Dislocation mechanics of high rate deformations

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1. Dislocation dynamics: $(d\varepsilon/dt) = (1/m)\rho b v \rightarrow (1/m)(d\rho/dt)b\Delta x_d$ 8 charts
   1.a. TASRA, Zerilli-Armstrong (Z-A) and Johnson-Cook relations
   1.b. The dislocation activation volume, $v^* = W_0/\tau_{Th}$
   1.c. Application to copper, steel and tantalum
2. Shear banding (1981/2,1993/4) 4 charts
   2.a. dislocation pile-up avalanche: $n\tau = \tau^*$
   2.b. Lueders-type and other type shear banding (Fe, Ti, Mg)
3. Shock loading *versus* isentropic compression experiments 6 charts
   3.a. Shock-induced dislocation generations: $(d\varepsilon/dt) = (1/m)(d\rho/dt)b\Delta x_d$
   3.b. Control by dislocation drag in ICEs: $\sigma_{Th} = (c/\beta_1)(d\varepsilon/dt)$
4. Hall-Petch for nanopolycrystals: $\sigma_\varepsilon = \sigma_{0\varepsilon} + k_\varepsilon \ell^{-1/2}$ 5 charts
   4.a. The dislocation number dependence: $\Delta n = 1.0$; $\Delta\tau = (-1/n)\tau$
   4.b. H-P strain rate sensitivity: $v^{*-1} = v_0^{*-1} + (k_\varepsilon/2m\tau_{C\varepsilon}v_C^*)\ell^{-1/2}$

Dislocation Dynamics: the TASRA

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

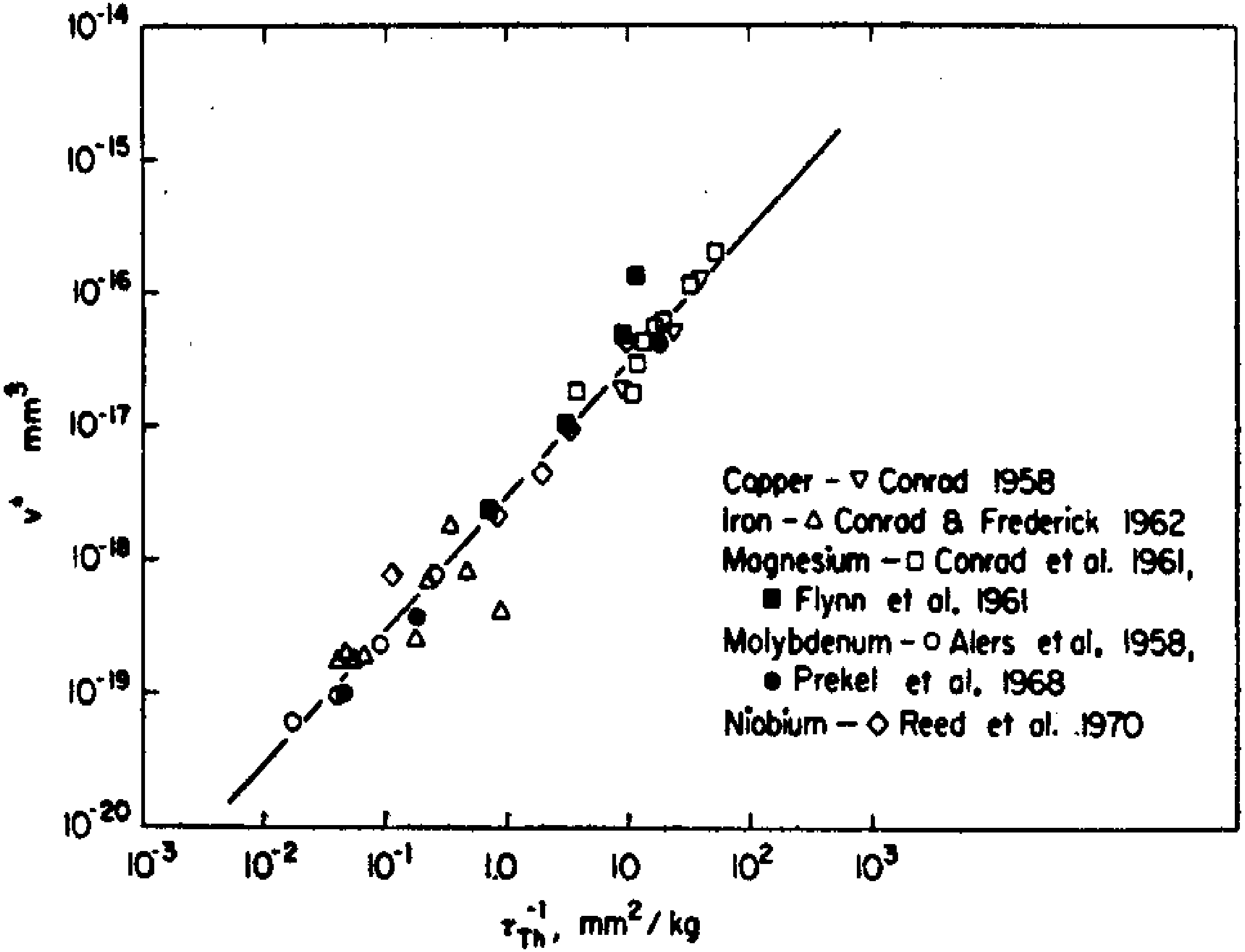
(2.2) fcc: $\sigma_\varepsilon = m\tau_\varepsilon = \sigma_{0G} + B_1[\varepsilon_r\{1 - \varepsilon/\varepsilon_r\}]^{1/2}\mathbf{exp}\{-\beta T\} + k_\varepsilon\ell^{-1/2}$

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

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

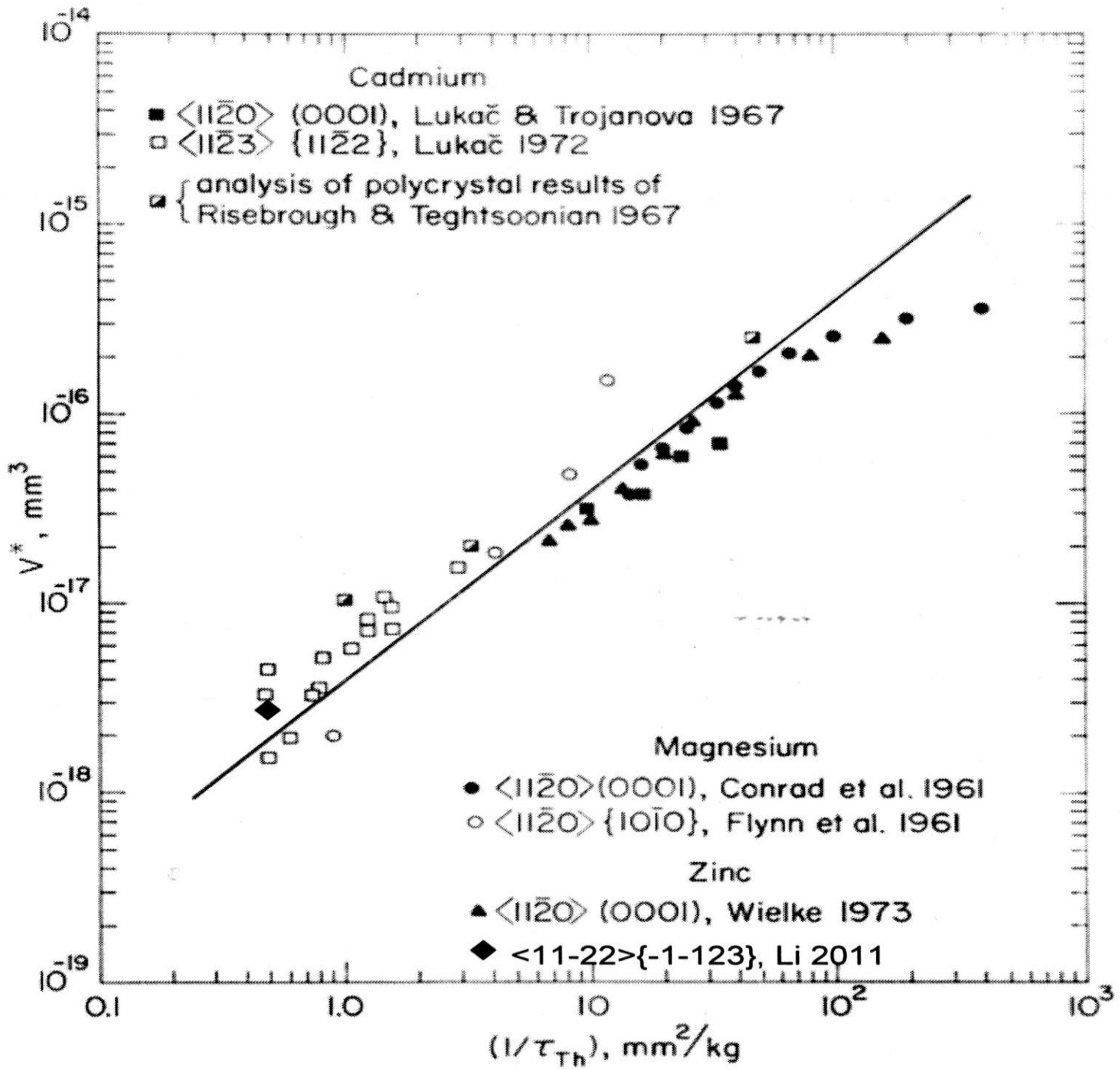
R.W. Armstrong, "Thermal Activation – Strain Rate Analysis (TASRA) for Polycrystalline Metals", *(Indian) J. Scient. Indust. Res*., **32**, 591-598 (1973); F.J. Zerilli and R.W. Armstrong, Dislocation-mechanics-based constitutive relations for material dynamics calculations, *J. Appl. Phys*. **61**, 1816-1824 (1987); R.W. Armstrong, "Dislocation mechanics description of polycrystal plastic flow and fracturing", In: *Mechanics and Materials: Fundamentals and Linkages*, M.A. Meyers, R.W. Armstrong and H.O.K. Kirchner (John Wiley & Sons, Inc., NY, 1999), pp. 363-398

A critical constitutive equation role for the thermal activation volume, $v^* = bA^* = kT\{\partial \mathbf{ln}[d\gamma/dt]/\partial \tau_{Th}\}_T$



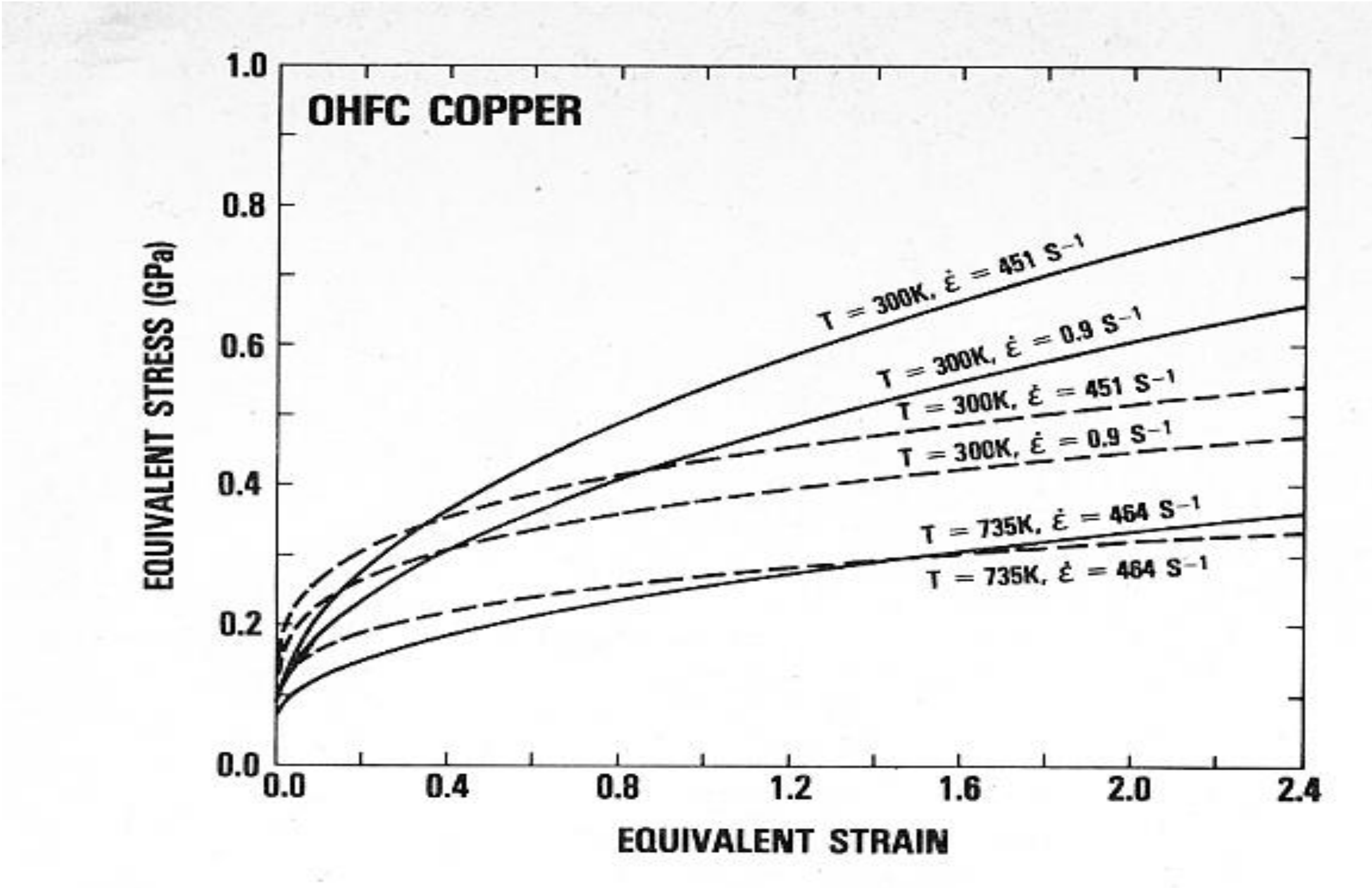
R.W. Armstrong, *(Indian) J. Sci. Indust. Res.*, **32**, 591-598 (1973)

Activation volume, v*, measurements for hcp metals



R.W. Armstrong, In: Nanometals – Status and Perspective, ed. S. Faester et al., 33rd Risoe International Symp., (Tech. Univ. Denmark, Risoe Campus, 2012) pp. 181-199; Q. Li, J. Appl. Phys., **109**, 103514 (2011)

Z-A and J-C stress-strain curves for Cu

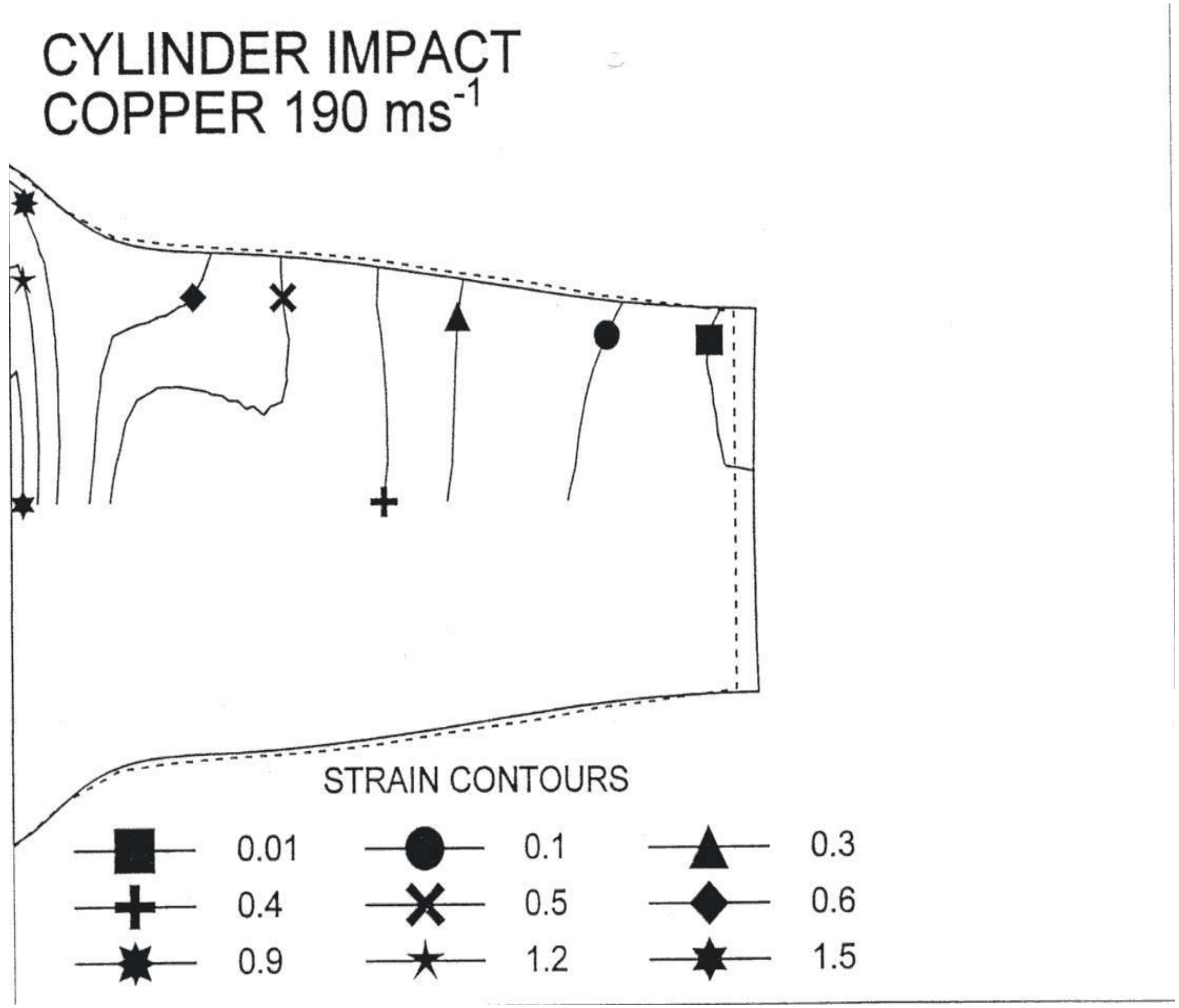


B_0 = 890 MPa, α_0 = 0.0028 K^{-1},α_1 = 0.000115 K^{-1}, $(\varepsilon/\varepsilon_r) < 1.0$, k_ε= 5 MPa.mm$^{1/2}$, $\sigma_G + k_\varepsilon \ell^{-1/2}$ = 65 MPa

F.J. Zerilli and R.W. Armstrong, *J. Appl. Phys.* **61**, [5], 1816-1826 (1987); G.R. Johnson and W.H. Cook, *Eng. Fract. Mech.*, **21**, 31-48 (1985)

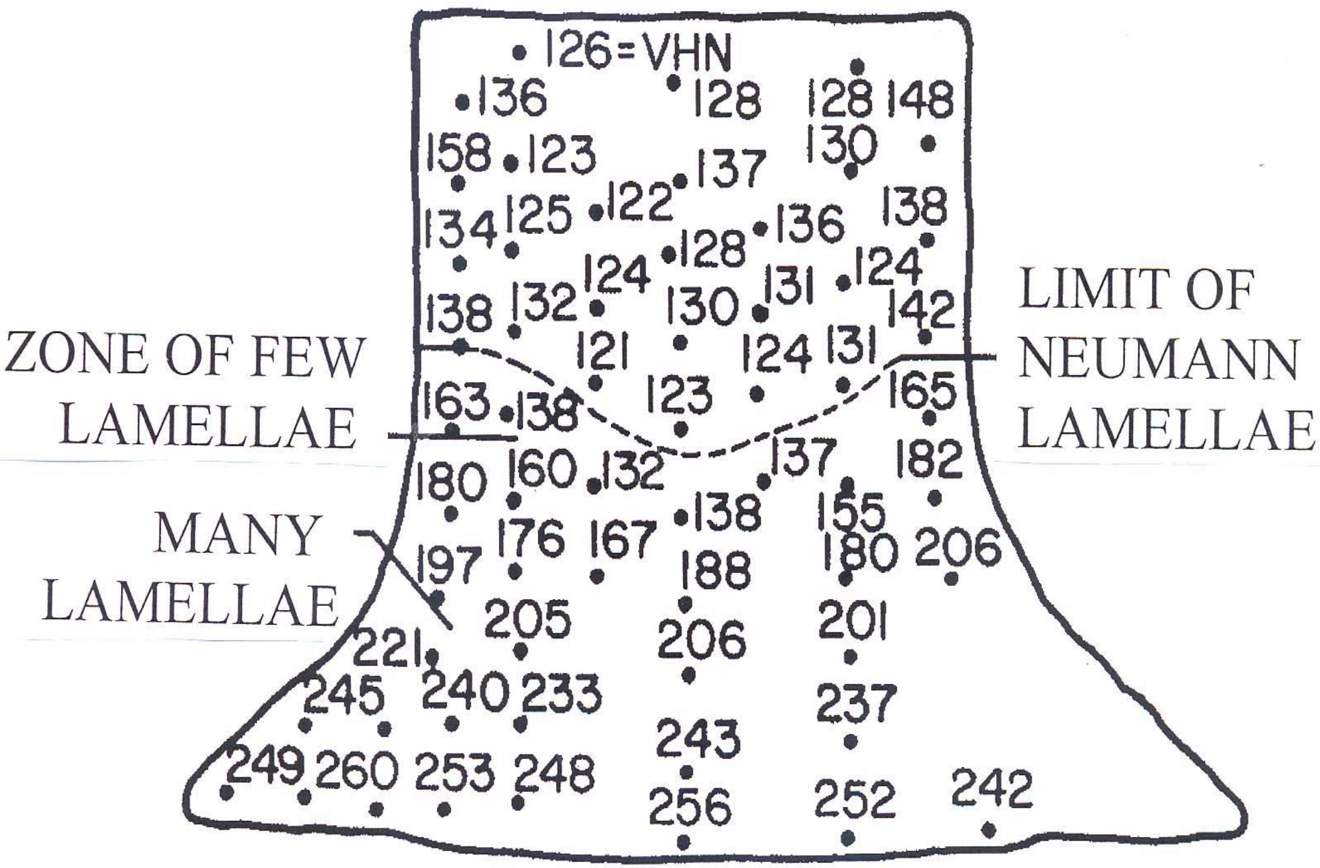
J-C/Z-A fcc Taylor test result

300 ≤ T ≤ ~600 K; 0 ≤ dε/dt ≤ ~10^5 s^{-1}



F.J. Zerilli and R.W. Armstrong, "Dislocation-mechanics-based constitutive relations for material dynamics calculations", *J. Appl. Phys.*, **61**, 1816-1825 (1987),

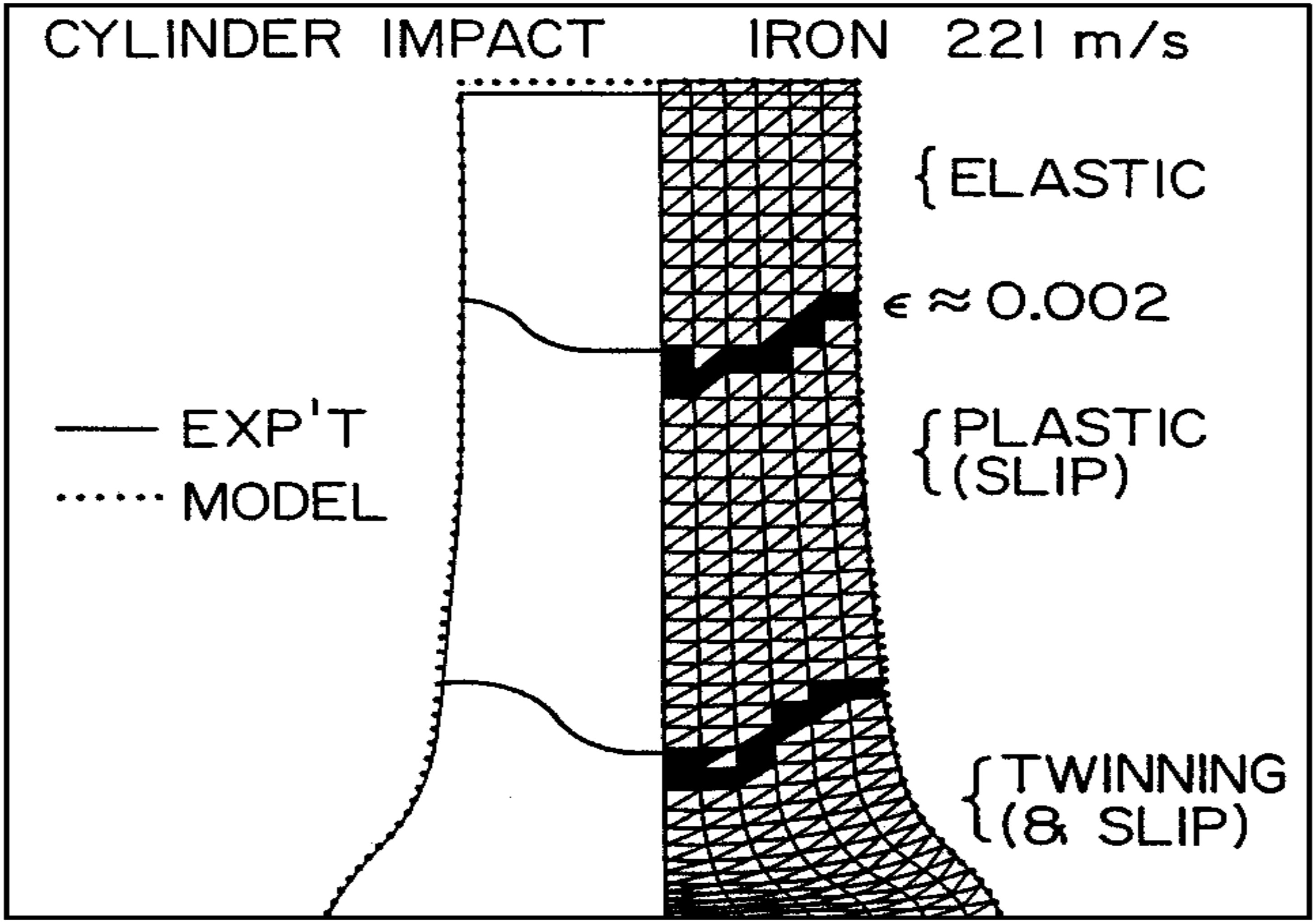
Original Taylor cylinder test result on mild steel



MILD STEEL CYLINDER. IMPACT VELOCITY 338 m/s

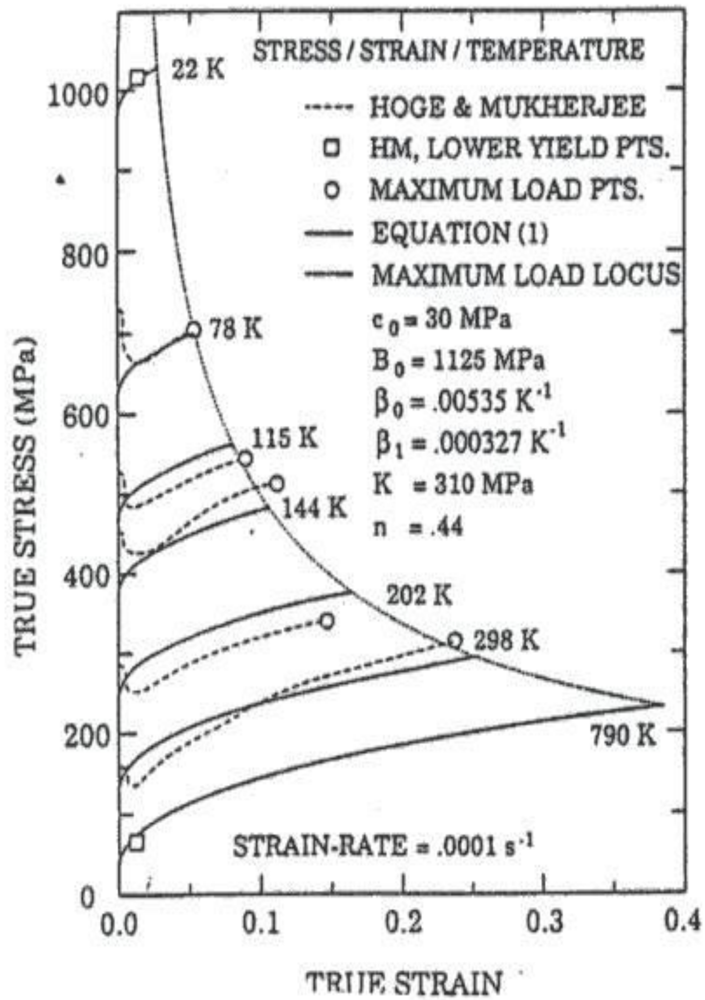
W.E. Carrington and M.L.V. Gaylor, *Proc. Roy. Soc. London A*, **194A**, 323-331 (1948)

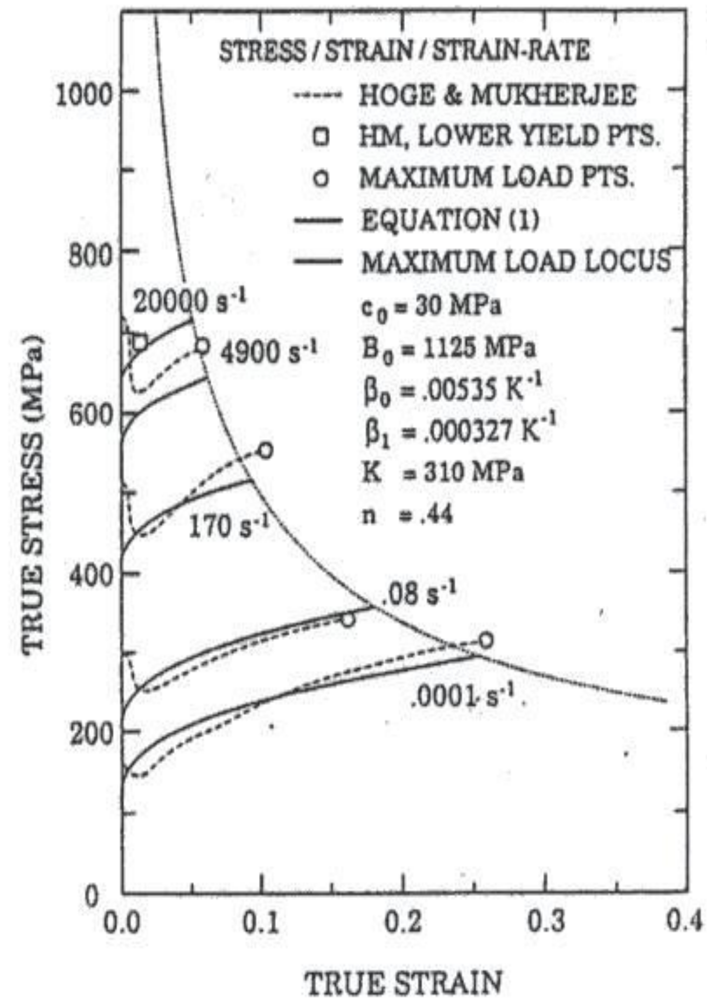
J-C/Z-A: twinning and slip in Armco iron



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

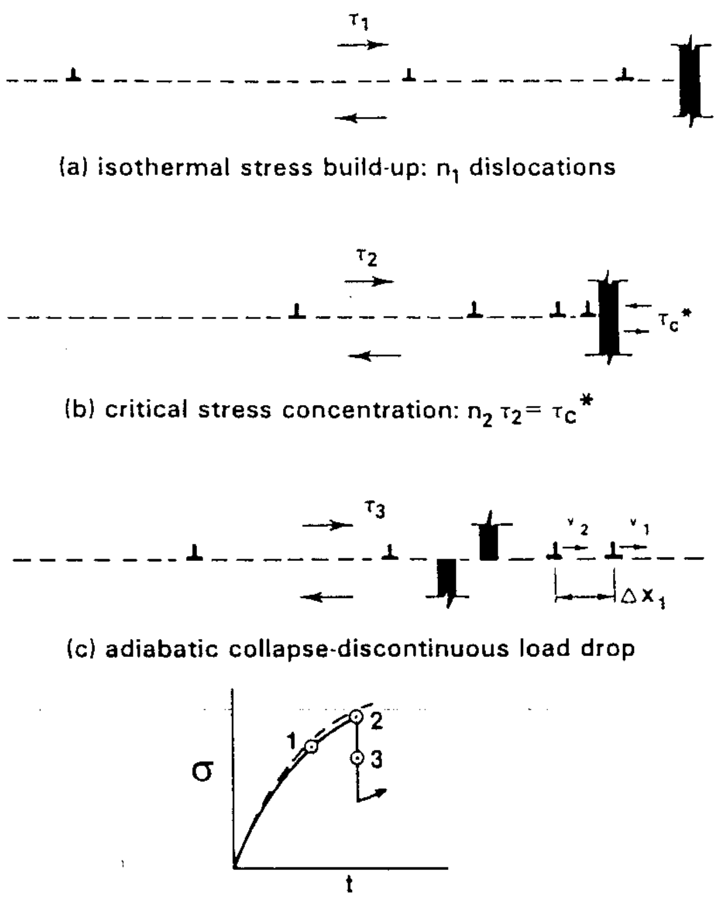
Tantalum: σ, dσ/dε over (T, [dε/dt], ε)





K.G. Hoge and A.K. Mukherjee, *J. Mater. Sci*., **12**, 1666-1672 (1977); F.J. Zerilli, R.W. Armstrong, *J. Appl. Phys*., **68**, 1580-1591 (1990); 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).

Dislocation pile-up avalanche model for hot spots and shear banding



(a) isothermal stress build-up: n_1 dislocations

(b) critical stress concentration: $n_2\, \tau_2 = \tau_c^*$

(c) adiabatic collapse-discontinuous load drop

(d) pressure-time curve for τ_1, τ_2, and τ_3

$$\Delta T \leq \frac{k_s\, l^{1/2}}{16\pi}\left(\frac{2\upsilon}{c^* b K}\right)^{1/2} \qquad if\left(\frac{2K}{c^*\upsilon b}\right) \leq 1.0$$

$$\dot{\gamma} = Nb\upsilon,$$

$$\upsilon = \upsilon_0 \exp\left[-\left(G_0 - \int_{\tau_{th}^0}^{\tau_{th}} bA^*\, d\tau_{th}\right)\Big/ kT\right],$$

$$bA^* = W_0/\tau_{th},$$

$$\tau_{th} \propto H_{50}^{1/n},$$

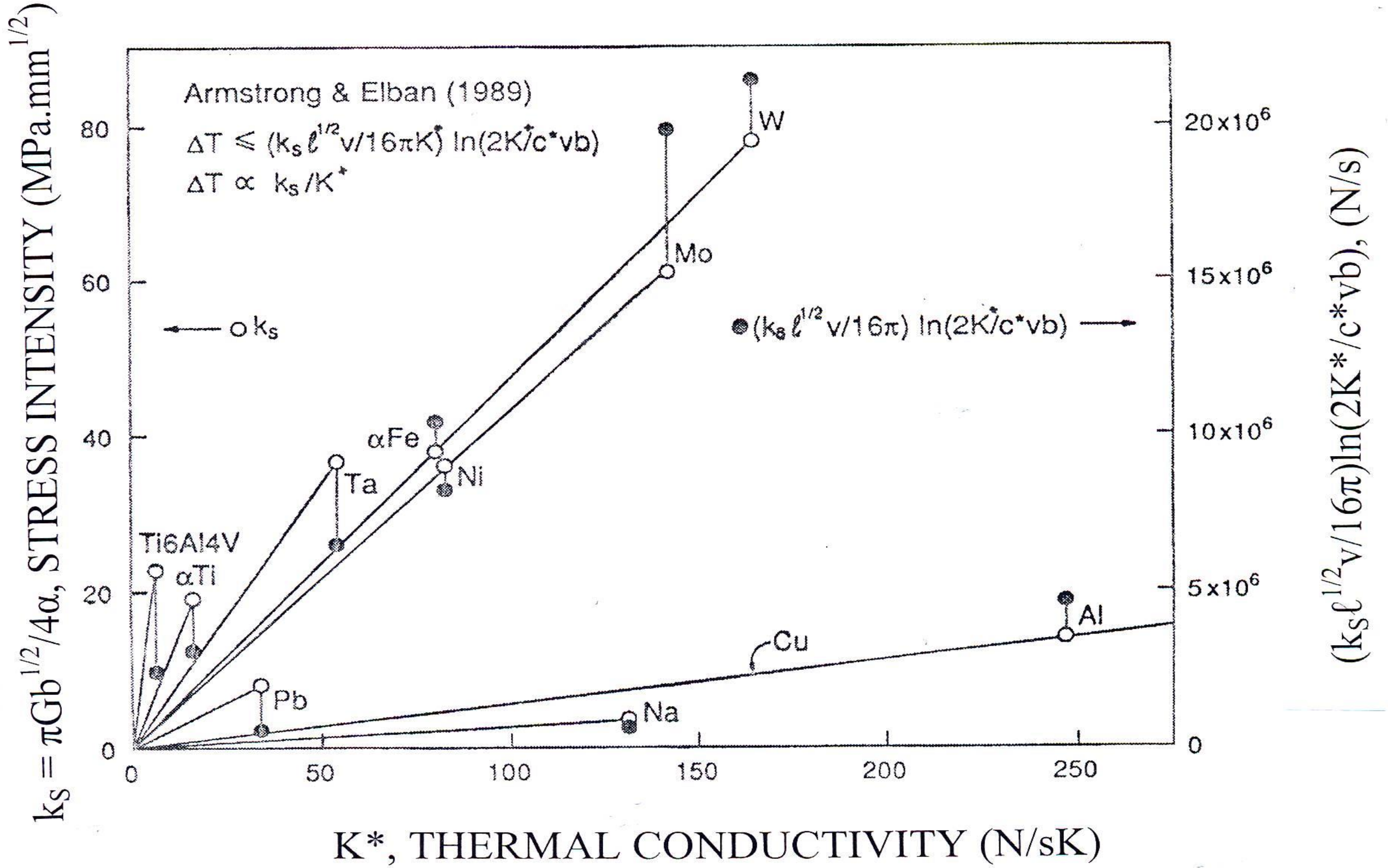
$$\upsilon = \upsilon_0 (H_{50}/H_{50}^0)^{W_0/nkT} \exp(-G_0/kT)$$

$$\log H_{50} = \log H_{50}^* + (n/m^*)\log\{[8\pi\sqrt{2}\Delta T \times K^{1/2} c^{*1/2} b^{1/2}/k_s \upsilon_0^{1/2} \times \exp(-G_0/2kT)]\, l^{-1/2}\}.$$

$$m^* = W_0/2kT$$

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

Shear band susceptibility: k_S/K^*

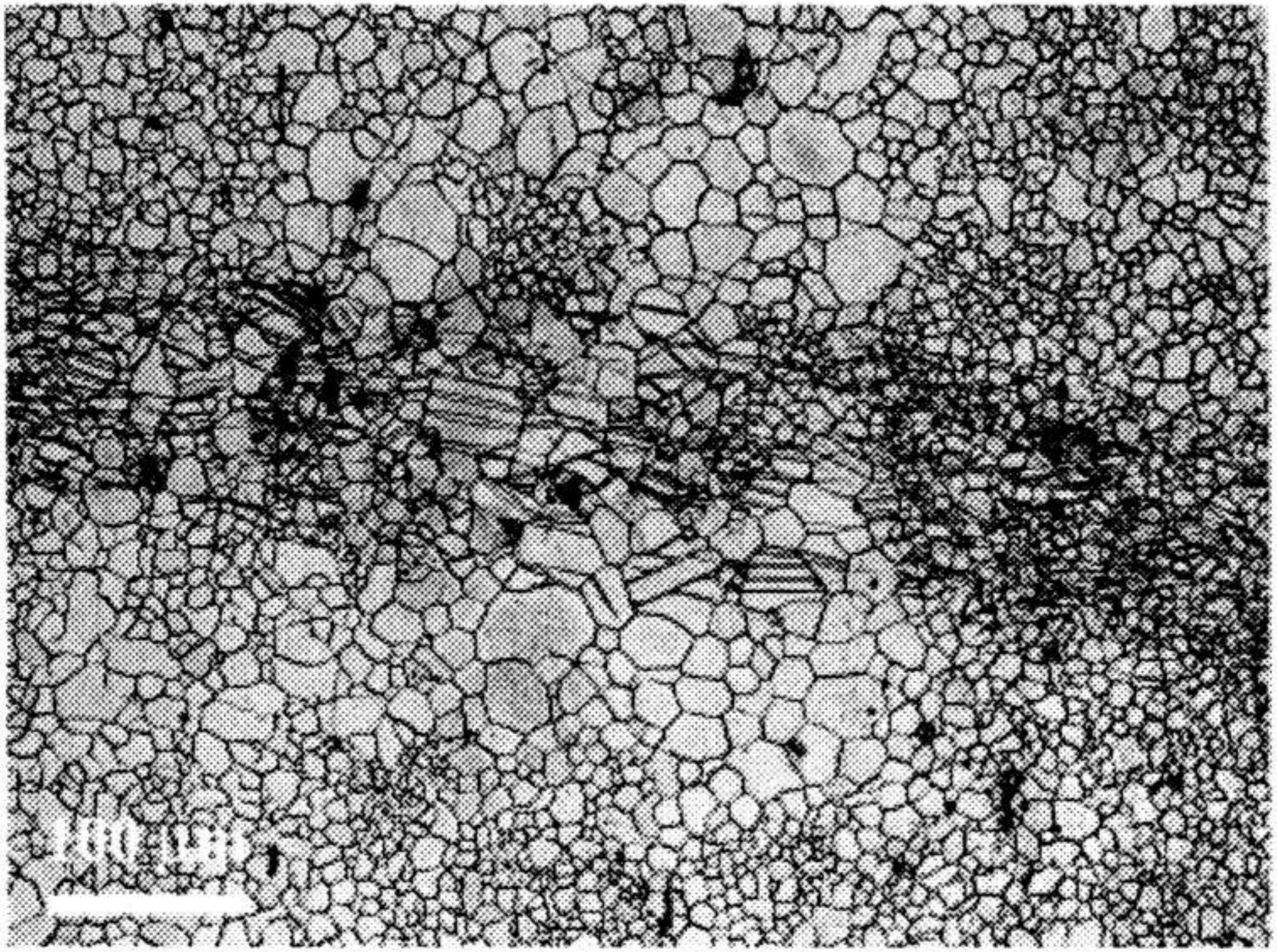


R.W. Armstrong and F.J. Zerilli, "Dislocation mechanics aspects of plastic instability and shear banding", In: ***Shear Instabilities and Viscoplasticity Theories***, edited by R.W. Armstrong, R.C. Batra, M.A. Meyers and T.W. Wright, *Mech. Mater.*, **17**, 319-327 (1994)

Molten metal spray on Ti6Al4V shear plug

W. H. Holt, W. Mock, Jr., W.G. Soper, C.S. Coffey, V. Ramachandran and R.W. Armstrong, “Reverse-ballistic impact study of shear plug formation and displacement in Ti6Al4V alloy”, *J. Appl. Phys*. **73**, 3753-3759 (1993).

Lueders bands in Mg



M.S. Tsai and C.P. Chang, “Grain size effect on deformation twinning in Mg-Al-Zn alloy (AZ31B)”, Mater. Sci. Tech, **29**, 759-763 (2013); S.D. Antolovich and R.W. Armstrong, “Plastic strain localization in metals: Origins and consequences”, Prog. Mater. Sci. **59**,1-160 (2014)

The progression

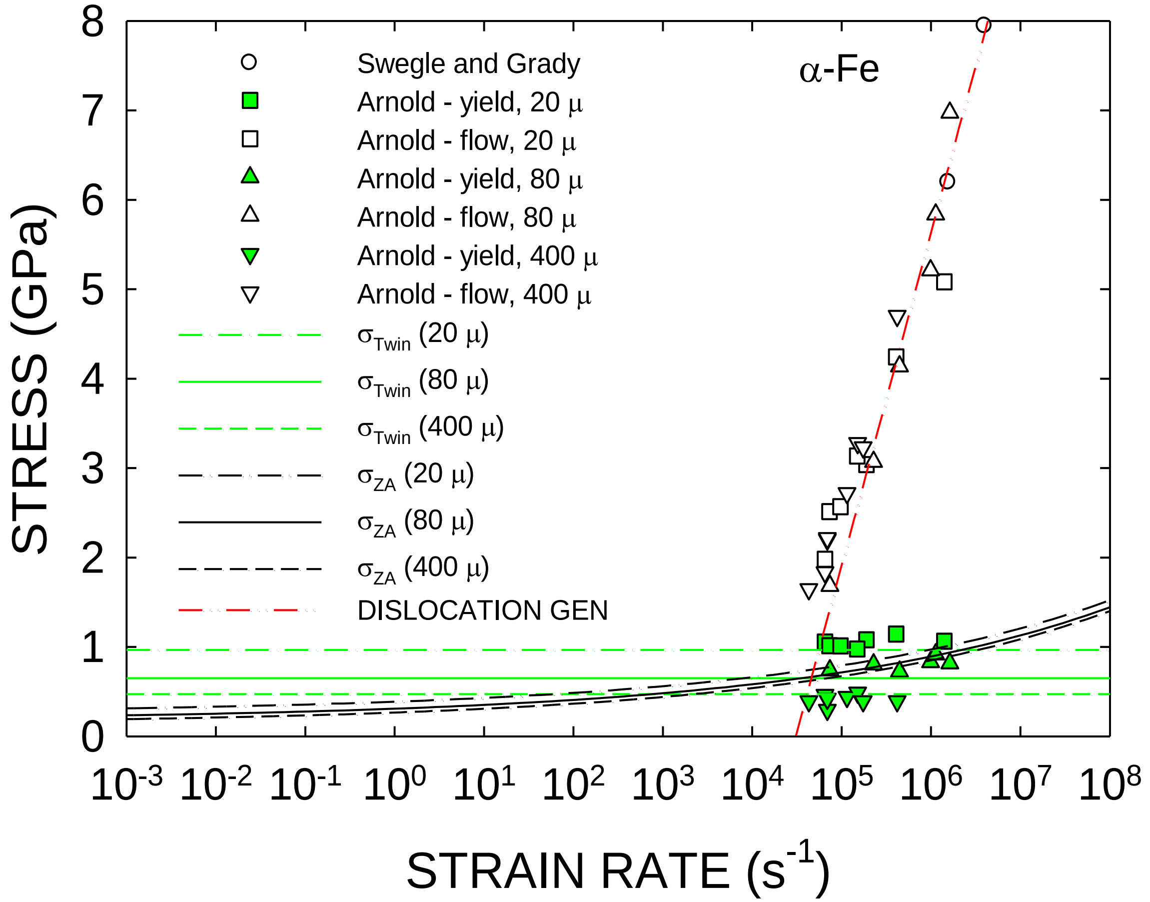
1. Beginning with the TASRA and leading to impact results obtained on copper and α-iron materials, then to shear banding, a rather smooth progression occurs for higher strength levels being achieved at higher applied plastic strain rates.

2. A much stronger strain rate dependence is obtained for shock-induced plastic flow stress levels because of enhanced dislocation generation occurring along the propagating shock front.

3. A comparably high drag-controlled plastic flow stress occurs for isentropic compression experiments (ICEs) because the initially resident dislocation density must move at high speed.

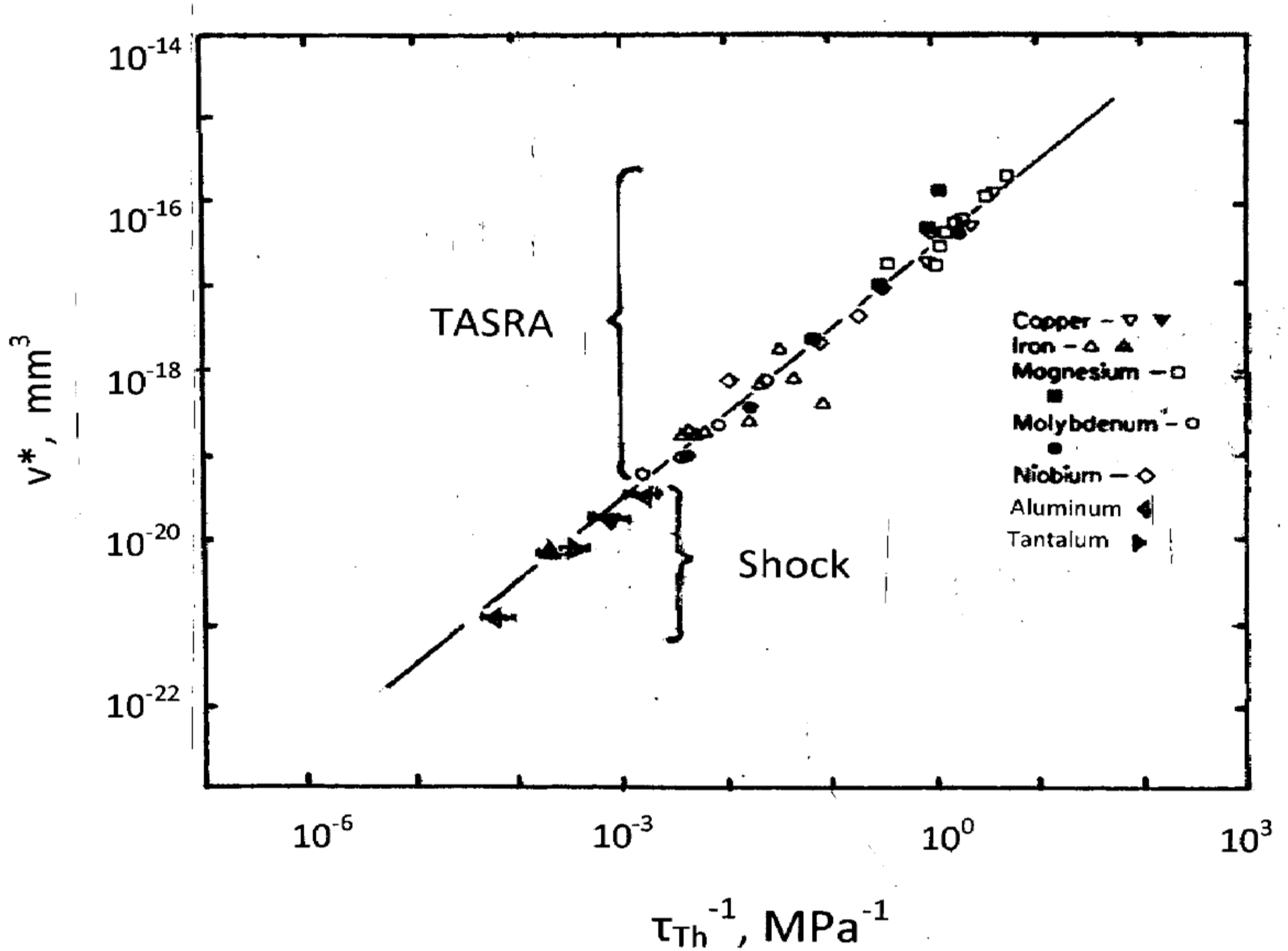
Shock-induced plasticity in Armco iron

[twinning-determined HEL & grain-size-independent (dε/dt)]



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).

TASRA correlation of shock measurements



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

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

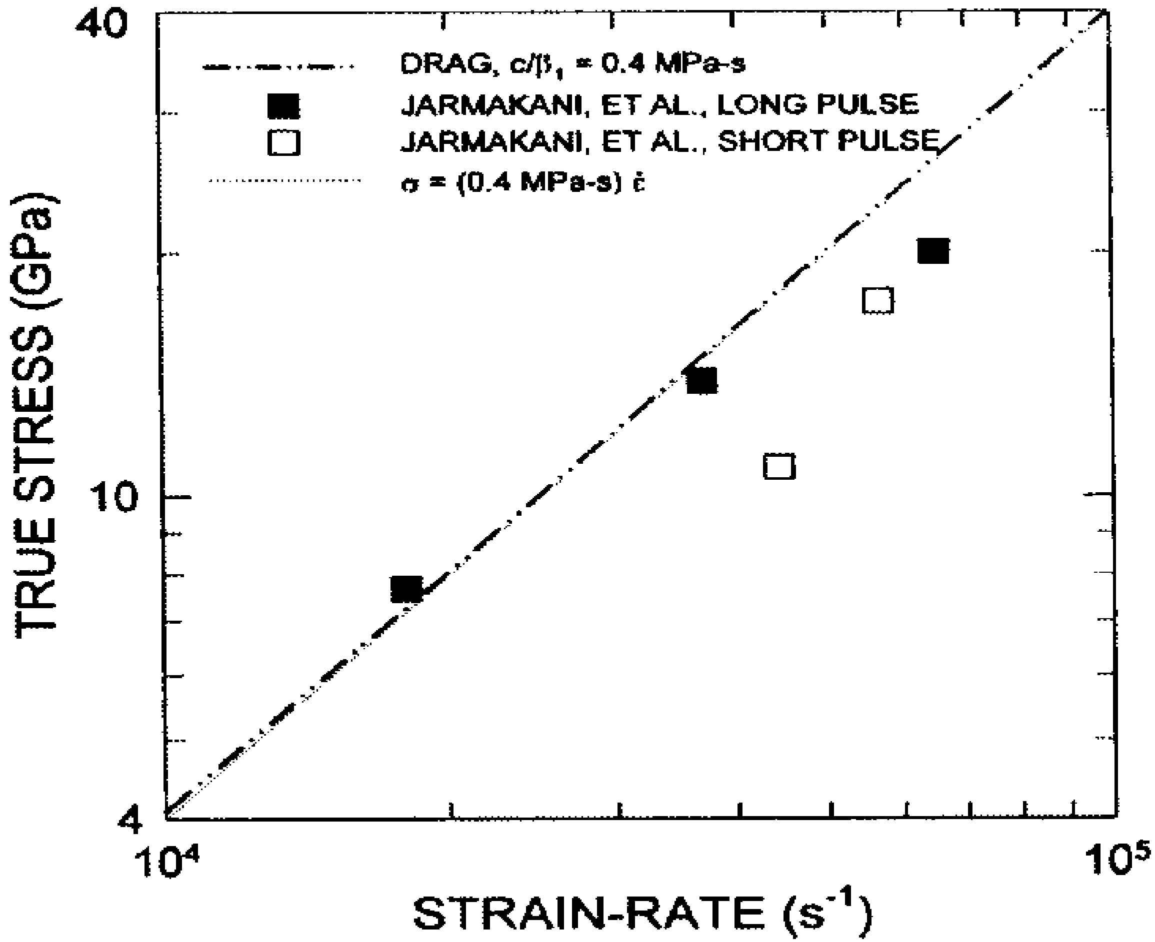
$$c = c_0 m^2\beta_1/\rho b^2 \quad \text{and} \quad b\tau_{Th} = c_0 v.$$

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

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

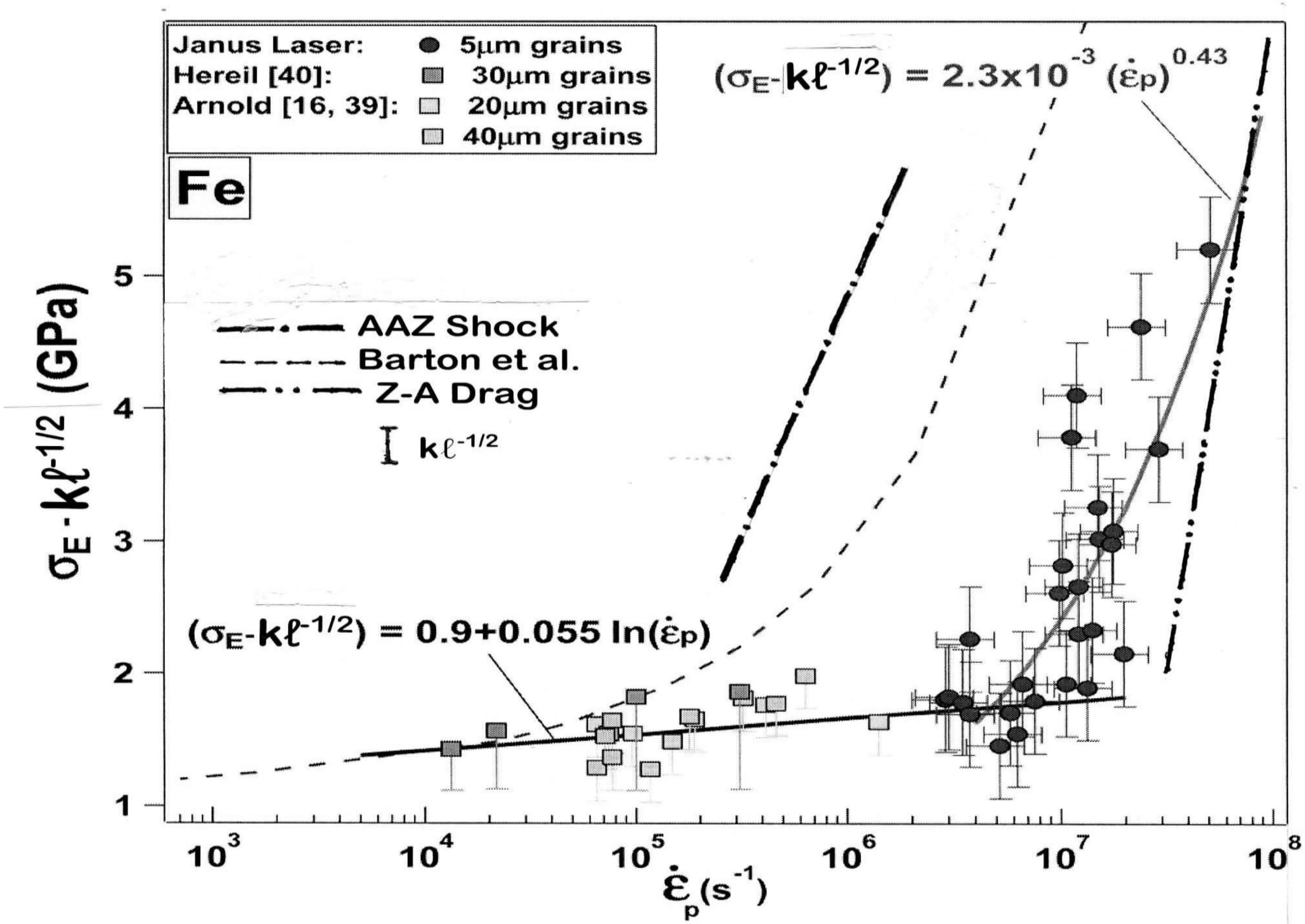
F.J. Zerilli and R.W. Armstrong, *Acta Mater.,* **40**, 1803-1808 (1992);
R.W. Armstrong, W. Arnold and F.J. Zerilli, *J. Appl. Phys.* **105**, 023511 (2009)

Drag control for (shockless) ICE on copper



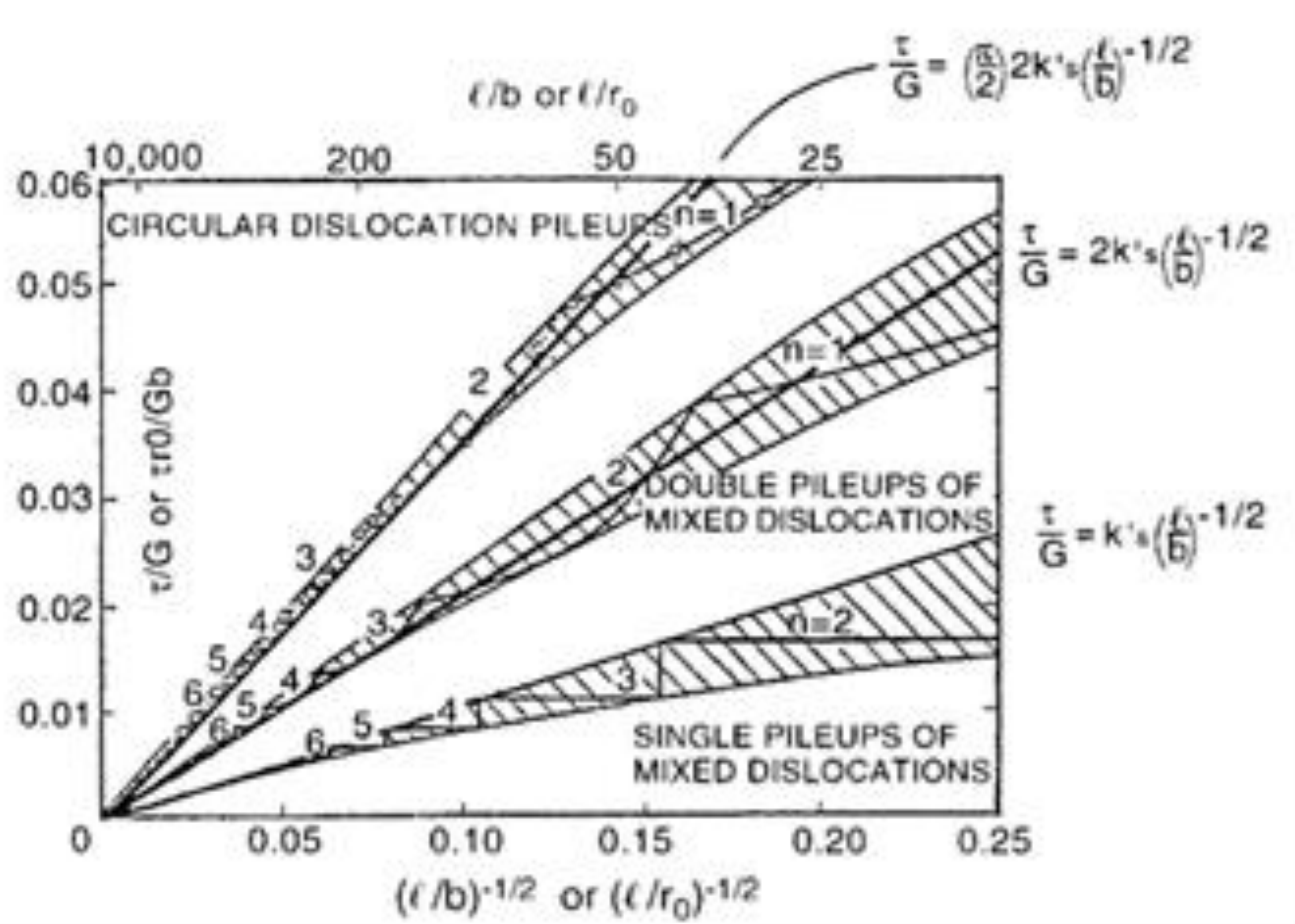
H. Jarmakani, J.M. McNaney, M.S. Schneider, D. Orlikowski et al., In: *Shock Compression of Condensed Matter - 2005*, M.D. Furnish, M. Elert, T.P. Russell and C.T. White, eds., (Amer. Inst. Phys., Melville, NY, 2006) **CP845**, Part 2, pp. 1319-1322; R.W. Armstrong, W. Arnold and F.J. Zerilli, *J. Appl. Phys*., **105** 023511 (2009)

SHPB, shock and ICE results on ARMCO iron



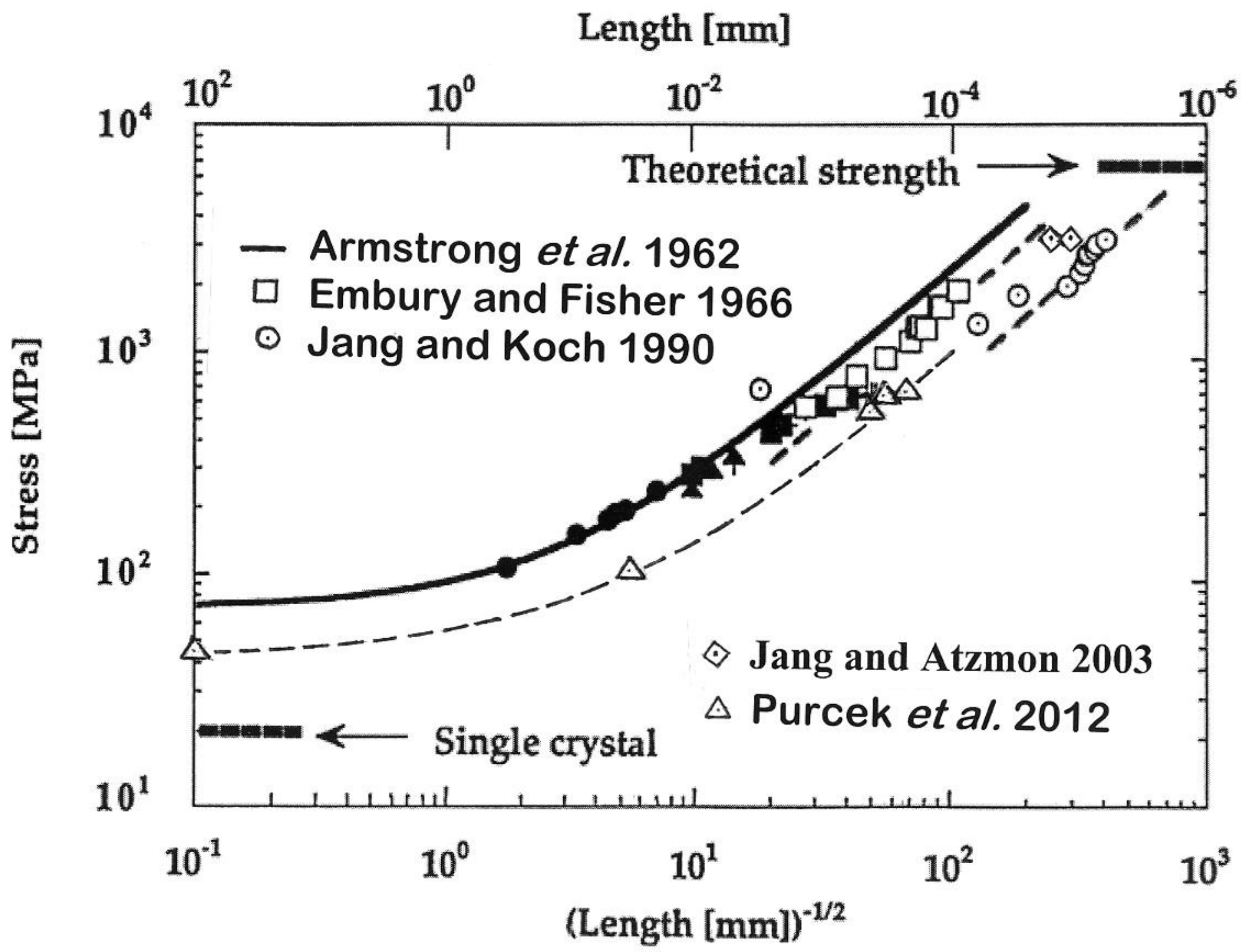
R.F. Smith, J.H. Eggert, R.E. Rudd, D.C. Swift, C.A. Bolme and G.W. Collins, *J. Appl. Phys*., **110**, 123515 (2011), see Fig. 9; N.R. Barton, J.V. Bernier, R. Becker, A. Arsenlis, R. Cavallo, J. Marian, M. Rhee, H.-S. Park, B. Remington and R.T. Olson, *J. Appl. Phys*. **109**, 073501 (2011); R.W.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

Hall-Petch/Griffith connection for ***k*** being described as a stress intensity



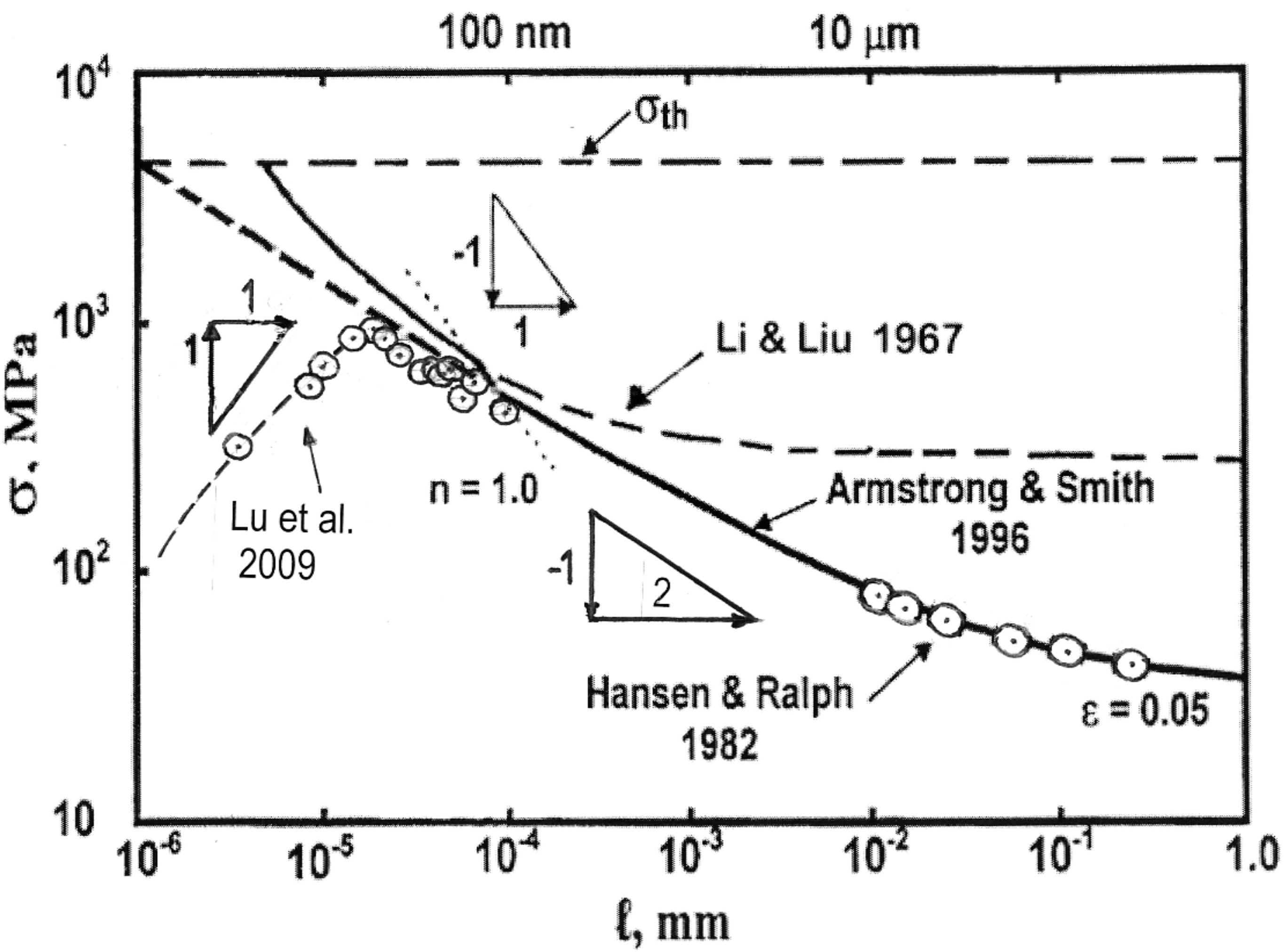
R.W. Armstrong, “Dislocation pile-ups: from {110} cracking in MgO to model strength evaluations”, *Mater. Sci. Eng. A*, **409**, 24-31 (2005)

The H-P dependence for iron and steel on a log/log basis



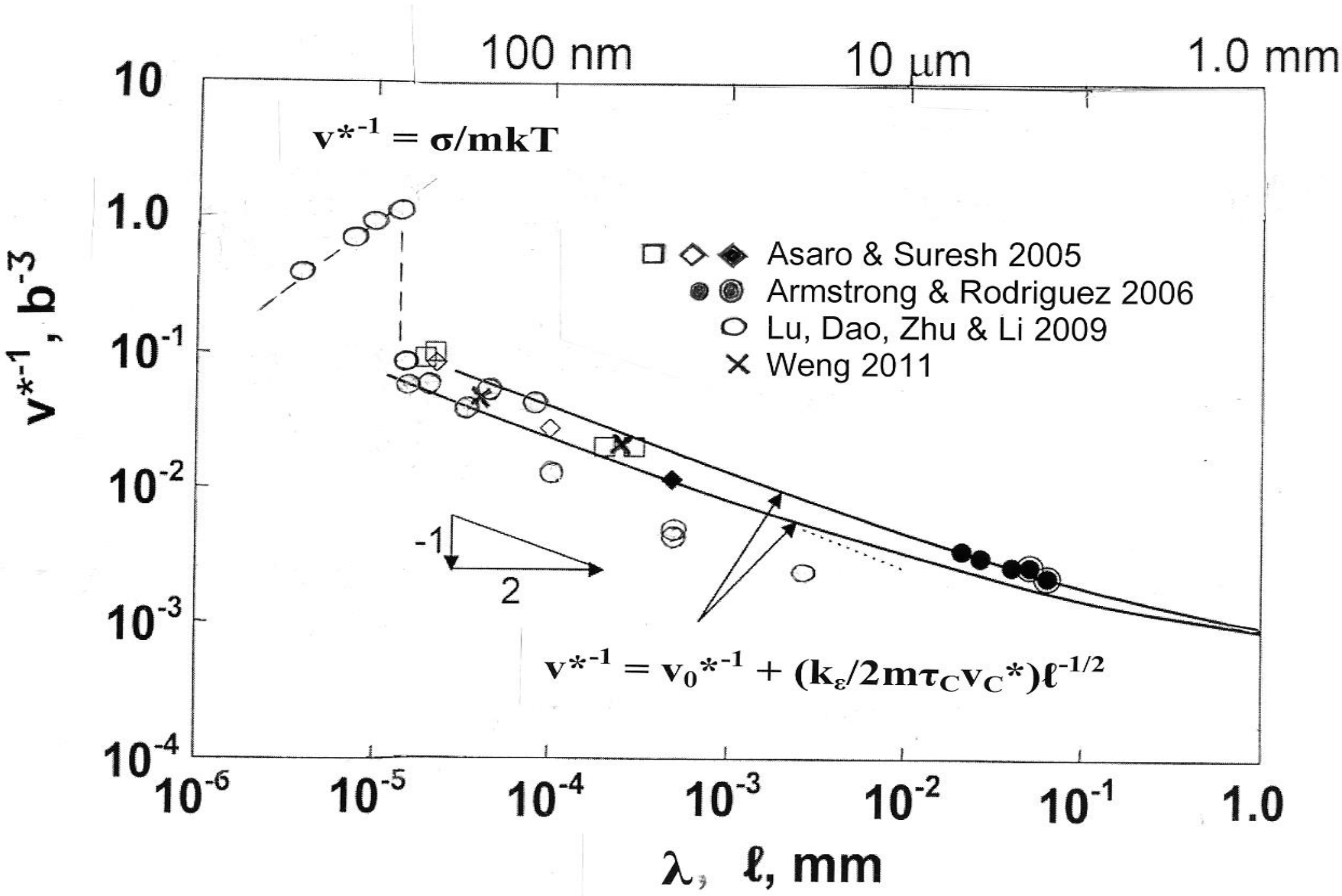
R.W. Armstrong, “Hall-Petch analysis: Past to present nano-scale connections”, in ***Strength of Fine Grained Materials – 60 Years of Hall-Petch***, *(Japan) Mater. Trans.* (2014)

Limiting H-P relation for one dislocation loop and H-P application for twin boundaries in copper



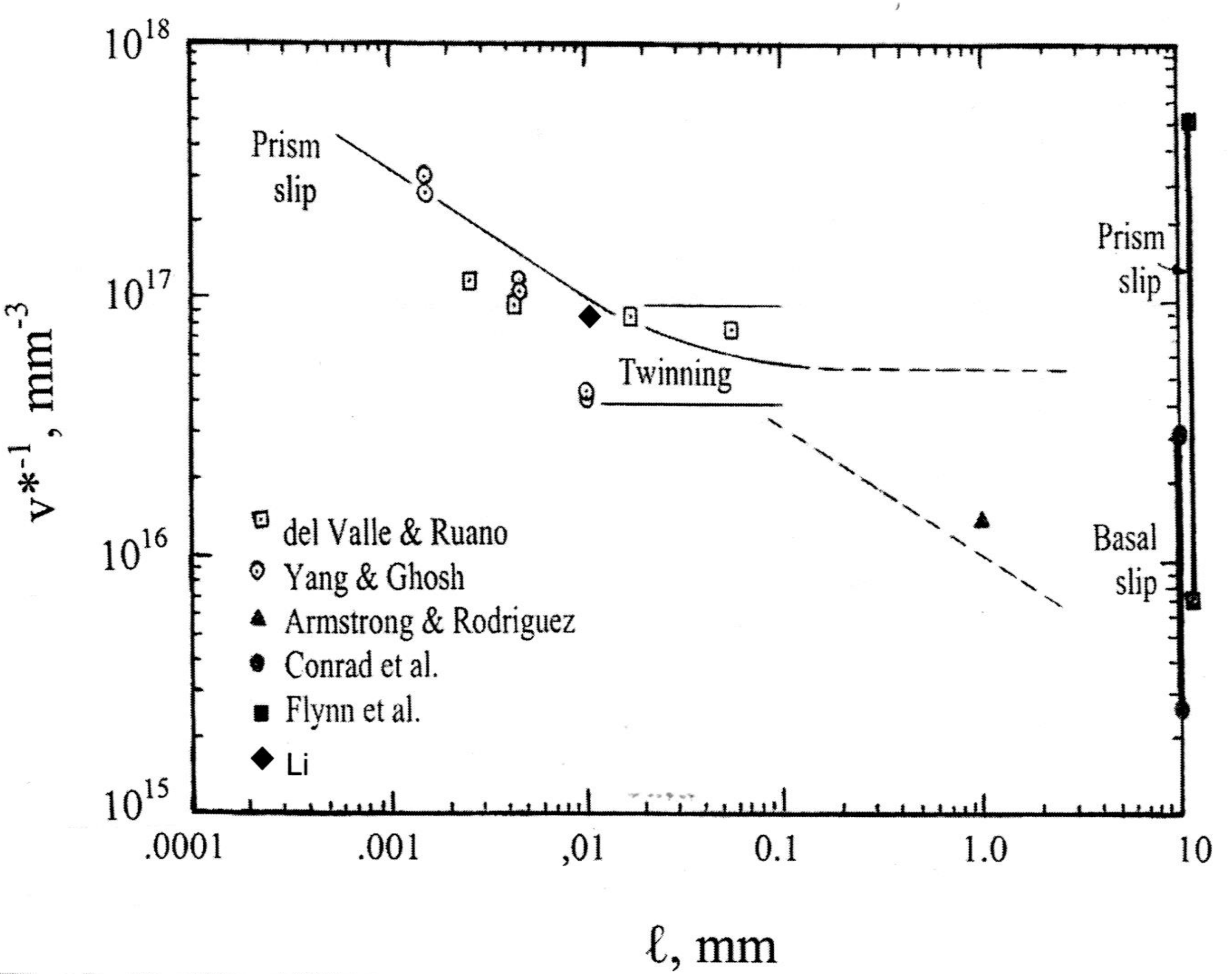
R.W. Armstrong, “60 Years of Hall-Petch: Past to Present Nano-Scale Connections”, *(Japan) Mater. Trans*., 55, [1], 2-12 (2014).

H-P description of Cu and Ni strain rate sensitivity, $v^* = kT\{\partial \ln[d\gamma/dt]/\partial\tau\}_T$



R.W. Armstrong and P. Rodriguez, *Philos. Mag*. **86**, 5787-5796 (2006); R.W. Armstrong, In: ***Strength of Fine Grained Materials – 60 Years of Hall-Petch***, *Mater. Trans*. **55**, 2-12 (2014).

Log/log grain size dependence of v* for Mg



R.W. Armstrong, In: *Nanometals – Status and Perspective*, 33rd Risoe Intern. Symp. On Mater. Sci. (Technical University of Denmark, Roskilde, DK, 2012) pp. 181-199; Q. Li, *Mater. Sci. Eng. A*, **540**, 130-134 (2012)

SUMMARY

1. Dislocation dynamics results were described on the basis of the thermal activation – strain rate analysis and the Z-A equations (1973, 1987,1999).

2. Dislocation pile-up avalanches are proposed to provide a fundamental explanation of shear banding behavior (1981/2,1993/4).

3. Modeling of shock-induced deformations places emphasis on dislocation generations (1992, 2009).

4. Shockless Isentropic Compression Experiments are explained in terms of dislocation drag (ICEs, 2006/7).

5. Hall-Petch results were demonstrated for nanopolycrystalline materials (1962, 1969/70, 2006).