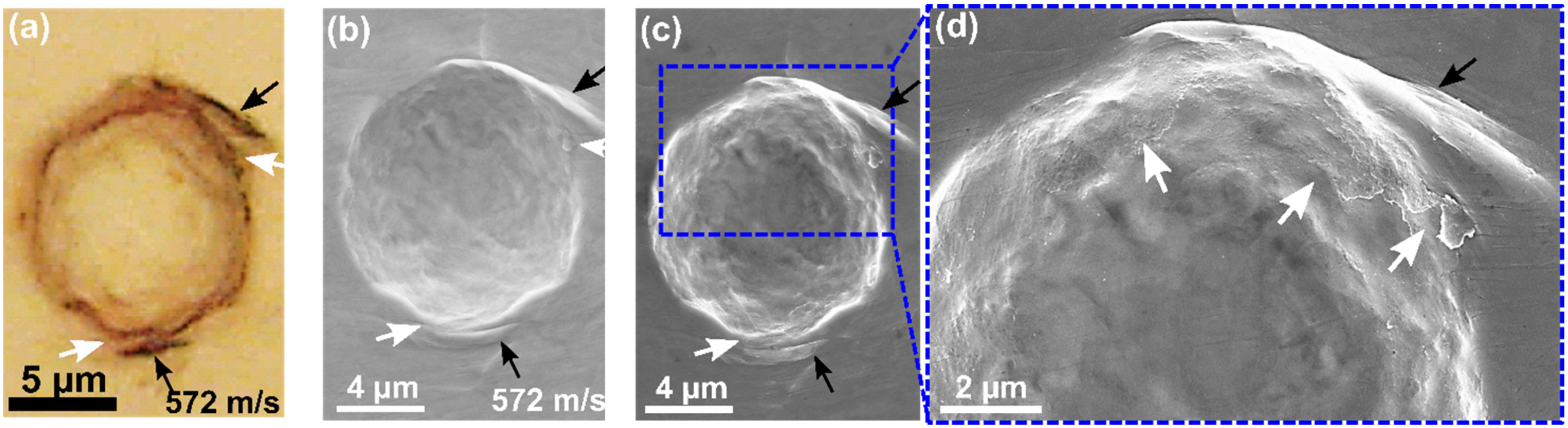




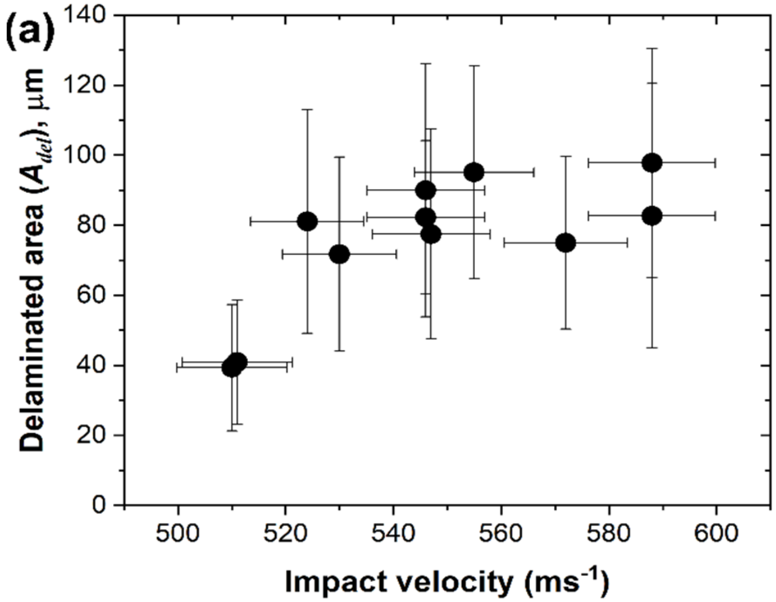

Particle
Native oxide layer
Substrate

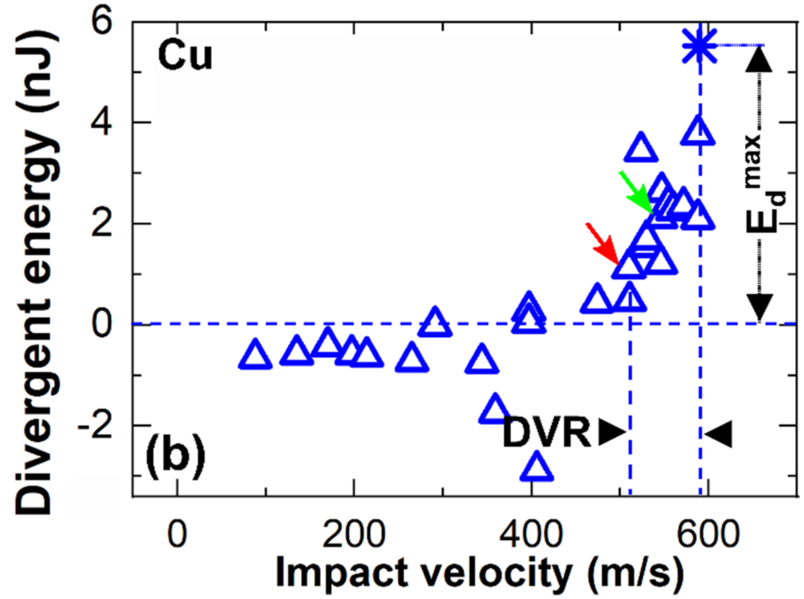

(a)
Cu 12.0 ± 1 μm (Sun et al. 2020, Tiamiyu et al. 2021)
Cu 12.0 ± 1 μm
Coefficient of restitution (v_r/v_i)
Impact velocity (v_i)
v_{cr}
0.24
0.20
0.16
0.12
0.08
0.04
0.00
0
200
400
600
800
1000
(c1)
10 μm
397 m/s
(c2)
546 m/s
(c5)
1058 m/s

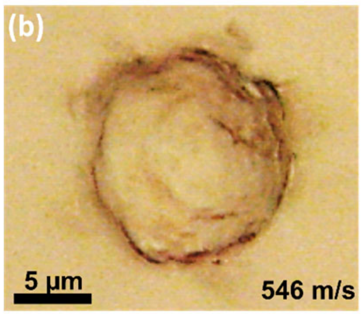
In-lens detector shows the oxide transfer

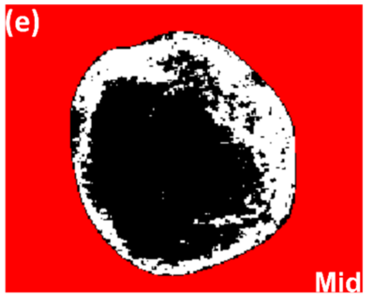


How much oxide delamination is there?









Where does the energy go?

- Oxide rupture?

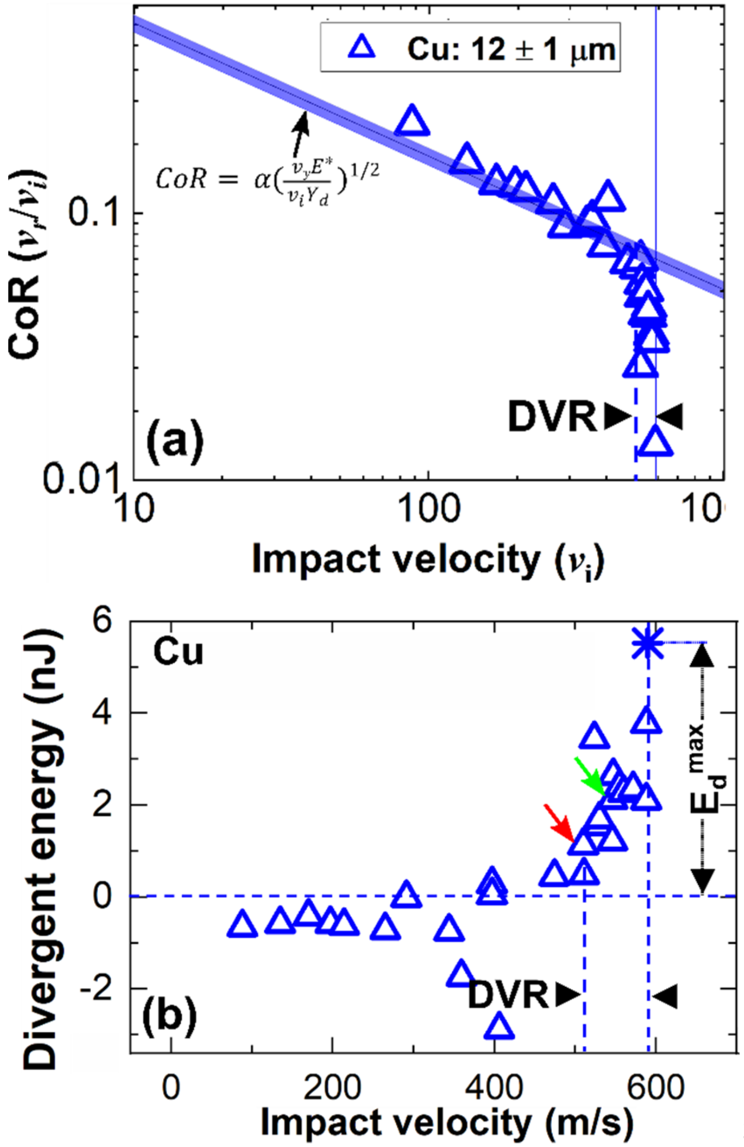
$$E_d^{(D)} \approx \frac{K_{IC}^2}{E} A$$ = about 1-2 nJ, or 1/3 of the total

- Jetting: lost mass and kinetic energy?

$$E_d^{(K)} = \frac{1}{2} m_j V_j^2$$ ~1 km/s

= ???????

(loss of 0.2% of the particle mass would explain it all…)



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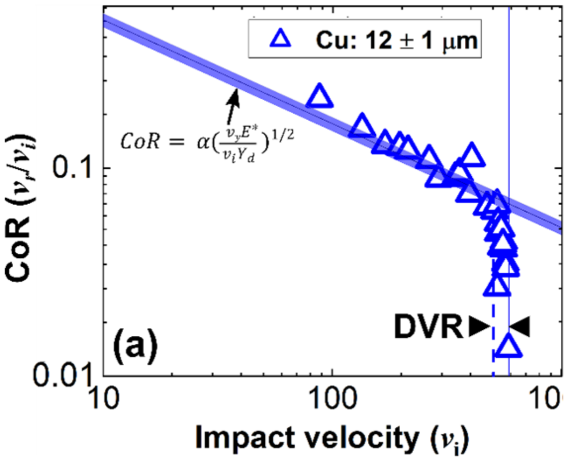
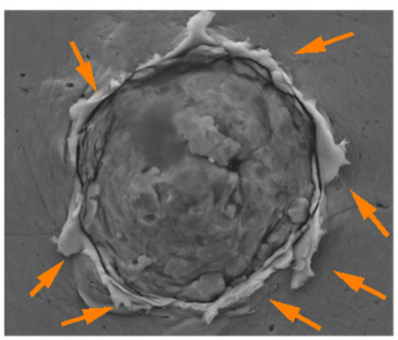
Can we measure a splash?

Copper: jetting

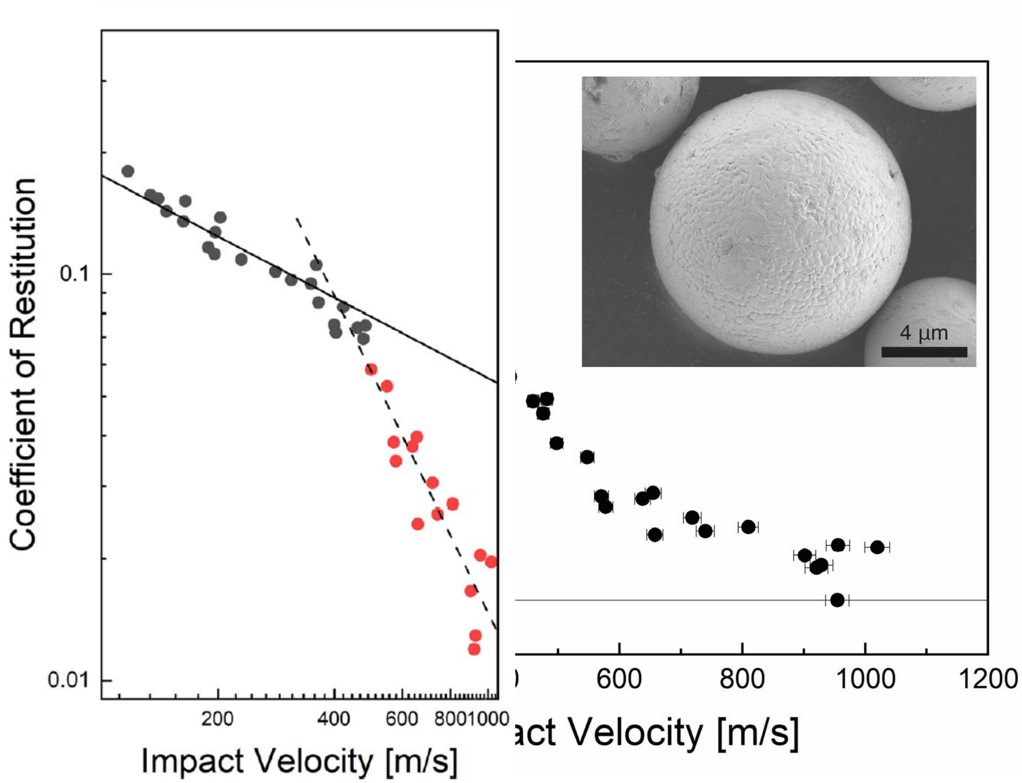
1: a very small phenomenon (~ μm^3)
2: mostly for stuck particles (conflation of volumes)

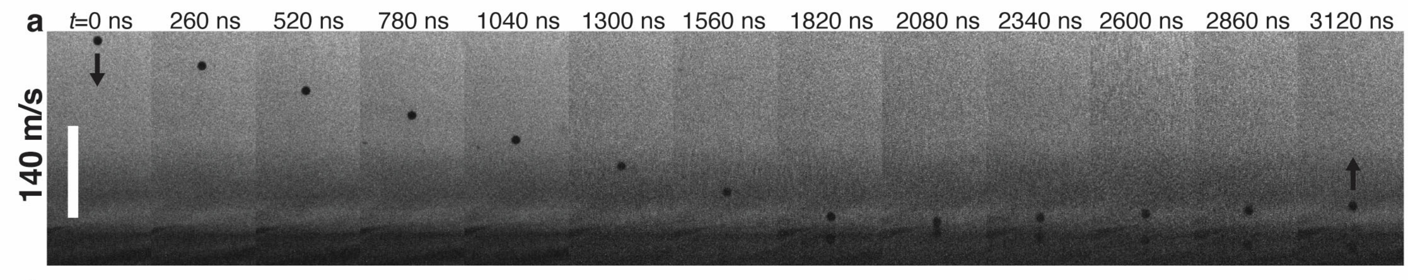
1: focus on a larger softening response
2: use particles that don't stick

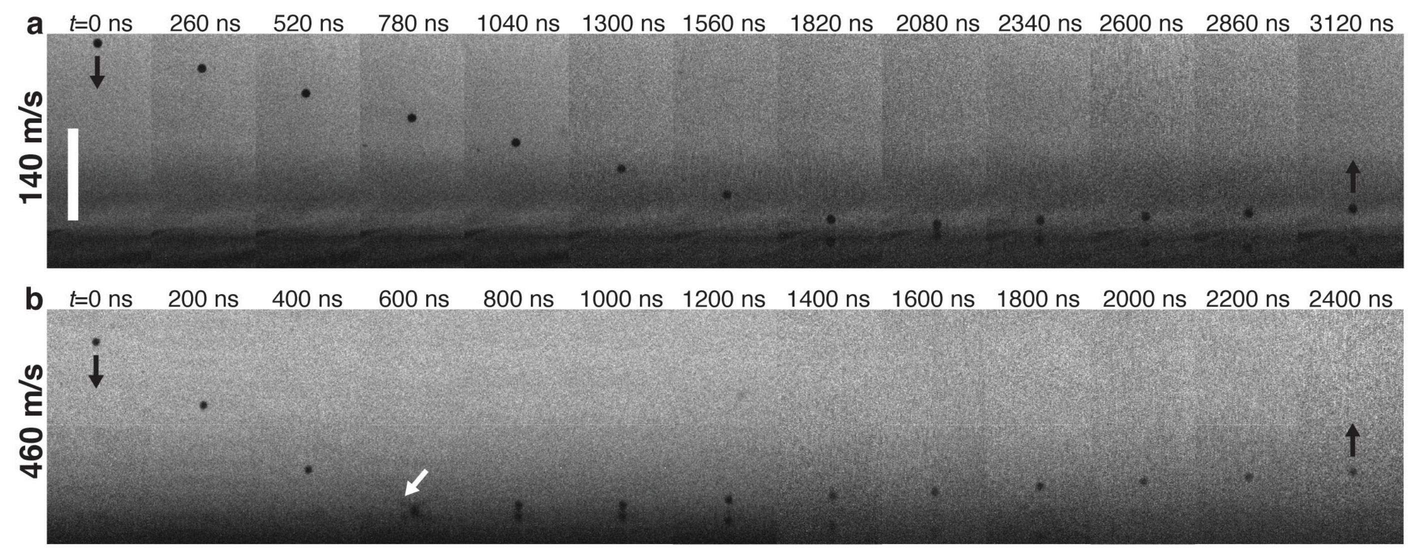


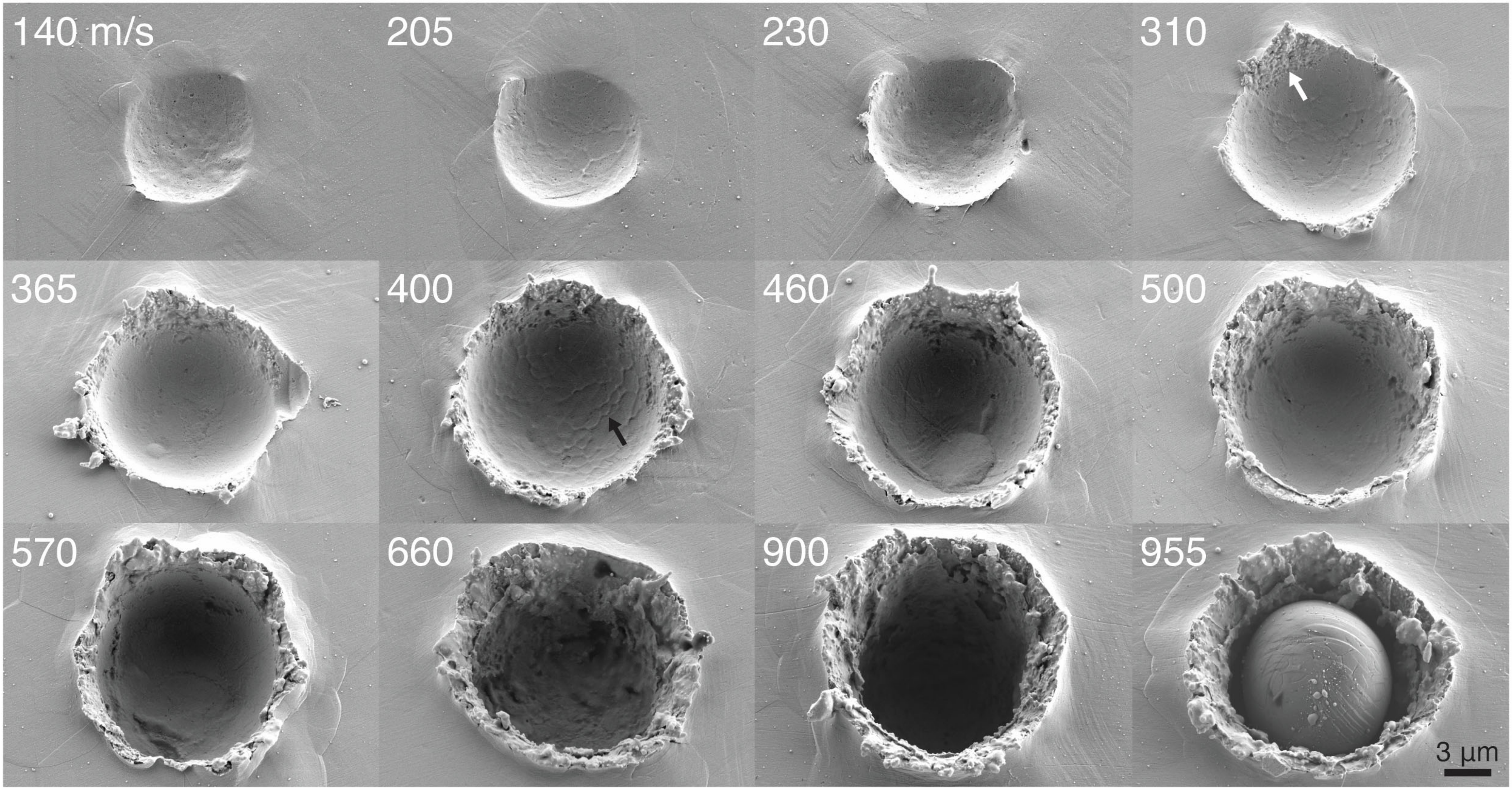


Stainless steel on tin: melting and rebound




a
t=0 ns
260 ns
520 ns
780 ns
1040 ns
1300 ns
1560 ns
1820 ns
2080 ns
2340 ns
2600 ns
2860 ns
3120 ns
140 m/s


a
t=0 ns
260 ns
520 ns
780 ns
1040 ns
1300 ns
1560 ns
1820 ns
2080 ns
2340 ns
2600 ns
2860 ns
3120 ns
140 m/s
b
t=0 ns
200 ns
400 ns
600 ns
800 ns
1000 ns
1200 ns
1400 ns
1600 ns
1800 ns
2000 ns
2200 ns
2400 ns
460 m/s



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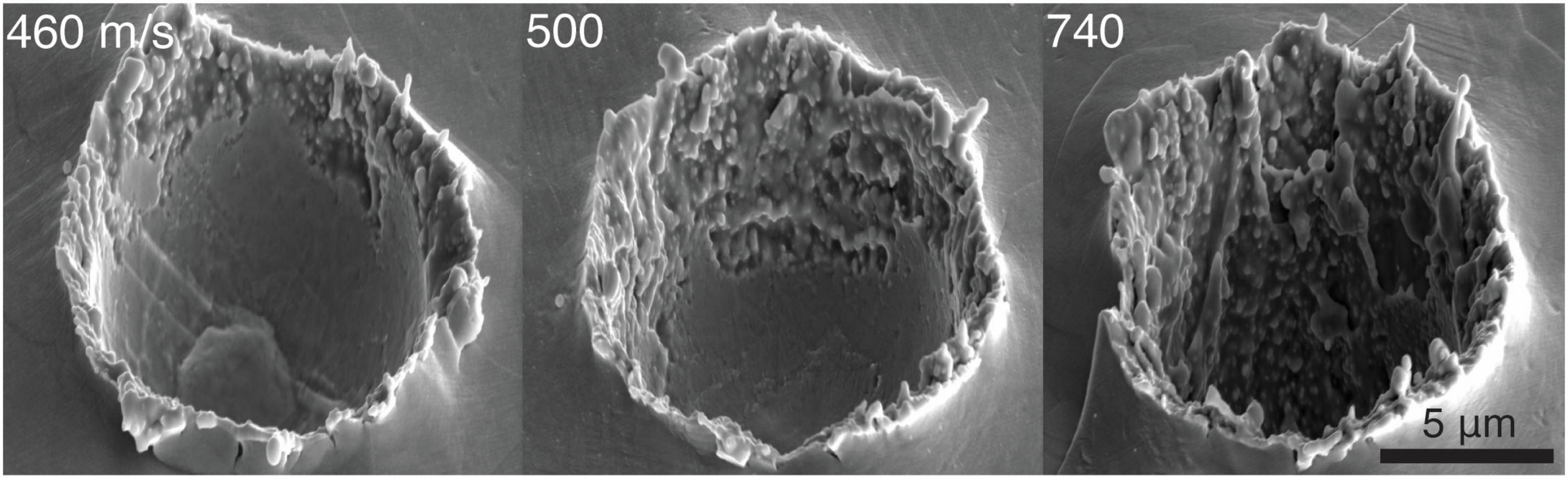
The splash is melting



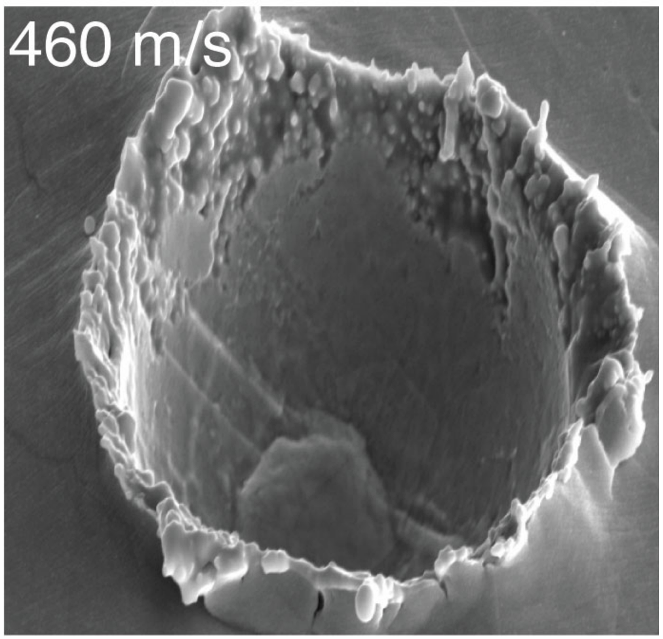
For shock-induced melting: P = 50 GPa needed

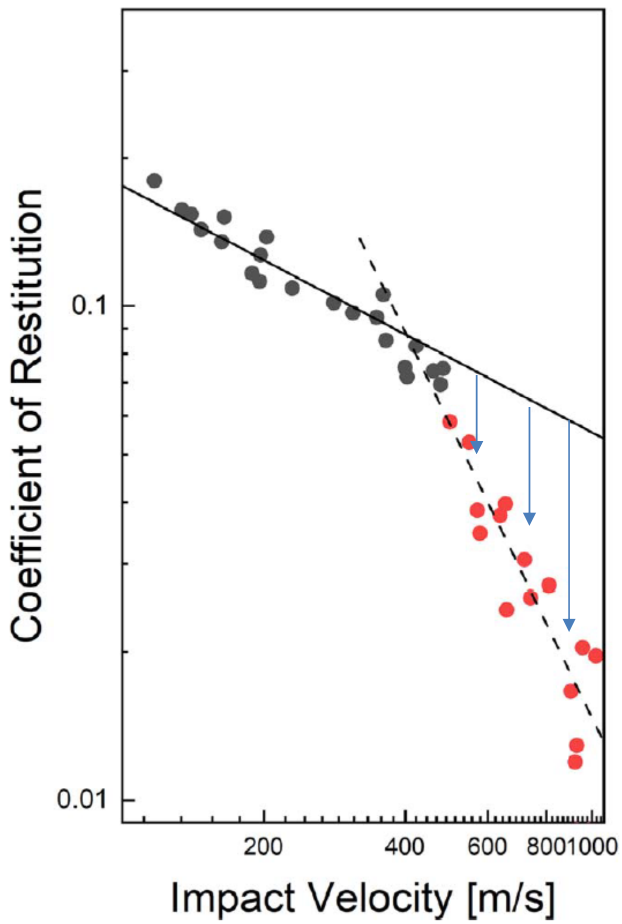
For pressure release melting: P = 25 GPa needed

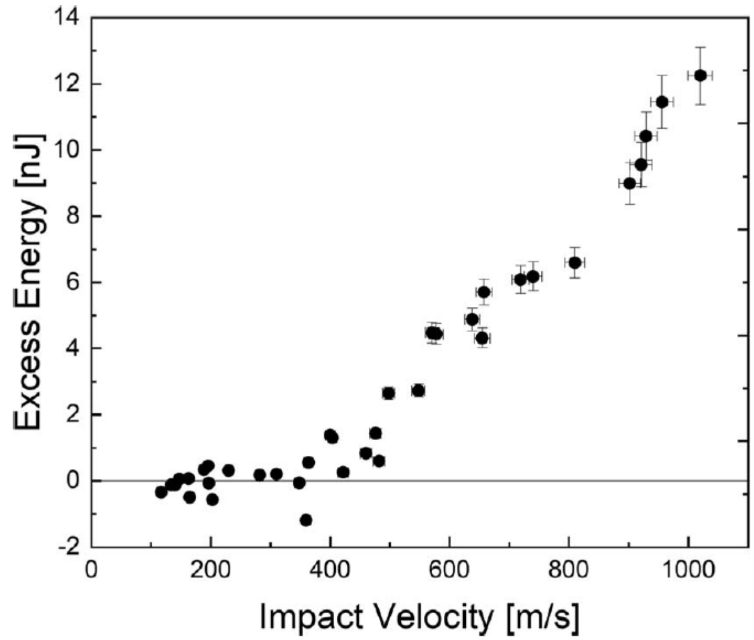
Our shock pressure: < 16 GPa

Adiabatic heat of plasticity causes melting!

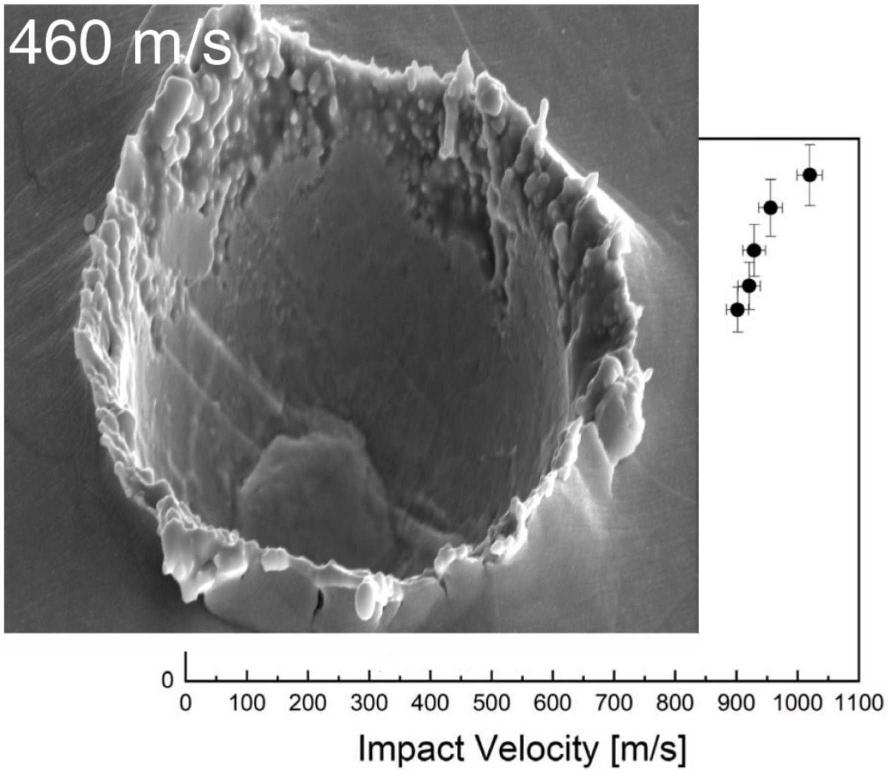
The splash is melting

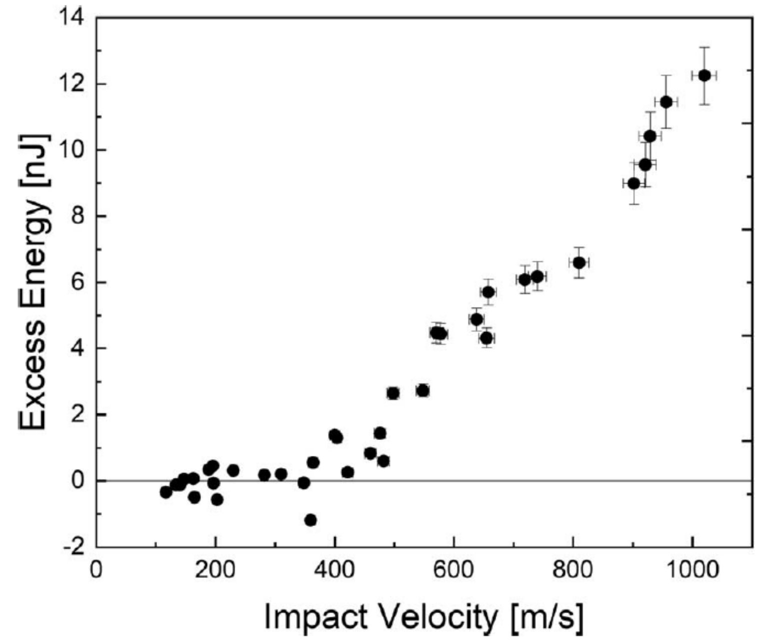






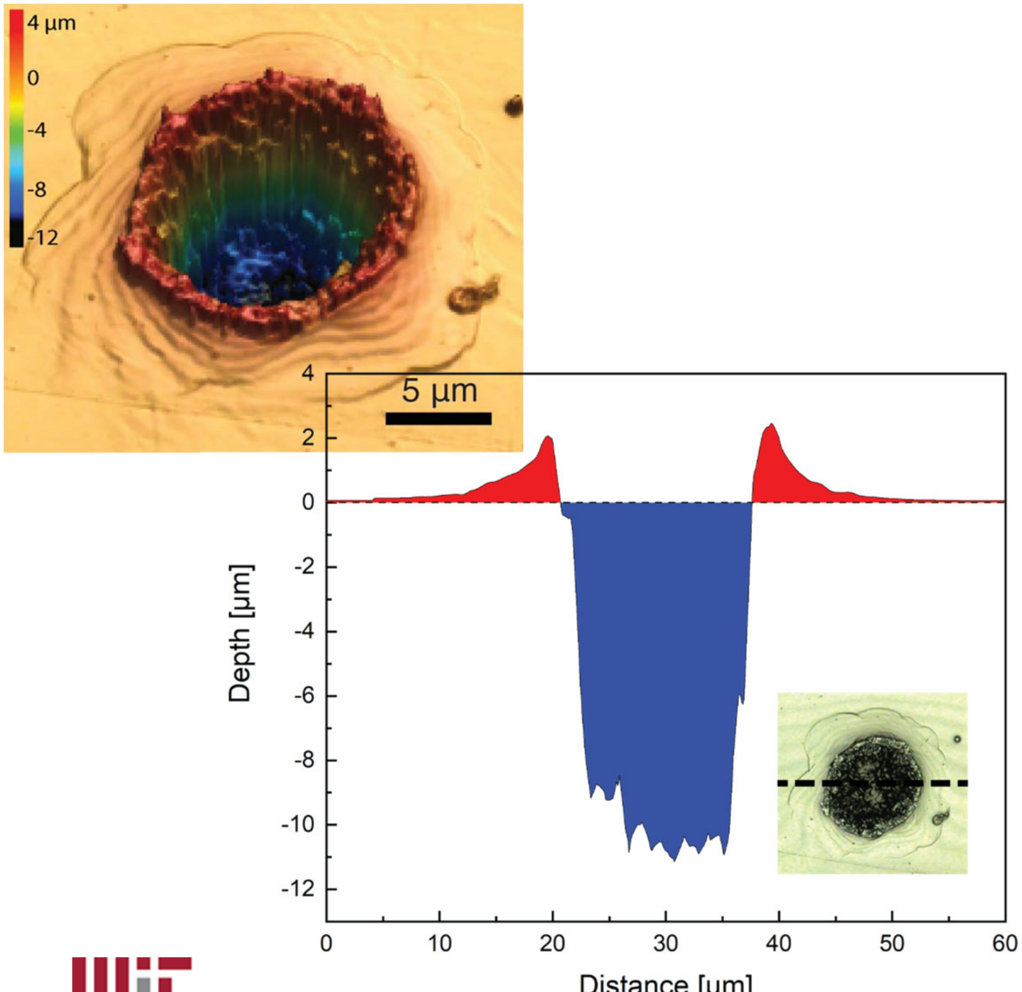
How much melted volume explains this lost energy?

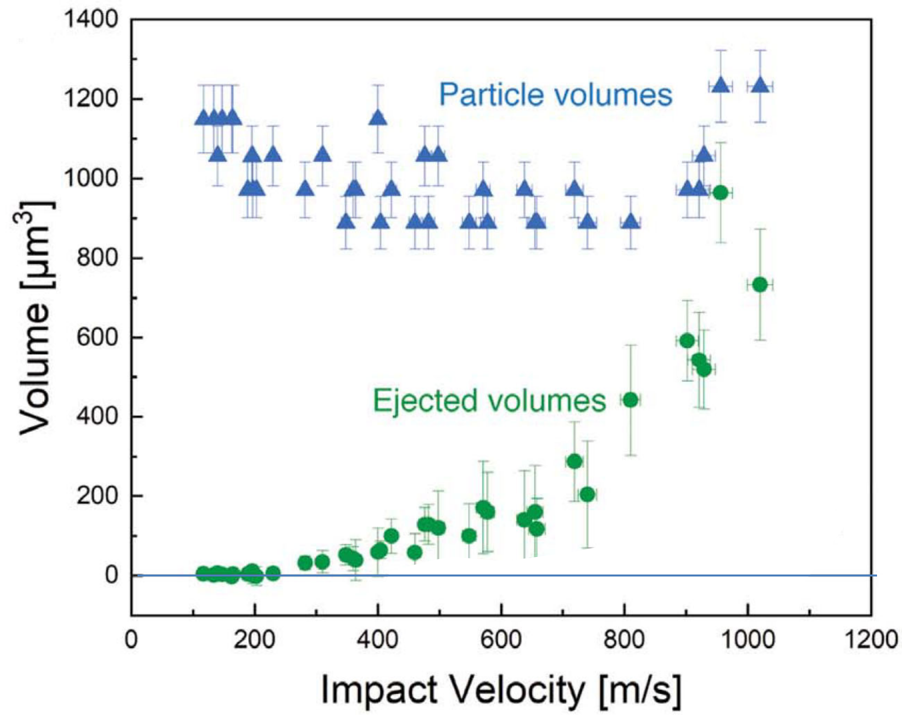




$$e_{melt} = \rho_{sub} V_{melt} H_f$$

An independent measurement: how big is the splash?





The splash is MOSTLY SOLID (!)

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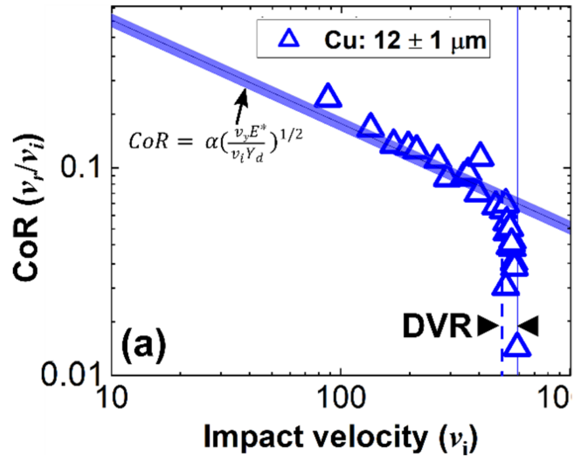
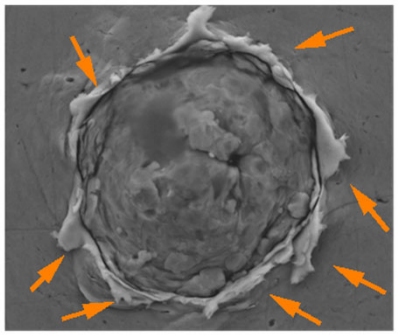
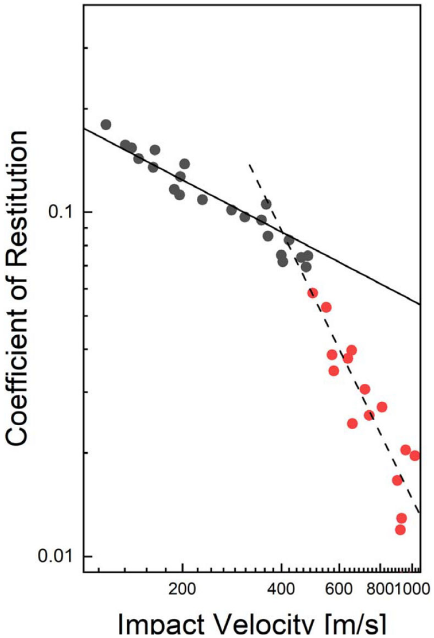
LIPIT measurements + microscopy: a powerful quantitative approach to understand softening and ejecta

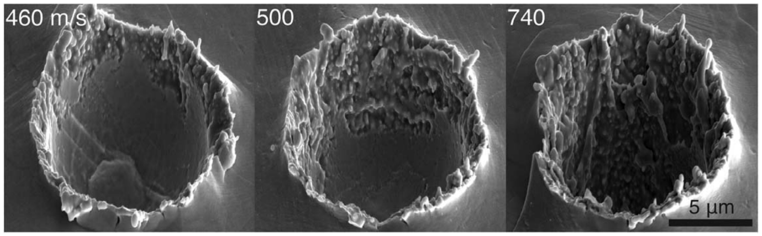
Copper: jetting





Steel on tin: melting





Quantitative Studies of Supersonic Microparticle Impacts on Metals

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Financial Support: DOE BES (work on hydrodynamic effects, extreme phenomena)
ARL Cold Spray Team (work on oxides in cold spray)
LLNL (work on impact melting)

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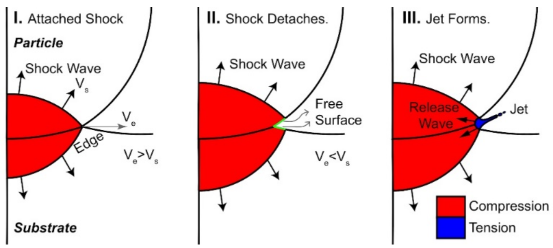
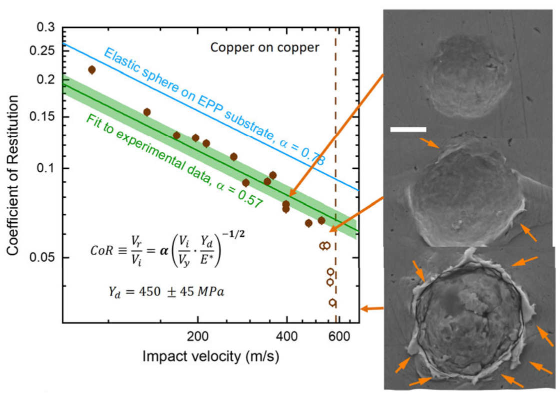
Thank You!





LIPIT is a quantitative tool for high rate mechanical studies of materials.

Impacts follow a power-law scaling governed by plasticity, until the onset of a rapid softening event that damps out excess energy.

The new event in matched metals is hydrodynamic jetting at the edge of the contact, which breaks oxide and leads to bond.

The new event for some systems (steel on tin) is melting, which we can quantify in terms of the lost substrate volume.

Combining LIPIT impacts with post-mortem microstructure studies is a frontier for understanding materials physics at high strain rates

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