Dislocation Mechanics of High Strain Rate Deformations and Hot Spots in Explosives; Bertram Hopkinson Centenary Conference,

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Bertram Hopkinson connections

1. Harry-Kolsky-sponsored application to cleavage of [0001]-axis zinc crystals by reflected compression waves.

Oliver, L.R., Armstrong, R.W., Clifton, R.J. & Kolsky, H. 1967 Cleavage of zinc single crystals induced by stress waves. *Nature* **216**, 910.

2. Zerilli-Armstrong constitutive equation development relating to rapid increase of split Hopkinson pressure bar (SHPB) flow stress at limiting high loading rate.

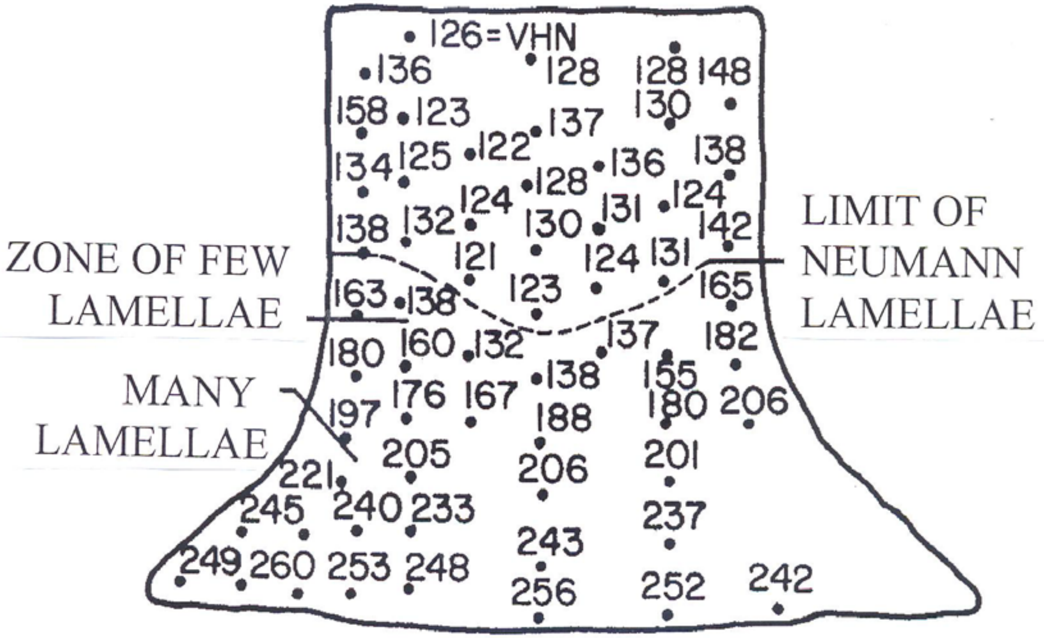
Armstrong, R.W., & Zerilli, F.J. 1988 Dislocation mechanics based analysis of material dynamics behavior. *J. Phys. Fr. Colloq*. **49**, 529-534.

3. Dislocation pile-up avalanche model of hot spot development for drop-weight testing of explosive crystals

Armstrong, R.W., Coffey, C.S. & Elban, W.L. 1982 Adiabatic heating at a dislocation pile-up avalanche. *Acta Metall*. **30**, 2111-2118.

Taylor solid cylinder impact tests
(after Hopkinson 1914 mushroomed lead bullet)

"Dynamic yield stress": $\sigma = (\rho_C u_C^2/2)(L - X)/[(L - L_1)\,\mathbf{ln}(L/X)]$



MILD STEEL CYLINDER. IMPACT VELOCITY
338 m/s

G.I. Taylor, *Proc. Roy. Soc. London A*, **194A**, 289-299 (1948); A.C. Wiffin, *Ibid*. 300-322; W.E. Carrington and M.L.V. Gaylor, *Ibid*., 323-331

Constitutive Relations

(1) Johnson - Cook: $\sigma = (A + B\varepsilon^n)(1 + C\mathbf{ln}[d\varepsilon/dt])(1 - T^{*m})$

$$T^* = (T - T_A)/(T - T_M)$$

(2) Z - A: $[d\gamma/dt] = [d\gamma/dt]_0\mathbf{exp}\{(-G_0 + \int v^* d\tau_{Th})/kT\}$

$$v^* = kT[\partial\mathbf{ln}[d\gamma/dt]/\partial\tau_{Th}]_T = W_0/\tau_{Th}$$

(2.1) bcc case: $\sigma_\varepsilon = m\tau_\varepsilon = \sigma_{0G} + B_0\mathbf{exp}\{-\beta T\} + K\varepsilon^n + k_\varepsilon \ell^{-1/2}$

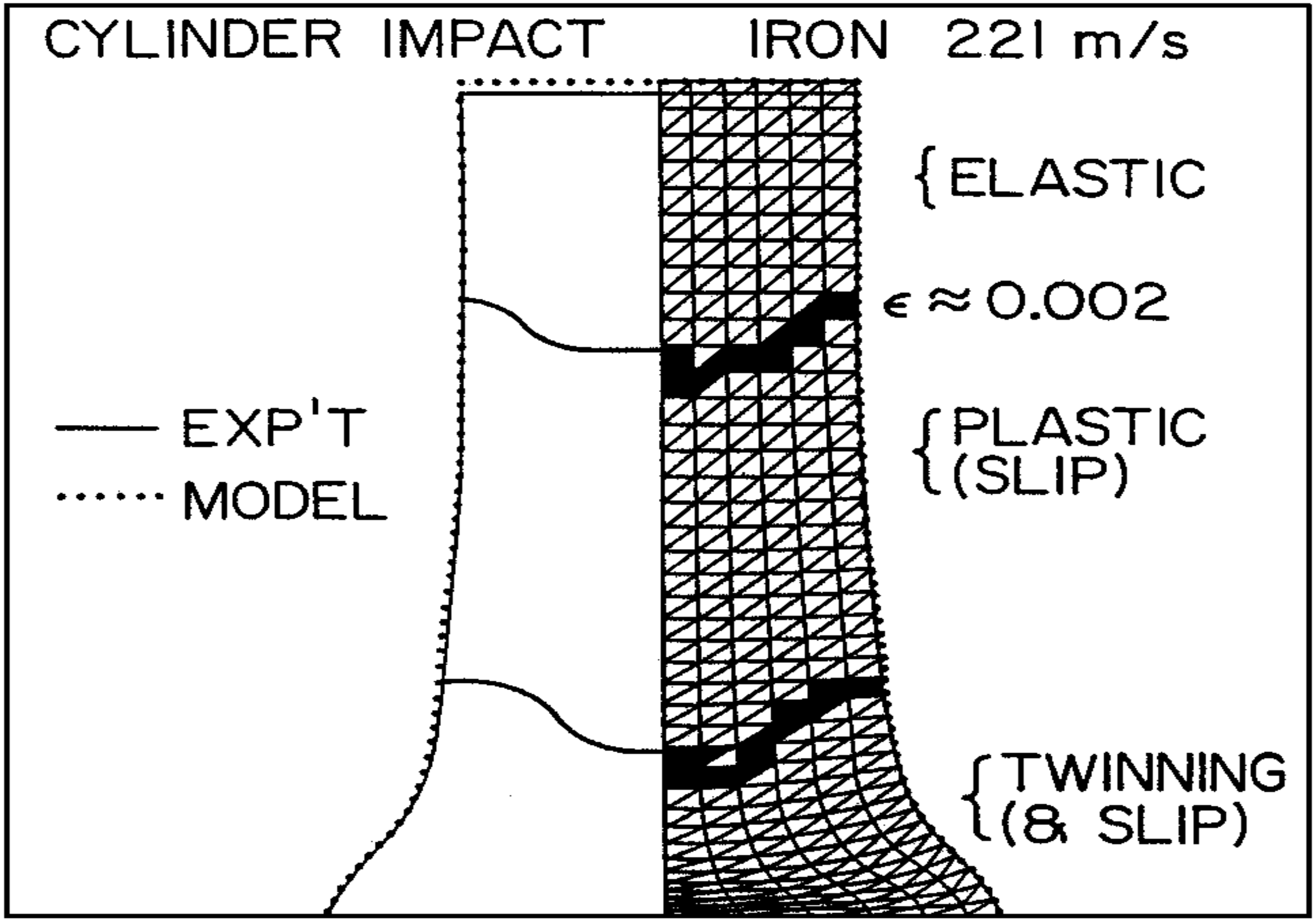
(2.2) fcc: $\sigma_\varepsilon = m\tau_\varepsilon = \sigma_{0G} + B_1[\varepsilon_r\{1 - \varepsilon/\varepsilon_r\}]^{1/2}\mathbf{exp}\{-\beta T\} + k_\varepsilon \ell^{-1/2}$

$$\beta = \beta_0 - \beta_1\mathbf{ln}[d\varepsilon/dt]$$

(3) (Hall-Petch) Twinning: $\sigma_T = \sigma_{0T} + k_T \ell^{-1/2}$; $k_T > k_\varepsilon$

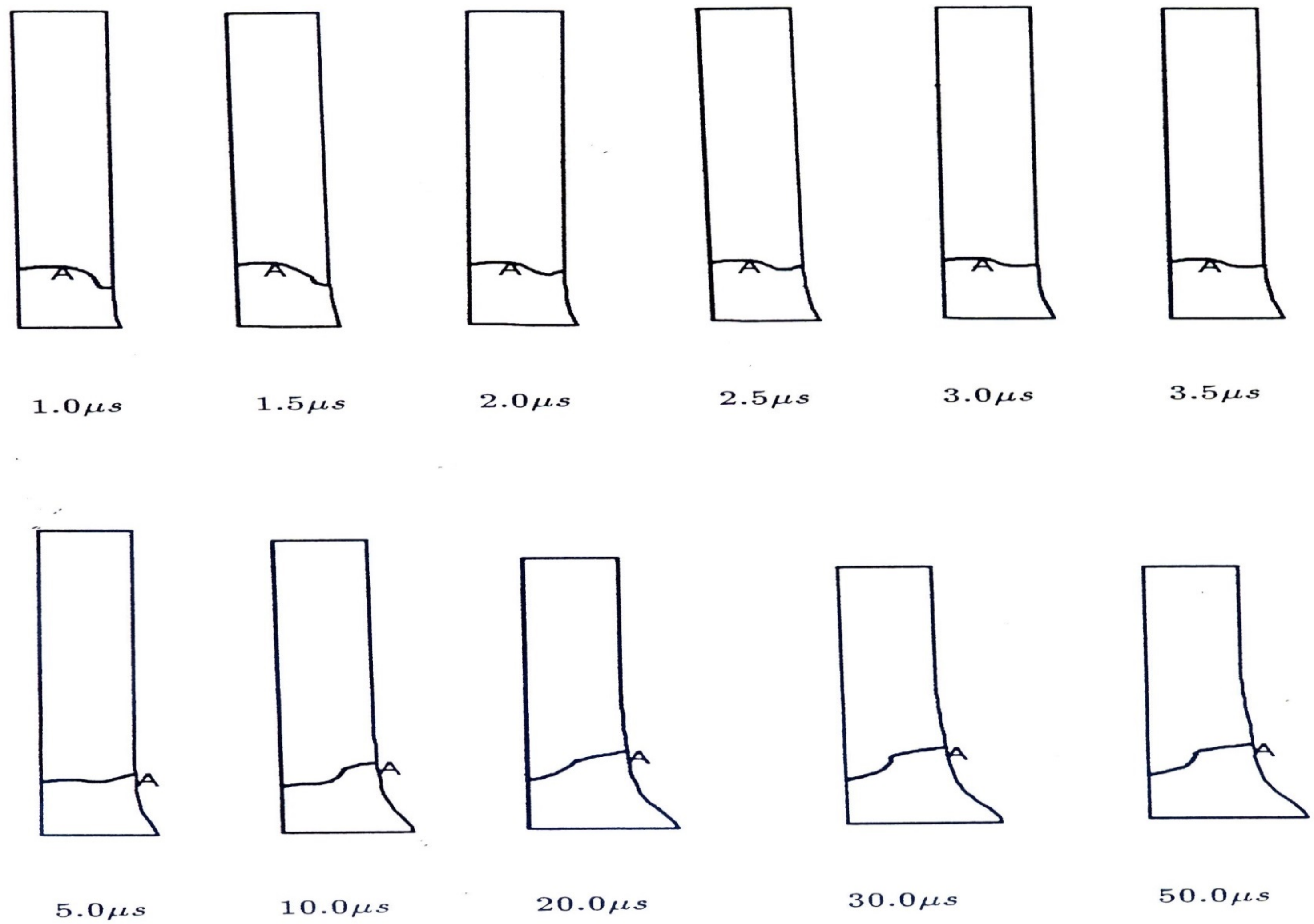
F.J. Zerilli and R.W. Armstrong, Dislocation-mechanics-based constitutive relations for material dynamics calculations, *J. Appl. Phys*. **61**, 1816-1824 (1987)

J-C/Z-A Taylor test of Armco iron



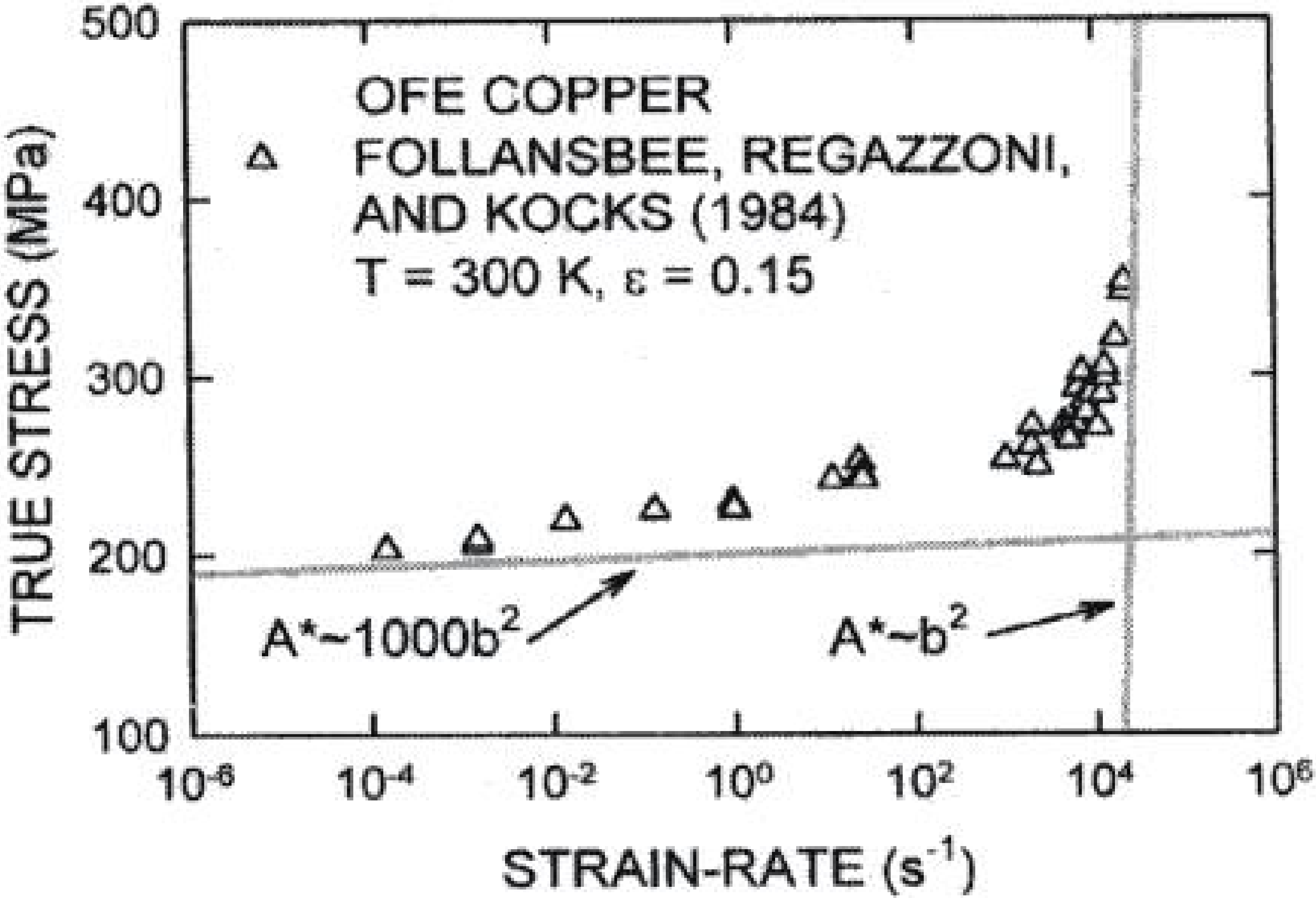
F.J. Zerilli and R.W. Armstrong, *Shock Compression of Condensed Matter* (SCCM) , edited by S.C. Schmidt and N.C. Holmes (Elsevier Sci. Publ. B.V., N.Y., 1988) pp. 273-277

Slip preceded by twinning in Taylor impact
(corresponding to Hopkinson time estimation)



J.B. McKirgan, *Microstructurally-based EPIC simulation of Taylor impact tests*, M.Sc. Thesis, University of Maryland, College Park, 1990.

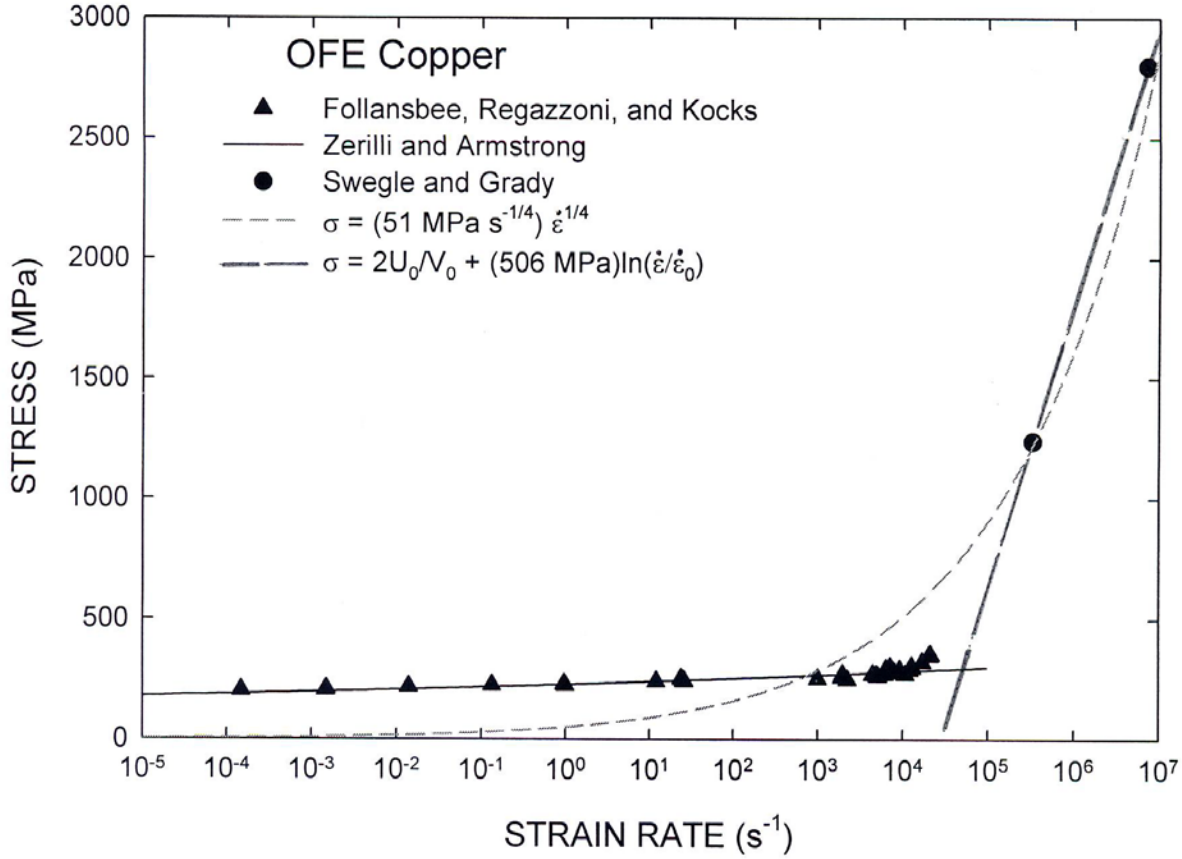
Upturn in SHPB strain rate dependence of the copper flow stress



P.S. Follansbee, G. Regazzoni, and U.F. Kocks, *Inst. Phys. Conf. Ser.*, **70**, 71-80 (1984);
R.W. Armstrong, W. Arnold, F.J. Zerilli, *Metall. Mater. Trans. A*, **38A**, 2605-2610 (2007).

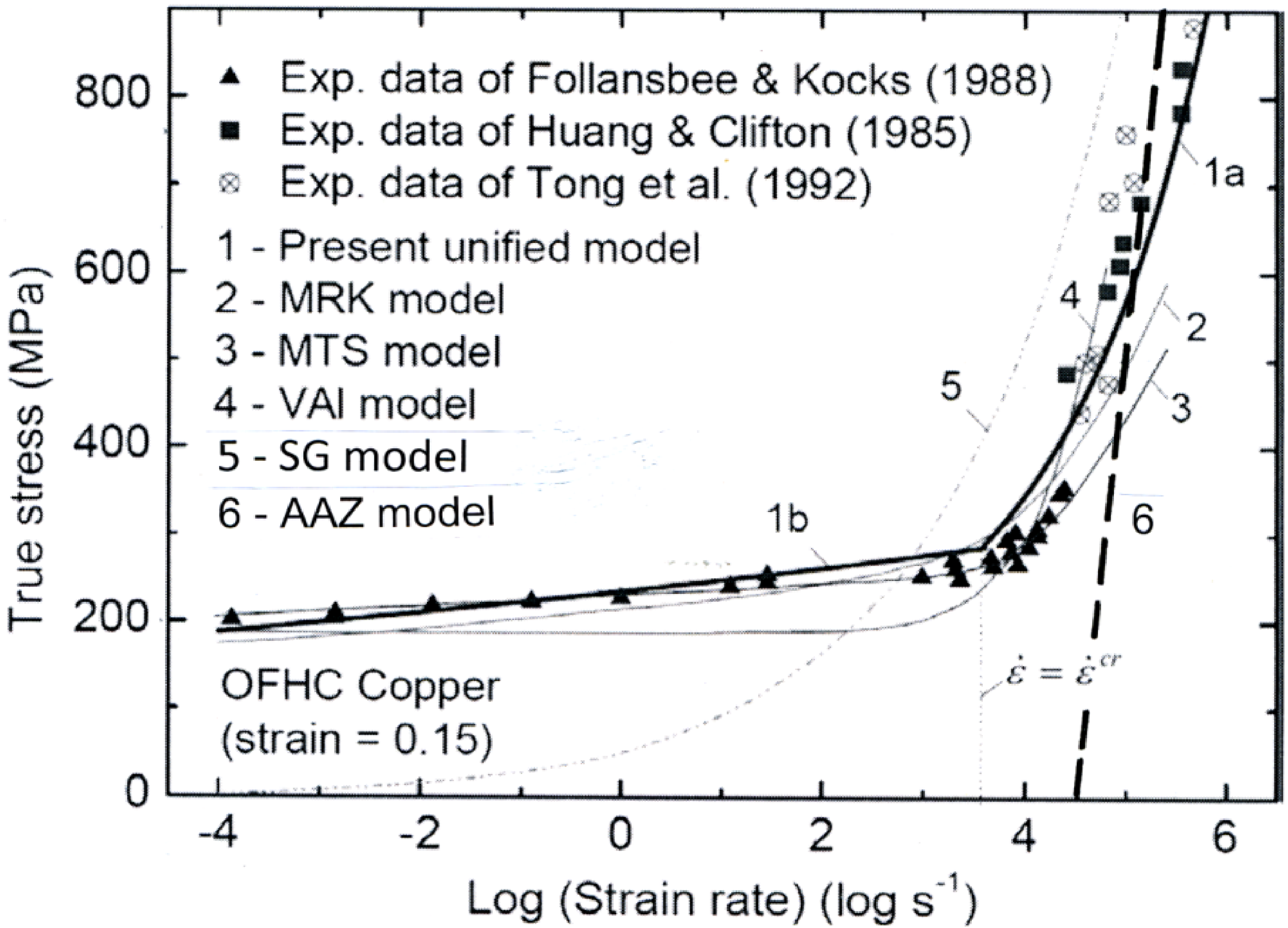
SHPB/Shock connection for copper

$\sigma = (2U_0/v_0) + (2kT/v_0)\ln [(d\varepsilon/dt)/ [(d\varepsilon/dt)_0]$



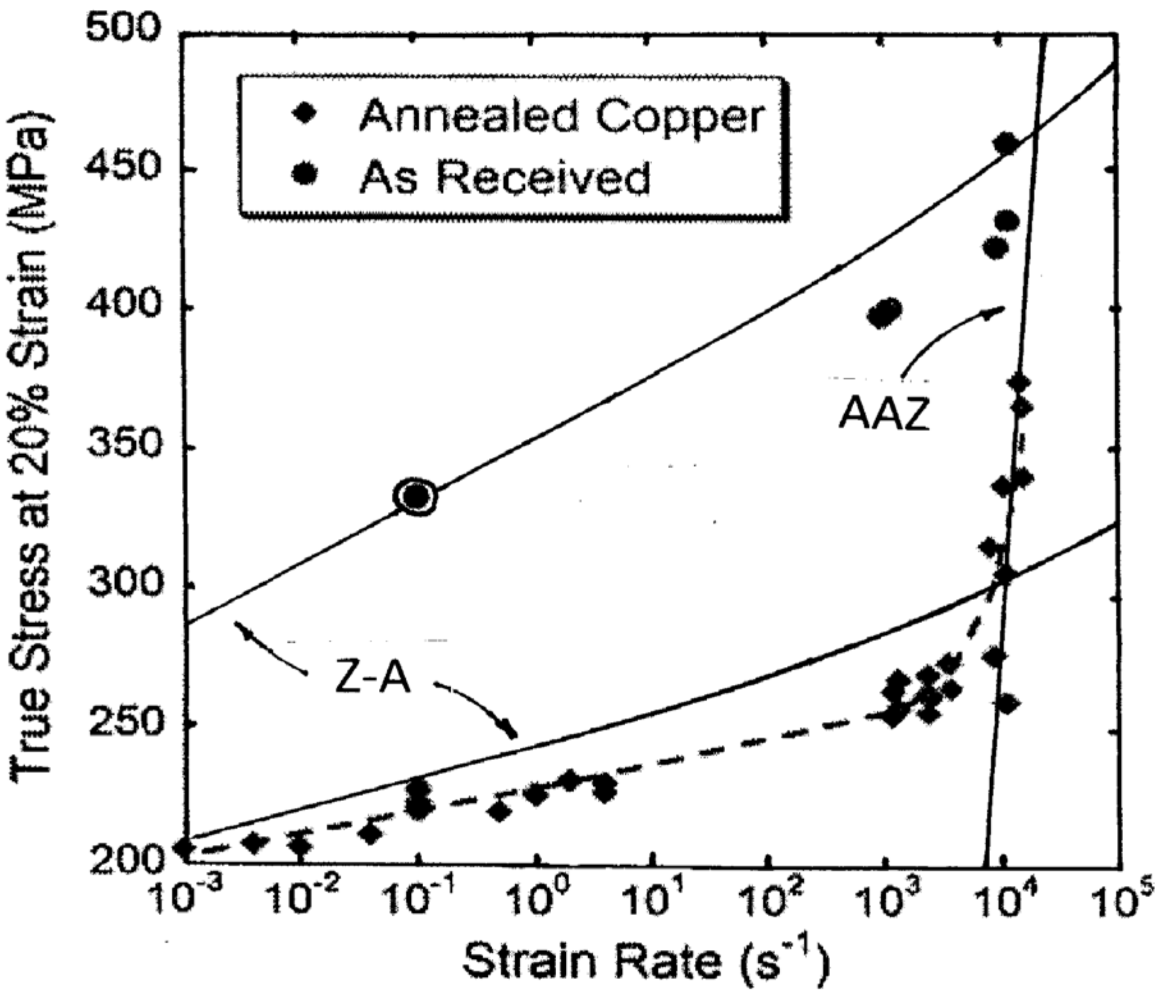
P.S. Follansbee, G. Regazzoni and U.F. Kocks, *Inst. Phys. Conf. Ser.*, **70**, 71-80 (1984); J. W. Swegle and D.E. Grady, *J. Appl. Phys.*, **58**, 692-701 (1985).

Cu measurements and model compilations



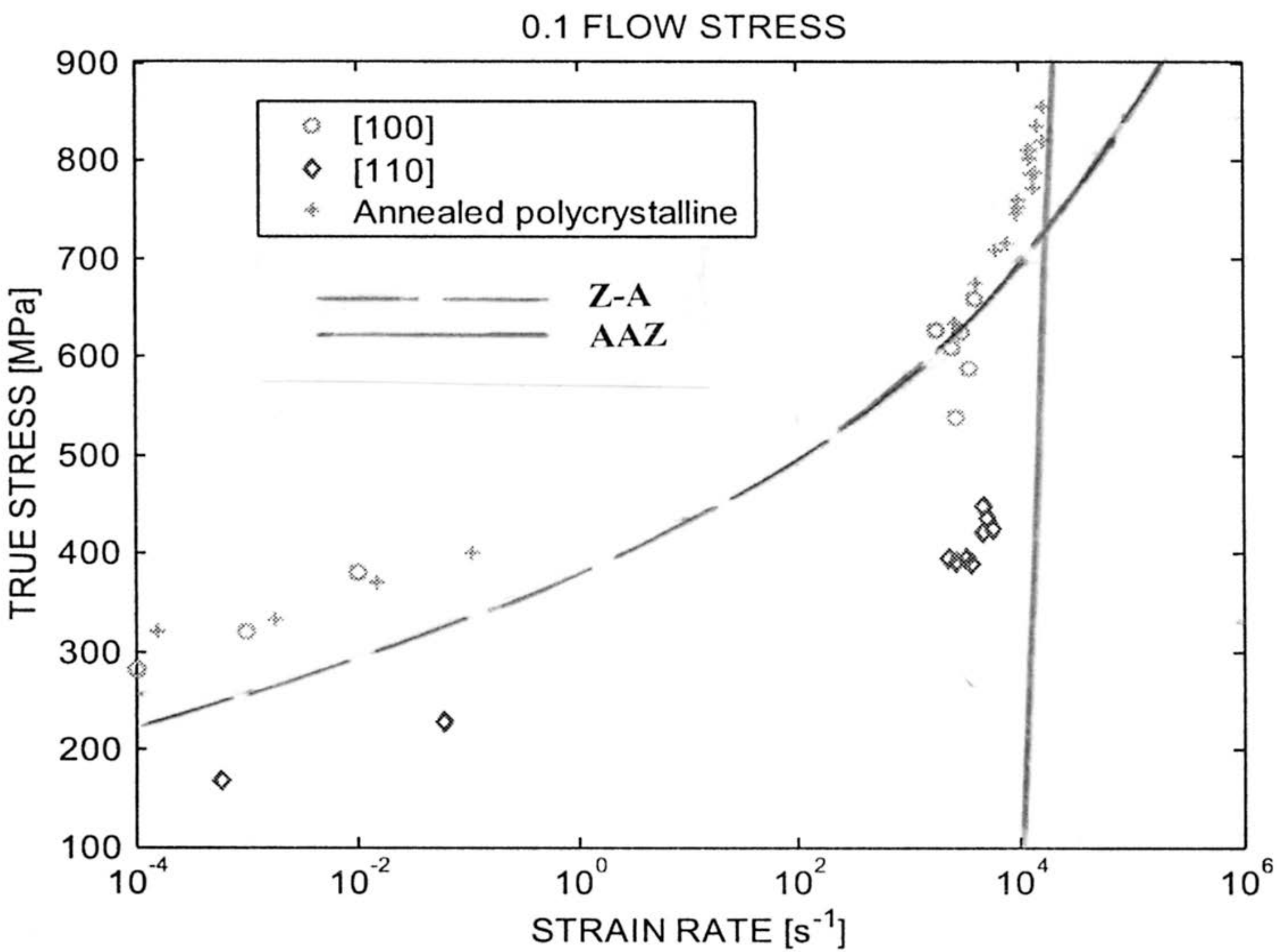
Modification of Gao, C.Y. & Zhang, L.C. 2012 Constitutive modelling of plasticity of fcc metals under extremely high strain rates. *Int. J. Plast*. **32-33**, 121-133

Z-A, SHPB and AAZ comparison for copper



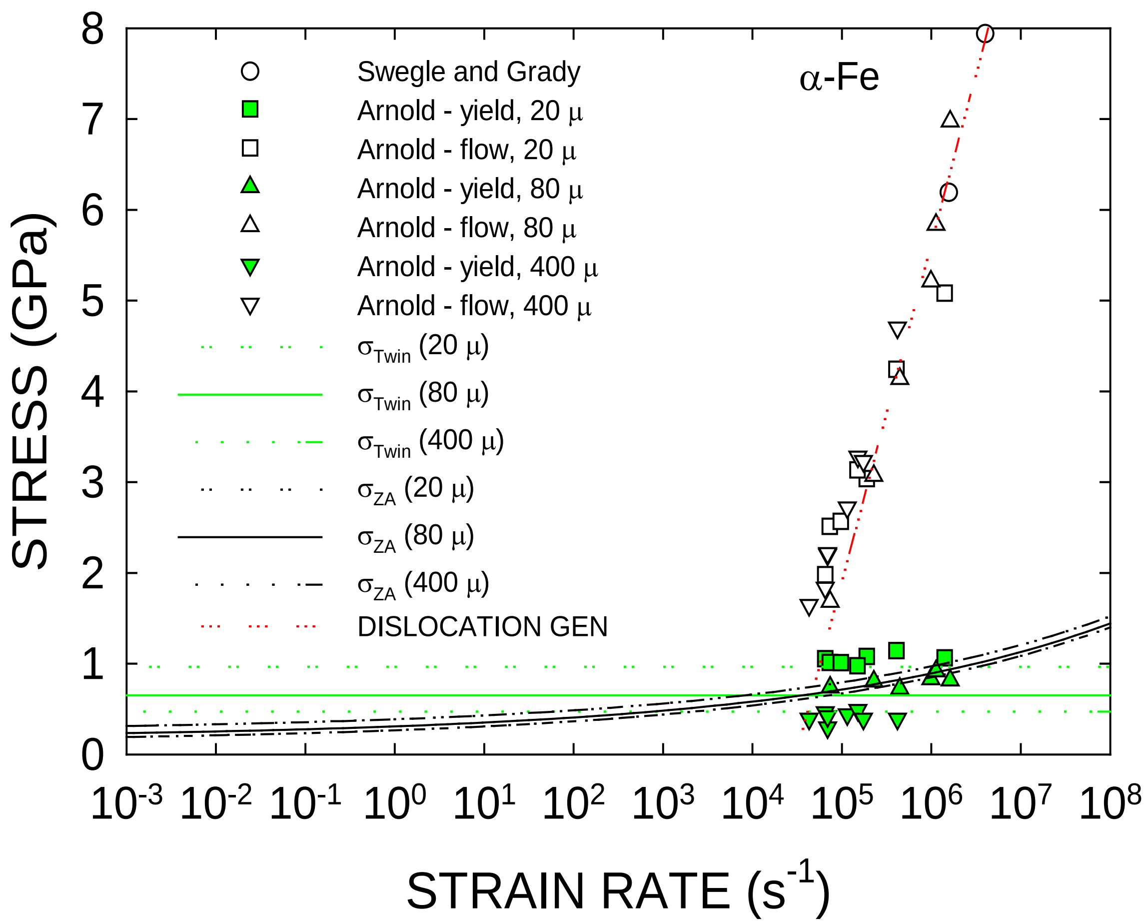
R.W. Armstrong, *Int. Symp. Plast. & Its Curr. Applic*., 2014; J.L. Jordan, C.R. Siviour, G. Sunny, C. Bramlette and J.E. Spowart, *J. Mater. Sci*., **48**, 7134-7141 (2013).

Z-A, SHPB and AAZ comparison for tantalum



D. Rittel, M.L. Silva, B. Poon and G. Ravichandran, *Mech. Mater.*, **41**, 1323-1329 (2009); R.W. Armstrong and F.J. Zerilli, *J. Phys. D: Appl. Phys.*, **43**, 492002 (2010)

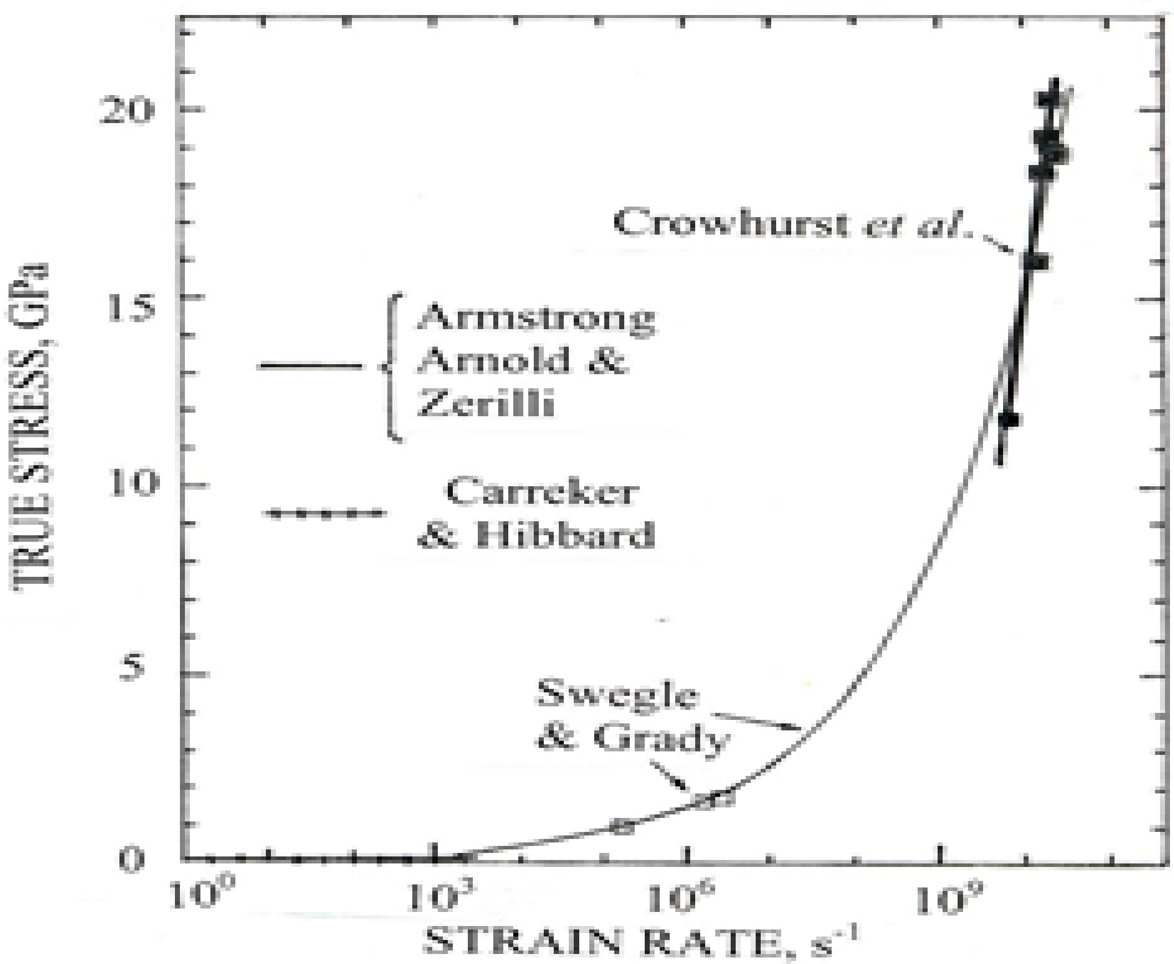
Shock results on Armco iron



W. Arnold, *Dynamisches Werkstoffverhaltern von Armco-Eisen Stosswellbelastung*, Fortschrittberiche VDI 5 (VDI Verlag GmbH, Duesseldorf, DE, 1992); R.W. Armstrong, W. Arnold and F.J. Zerilli, *J. Appl. Phys*., **105**, 023511 (2009).

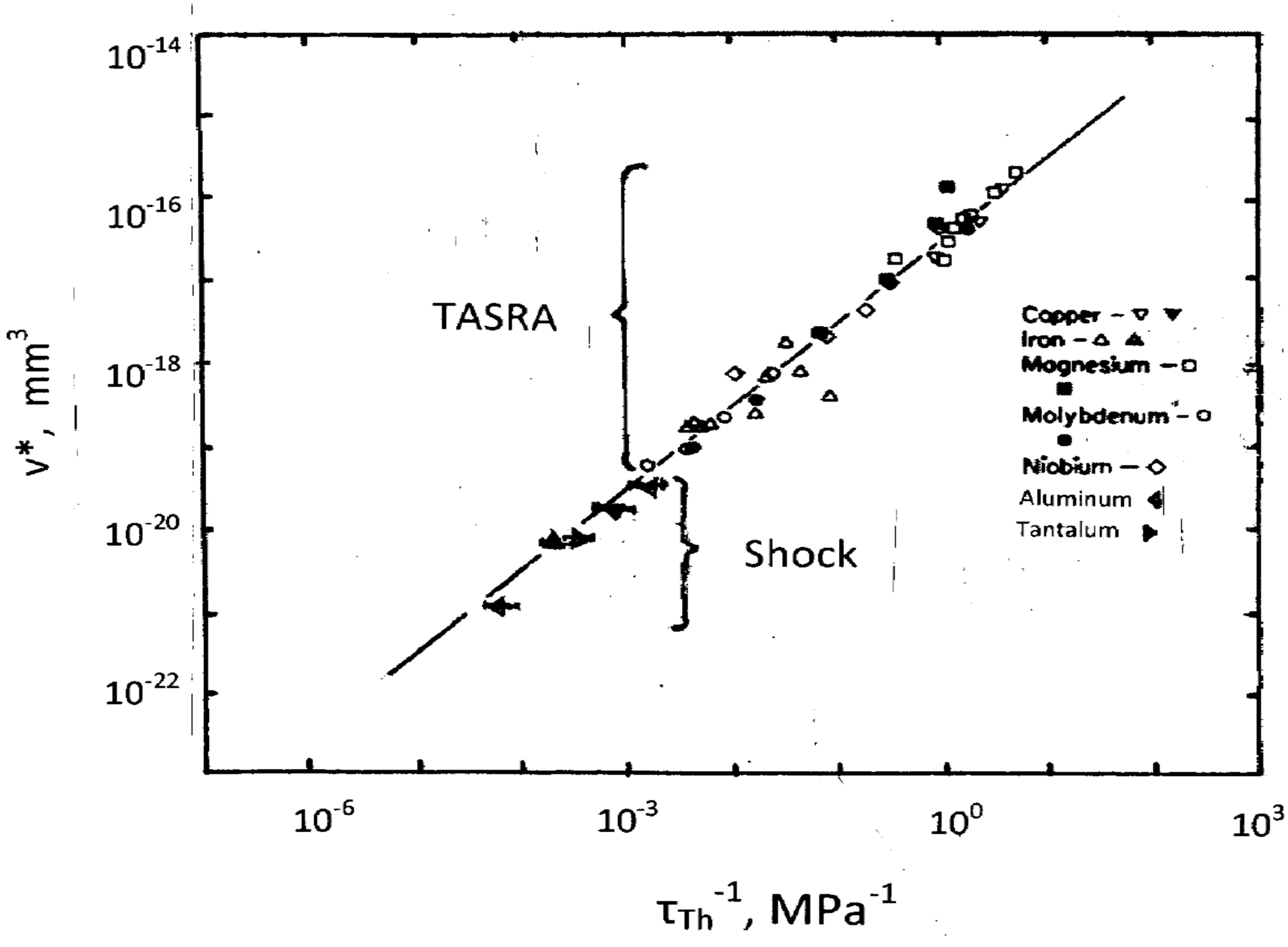
Shock results on <u>aluminum</u>

(aluminum is different!)



R.W. Armstrong, "Dislocation mechanics of high rate deformations", ***Plasticity, Damage & Fracture '14***, Freeport, Bahamas, 3-8 January, 2014.

TASRA correlation of shock measurements



R.W. Armstrong, *Int. Symp. Plasticity, Damage & Fracture, Bahamas*, 1/3-8/14

Comparison of dislocation generation and mobility equations

(1) Orowan velocity vs dislocation generation rate eqns

$$(d\gamma/dt) = \rho b v \quad \textbf{vs.} \quad (d\gamma/dt) = (d\rho/dt) b \Delta x$$

(2) For aluminum* at P = ~35 GPa, with $(d\varepsilon/dt) = (d\gamma/dt)/m$ = ~10^{10} s^{-1}, b = 0.28 nm, $v = v_S$ = 3.2×10^3 m/s, and m = 2.0,

$$\rho = \sim 2.2 \times 10^{16}\ m^{-2}$$

thus representing a substantial increase in ρ over any initial ρ_i.

(3) With Δx = ~10 nm,

$$(d\rho/dt) = \sim 1.1 \times 10^{28}\ m^{-2}\ s^{-1}$$

thus representing a substantial rate of dislocation generation.

*J. C. Crowhurst *et al*., ***Phys. Rev. Letts***., **107**, 144302 (2011); G.A. Malygin *et al*., ***(RU) Phys. Sol. State***., **55**, [4], 780-786 (2013).

Dislocation drag control for (shockless) isentropic compression

The resident dislocation density is required to “carry the load”, and because ρ_N is low, v_N is so high as to be controlled by “drag”!

$$\sigma_{Th} = \{1 - [c(d\varepsilon/dt)/\beta_1\sigma_{Th}]^{-\beta 1T}\}[B\mathbf{exp}(-\beta T)]$$

in which

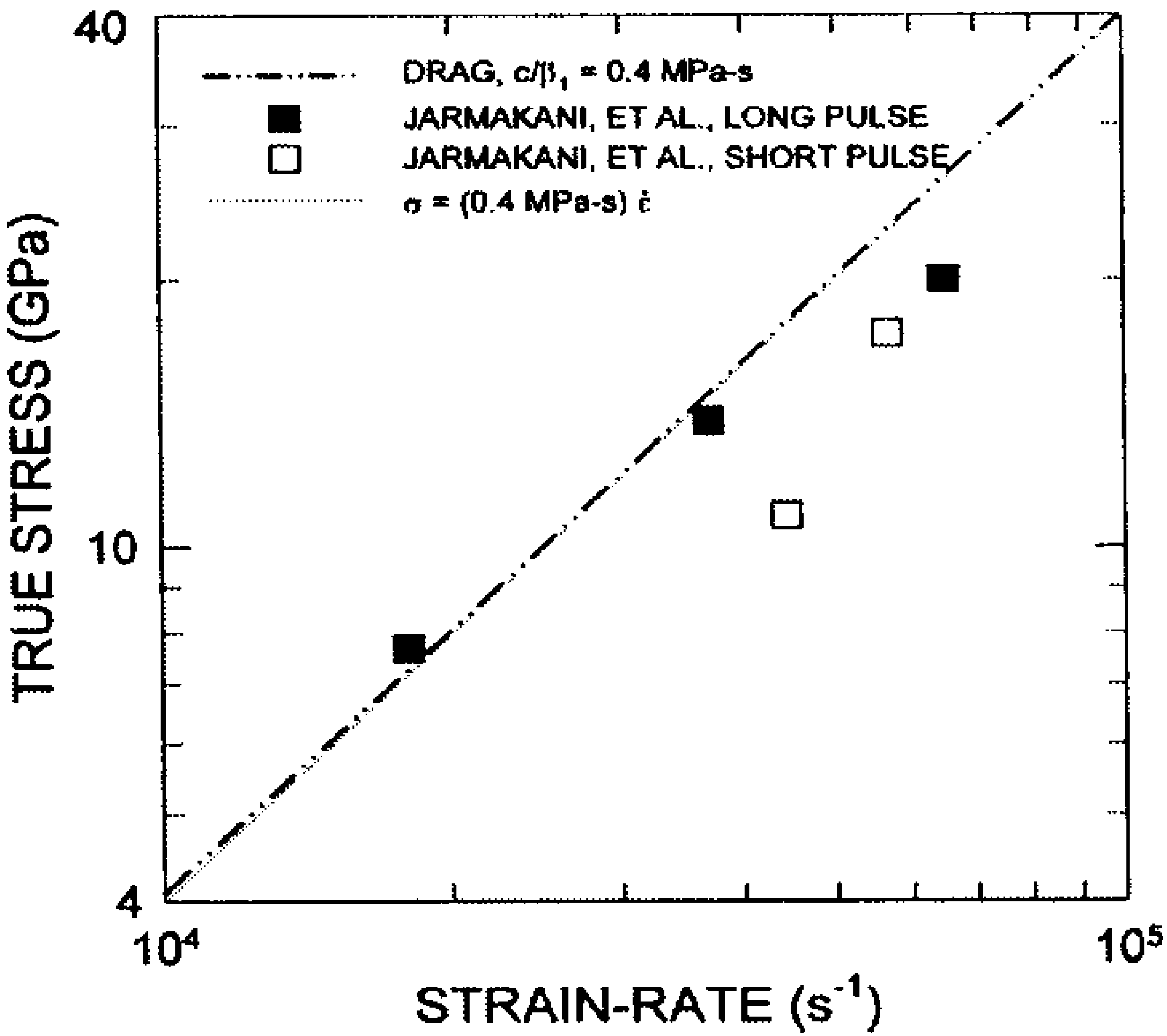
$$c = c_0 m^2 \beta_1/\rho b^2 \quad \text{and} \quad b\tau_{TH} = c_0 v.$$

At high $(d\varepsilon/dt)$:

$$\sigma_{Th} = (c_0 m^2/\rho b^2)(d\varepsilon/dt)$$

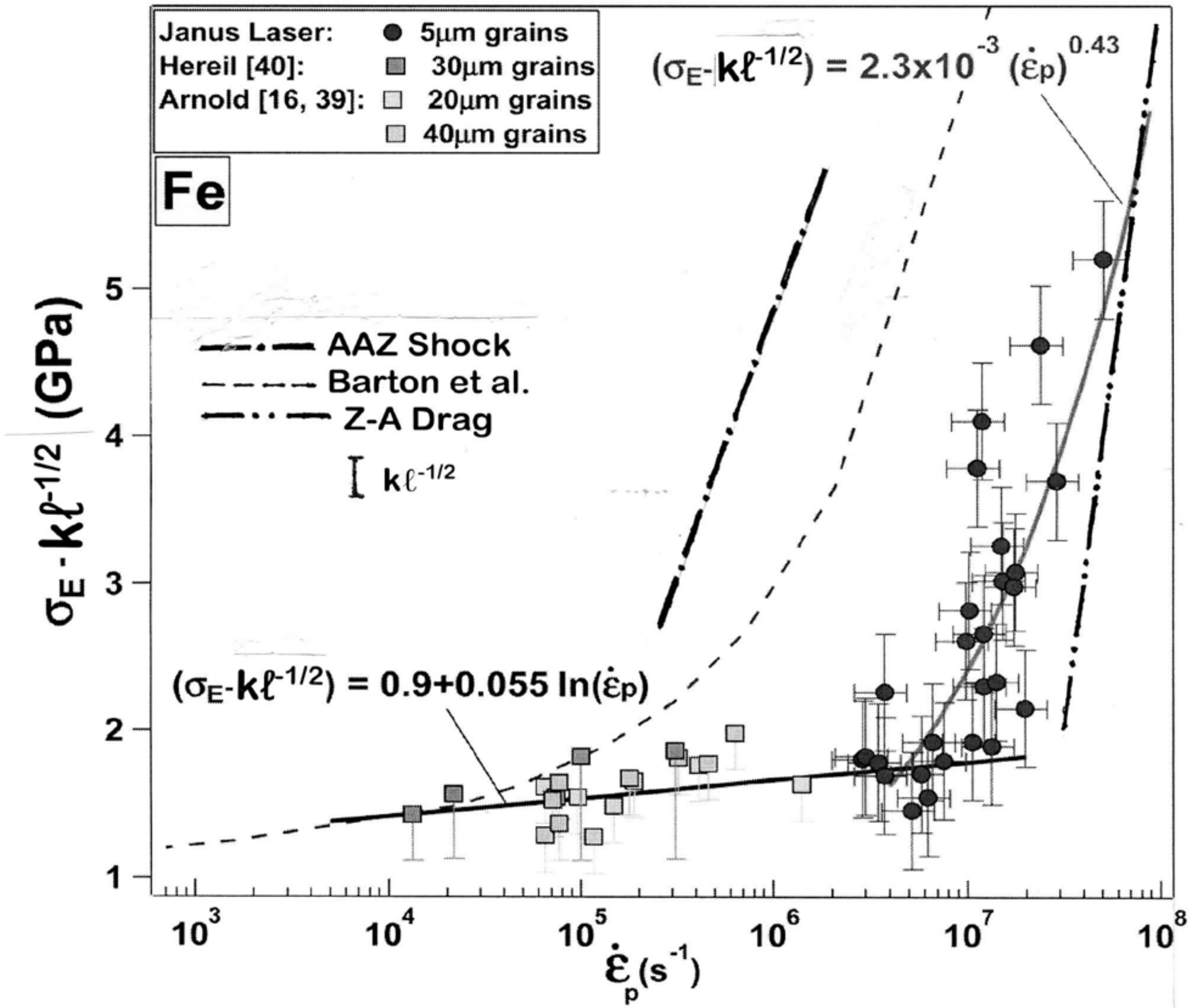
F.J. Zerilli and R.W. Armstrong, *Acta Mater.,* **40**, 1803-1808 (1992);
R.W. Armstrong, W. Arnold and F.J. Zerilli, *J. Appl. Phys.* **105**, 023511 (2009)

Drag control for (shockless) ICE on copper



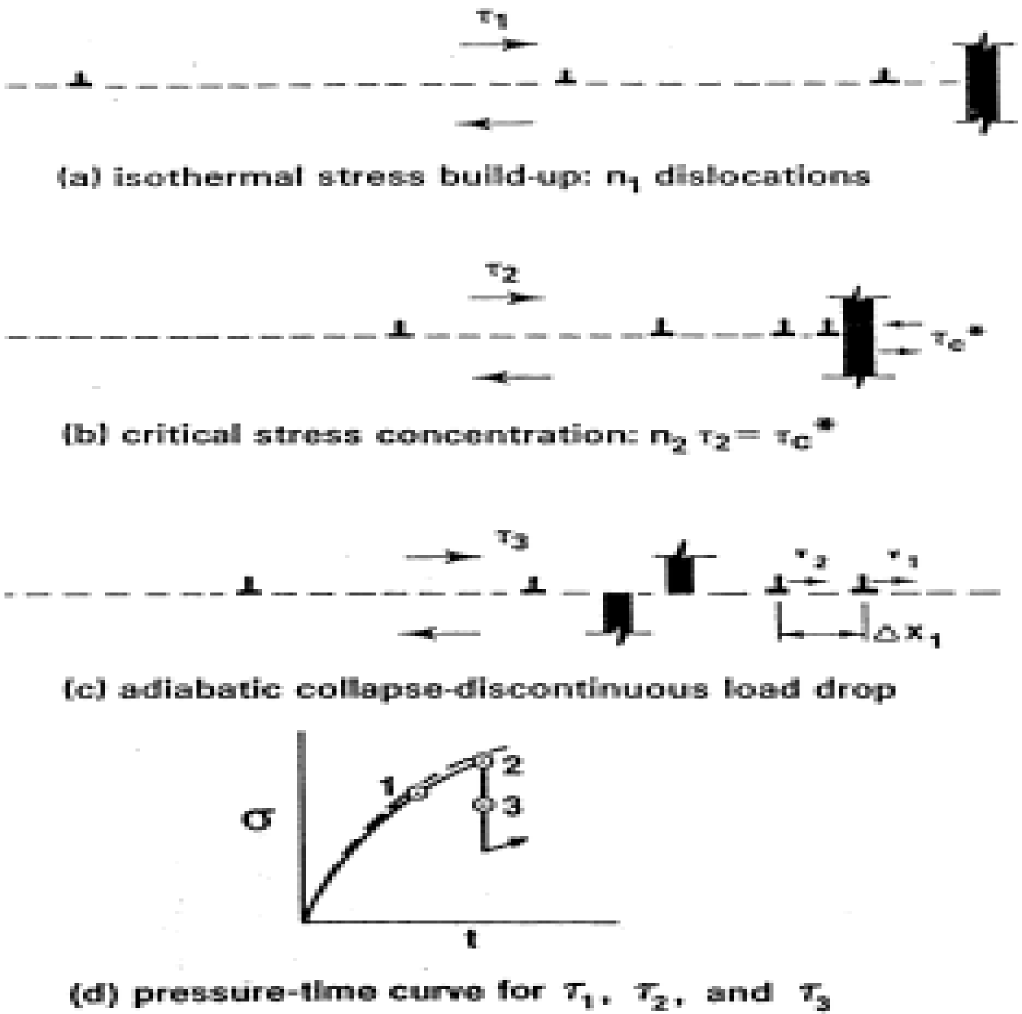
R.W. Armstrong, W. Arnold and F.J. Zerilli, *J. Appl. Phys*., **105** 023511 (2009)

SHPB, shock and ICE results on ARMCO iron



R.F. Smith, J.H. Eggert, R.E. Rudd, D.C. Swift, C.A. Bolme and G.W. Collins, *J. Appl. Phys*., **110**, 123515 (2011), see Fig. 9; N.R. Barton, J.V. Bernier, R. Becker, A. Arsenlis, R. Cavallo, J. Marian, M. Rhee, H.-S. Park, B. Remington and R.T. Olson, *J. Appl. Phys*. **109**, 073501 (2011); R.W. Armstrong, W. Arnold and F.J. Zerilli, J. Appl. Phys. **105**, 023511 (2009).

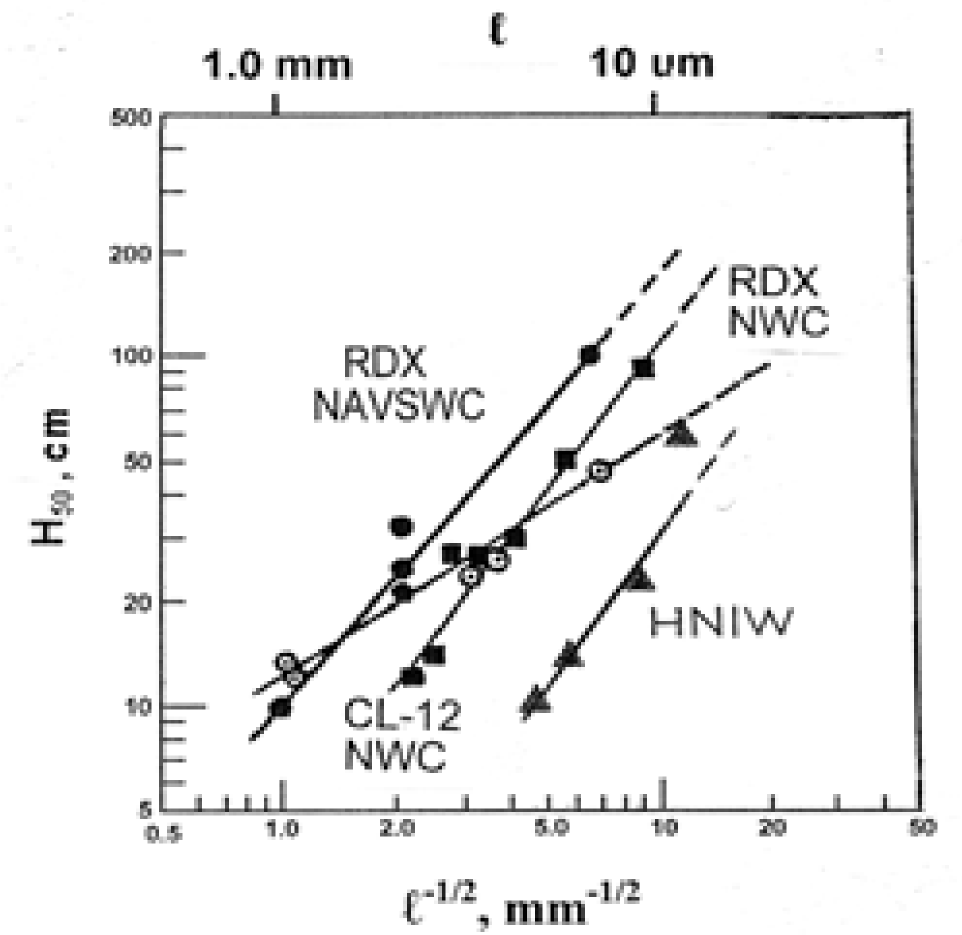
Post-Hopkinson dislocation mechanics model for thermal hot spots and adiabatic shear banding



R.W. Armstrong, C.S. Coffey and W.L. Elban, "Adiabatic heating at a dislocation pile-up avalanche", *Acta Metallurgica*, **30**, 2111-2118 (1982).

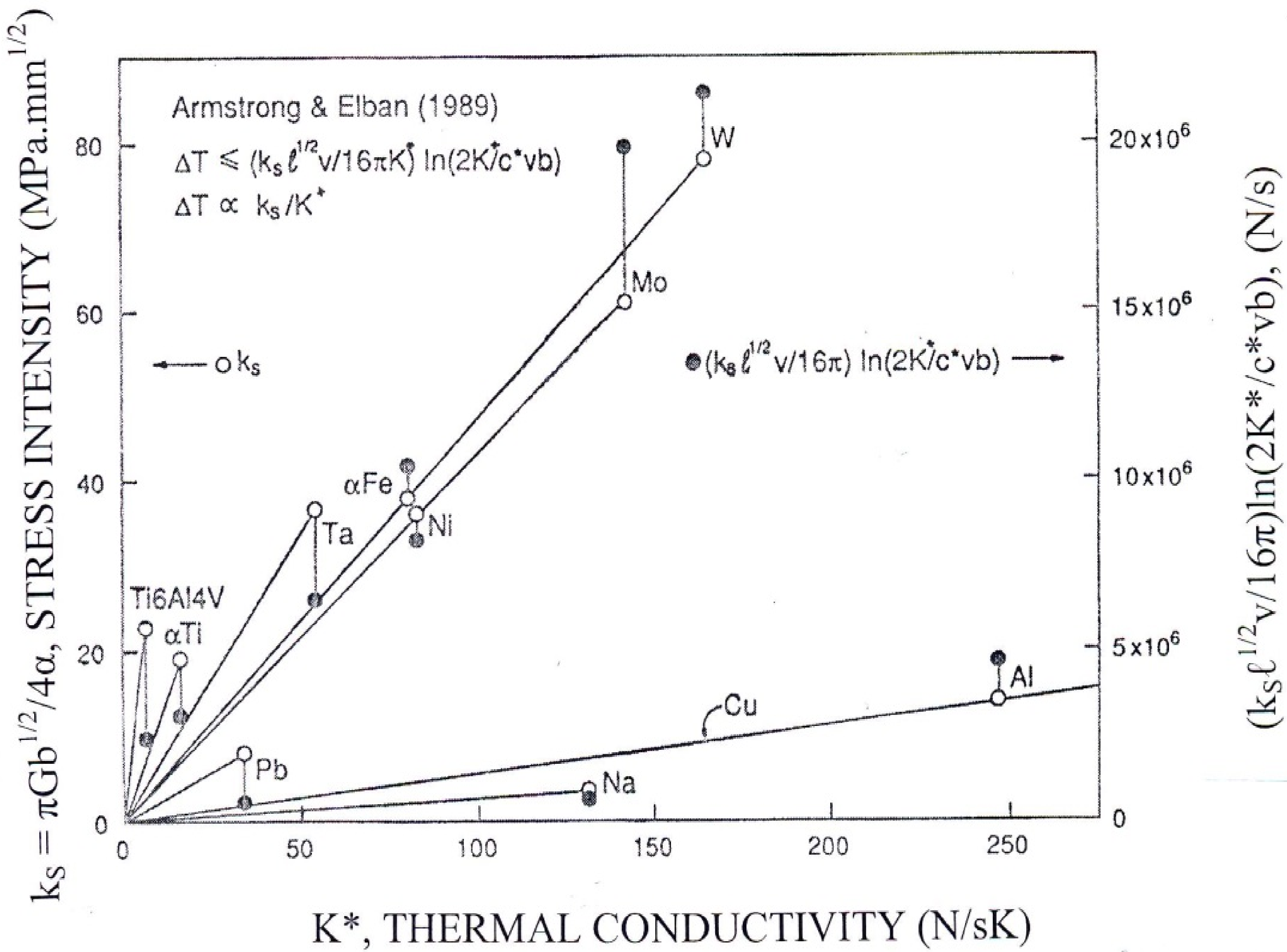
Hot spot model for drop-weight sensitivity

$$\log H_{50} \propto \left(\frac{nkT}{W_0}\right)\log\left(f\{\Delta T, T, \ldots\}\ell^{-1/2}\right)$$



R.W. Armstrong, S.G. Bardenhagen and W.L. Elban, "Deformation-induced hot-spot consequences …..", *Int. J. Energ. Mater. & Chem. Propuls.*, **11**, [5], 413-425 (2012).

Adiabatic shear band susceptibility



R.W. Armstrong and W.L. Elban, "Temperature rise at a dislocation pile-up breakthrough", *Mater. Sci. Eng.*, **A122**, L1-L3 (1989)

SUMMARY

1. Bertram Hopkinson was prescient in focusing both on better measuring and better understanding the nature of high rate deformation of metals and the effect of temperature on detonation of composite explosive material.

2. Continuing post-Hopkinson measurements of material deformations are being coupled with physically-based dislocation mechanics explanations of the material properties.

3. For copper and other metal systems, SHPB test results have provided connection with shock deformations and, more recently, with shock-less isentropic compression experiments.

4. For explosive crystals, Hopkinson's focus on deformation-induced temperature rises has led to understanding of hot spots in explosives and of adiabatic shear banding in metals