A modified Follansbee-Kocks model for 6061-T6 aluminum

Anup Bhawalkar and Biswajit Banerjee

Department of Mechanical Engineering, University of Utah

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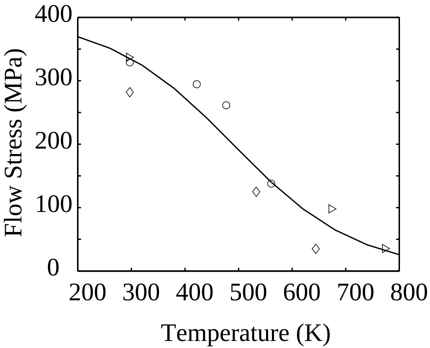
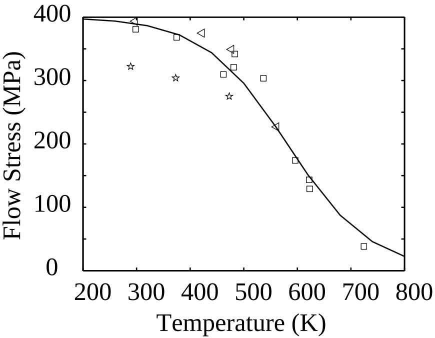
Outline

Temperature Dependence

Strain-Rate = 0.001 /s.



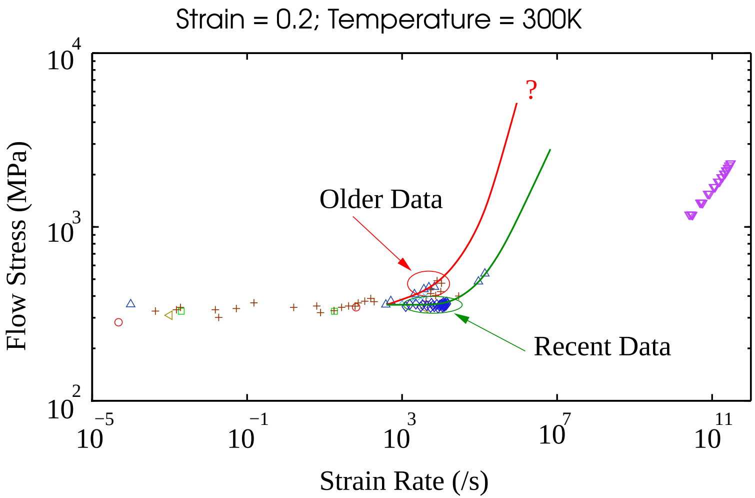
Strain-Rate = 1000 /s.



Sigmoidal curves?

For sources of data see Anup Bhawalkar's M.S. Thesis.

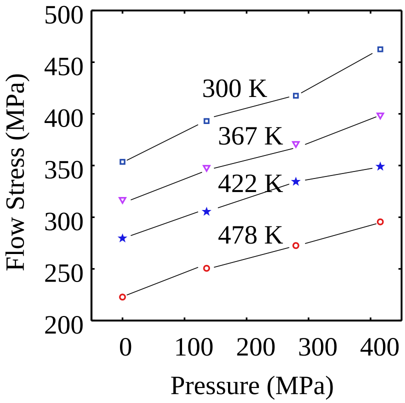
Strain-Rate Dependence



High temperature data?

Pressure Dependence

Strain Rate = 0.001/s; Plastic Strain = 0.05



High strain rate data?

Experimental data from Davidson, 1973

Can a single flow stress model predict all these behaviors?

Older Models

- Steinberg, Cochran, Guinan (1980), Steinberg and Lund (1989).
- Johnson and Cook (1983, 1985), Johnson and Holmquist (1988).
- Zerilli and Armstrong (1987, 1993), Abed and Voyidajis (2005).

Different regimes need different sets of parameters.

More Recent Models

- Mechanical Threshold Stress Model - Follansbee and Kocks (1988), Goto et al. (2000).
- Preston, Tonks, Wallace (2003).

Physically based to some extent. May be possible to extend so that the same parameters can be used for a large domain of regimes.

Original Follansbee-Kocks Model

$$\sigma_y(\sigma_e, \dot{\varepsilon}, p, T) = [\tau_a + \tau_i(\dot{\varepsilon}, T) + \tau_e(\sigma_e, \dot{\varepsilon}, T)]\,\frac{\mu(p, T)}{\mu_0} \quad (1)$$

where

σ_e = an evolving internal variable that has units of stress (also called the mechanical threshold stress)
$\dot{\varepsilon}$ = the strain rate
p = the pressure
T = the temperature
τ_a = the athermal component of the flow stress
τ_i = the intrinsic component of the flow stress due to barriers to thermally activated dislocation motion
τ_e = the component of the flow stress due to structure evolution (e.g., strain hardening)
μ = the shear modulus
μ_0 = a reference shear modulus at 0 K and ambient pressure.

Assumptions in Original Model

- Thermally activated dislocation motion dominant and viscous drag effects on dislocation motion are small.
    - This assumption restricts the model to strain rates of 10^4 s^{-1} and less.
- High temperature diffusion effects (such as solute diffusion from inside grains to grain boundaries) are absent.
    - This assumption limits the range of applicability of the model to temperatures less than around 0.6 T_m. For 6061-T6 aluminum alloy this temperature is approximately 450 - 500 K.

The Modified Follansbee-Kocks Model

A Simple Modification

$$\sigma_y(\sigma_e, \dot{\varepsilon}, p, T) = [\tau_a + \tau_i(\dot{\varepsilon}, T) + \tau_e(\sigma_e, \dot{\varepsilon}, T)] \frac{\mu(p, T)}{\mu_0}$$

Since hardening is relatively small we can

- Try to get the correct temperature dependence of μ and τ_i.
- Add a viscous terms that can account for viscous drag.
- Include a modification for overdriven shocks *a la* Preston-Tonks-Wallace.

to get

$$\sigma_y = \begin{cases} \min\left\{\left[\tau_v + (\tau_a + \tau_i + \tau_e)\frac{\mu}{\mu_0}\right] \quad , \quad \sigma_{ys}\right\} & \text{for} \quad T < T_m \\ \mu_v \; \dot{\varepsilon} & \text{for} \quad T \geq T_m \end{cases} \qquad (2)$$

A Model for the Shear Modulus

Temperature dependence from Nadal and LePoac (2003) and pressure dependence from Burakovsky and Preston (2005).

$$\mu(p,T) = \frac{1}{\mathcal{J}(\widehat{T},\zeta)}\left[\left\{\mu_0 + p\,\frac{\partial \mu}{\partial p}\left(\frac{a_1}{\eta^{1/3}} + \frac{a_2}{\eta^{2/3}} + \frac{a_3}{\eta}\right)\right\}(1-\widehat{T}) + \frac{\rho}{C\,M}\,k_b\,T\right] \tag{3}$$

$$\eta := \frac{\rho}{\rho_0}\,;\quad C := \frac{(6\pi^2)^{2/3}}{3} f^2\,;\quad \widehat{T} := \frac{T}{T_m}$$

$$\mathcal{J}(\widehat{T},\zeta) := 1 + \exp\left[-\frac{1+1/\zeta}{1+\zeta/(1-\widehat{T})}\right] \quad \text{for} \quad \widehat{T} \in [0, 1+\zeta]\,.$$

A Model for the Melt Temperature

The Burakovsky-Greeff-Preston model (2003):

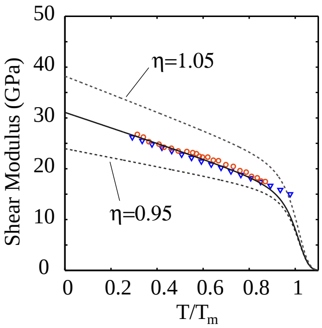
$$T_m(\rho) = T_{m0}\,\eta^{1/3}\,\exp\left\{6\Gamma_1\left(\frac{1}{\rho_0^{1/3}} - \frac{1}{\rho^{1/3}}\right) + \frac{2\Gamma_2}{q}\left(\frac{1}{\rho_0^{q}} - \frac{1}{\rho^{q}}\right)\right\}\,. \quad (4)$$

$$\eta := \frac{\rho}{\rho_0}$$

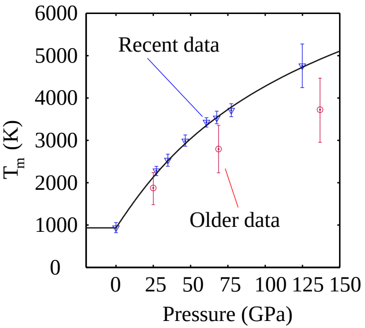
$$\Gamma(\rho) = \frac{1}{2} + \frac{\Gamma_1}{\rho^{1/3}} + \frac{\Gamma_2}{\rho^{q}}$$

Model Checks

Shear Modulus



Melt Temperature



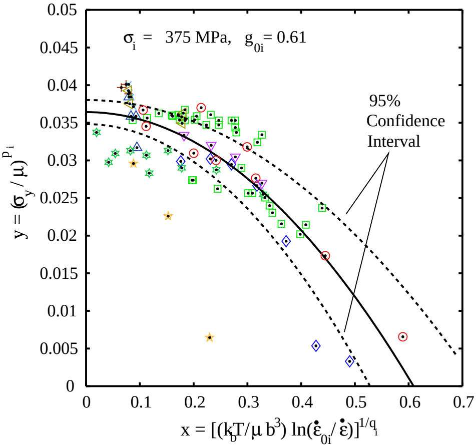
Models do reasonably well.

A Model for τ_i

Use a quadratic model to allow for rapid decrease in τ_i at high temperatures:

$$\tau_i = \sigma_i \left[1 - \left\{\left(\frac{k_b\, T}{g_{0i}\, b^3\, \mu(p,T)} \ln \frac{\dot{\varepsilon}_{0i}}{\dot{\varepsilon}}\right)^{1/q_i}\right\}^2\right]^{1/p_i} . \qquad (5)$$

Fit Parameters for τ_i



A Model for the Viscous Drag

Use ideas from Kumar and Kumble (1969) and Frost and Ashby (1971).

$$\tau_V = \frac{2}{\sqrt{3}} \frac{B}{\rho_m \, b^2} \, \dot{\varepsilon} \qquad (6)$$

Need to find drag coefficient B and the density of mobile dislocations ρ_m.

The Drag Coefficient

Assume that

$$B = B_e + B_p$$

where B_e = electron drag, B_p = phonon drag. Neglect B_e for temperatures greater than 50 K.

$$B \approx \lambda_p\, B_p = \frac{\lambda_p\, q}{10\, c_s} \langle E \rangle \qquad (7)$$

where q = cross-section of dislocation core, c_s = shear wave speed, and

$$\langle E \rangle = \frac{3\, k_b\, T\, \rho}{M} D_3 \left(\frac{\theta_D}{T}\right) \; ; \; \theta_D = \frac{h\, \bar{c}}{k_b} \left(\frac{3\, \rho}{4\, \pi\, M}\right)^{1/3}$$

Mobile Dislocation Density

Use simple model developed by Estrin and Kubin (1986) ?

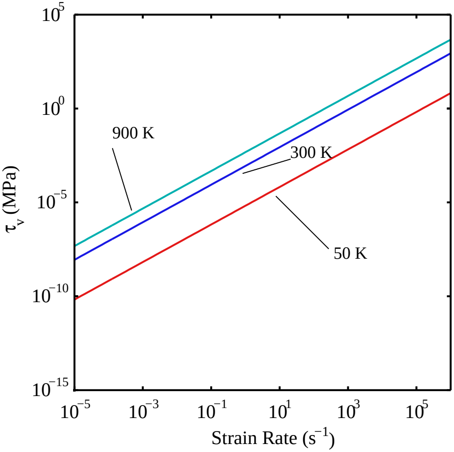
$$\begin{aligned} \frac{d\rho_m}{d\varepsilon_p} &= \frac{M_1}{b^2}\left(\frac{\rho_f}{\rho_m}\right) - I_2(\dot{\varepsilon}, T)\ \rho_m - \frac{I_3}{b}\sqrt{\rho_f} \\ \frac{d\rho_f}{d\varepsilon_p} &= I_2(\dot{\varepsilon}, T)\ \rho_m + \frac{I_3}{b}\sqrt{\rho_f} - A_4(\dot{\varepsilon}, T)\ \rho_f \end{aligned} \tag{8}$$

Stiff differential equations!

A model that works for our purposes is

$$\rho_m \approx \rho_{m0}(1 + \widehat{T})^m\ . \tag{9}$$

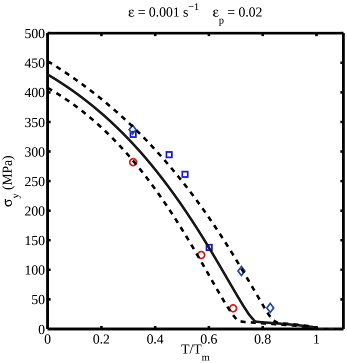
Check Viscous Drag Model



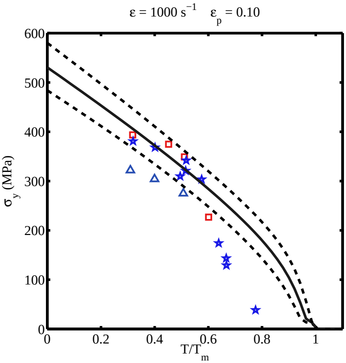
How well does our model do ?

Temperature Dependence

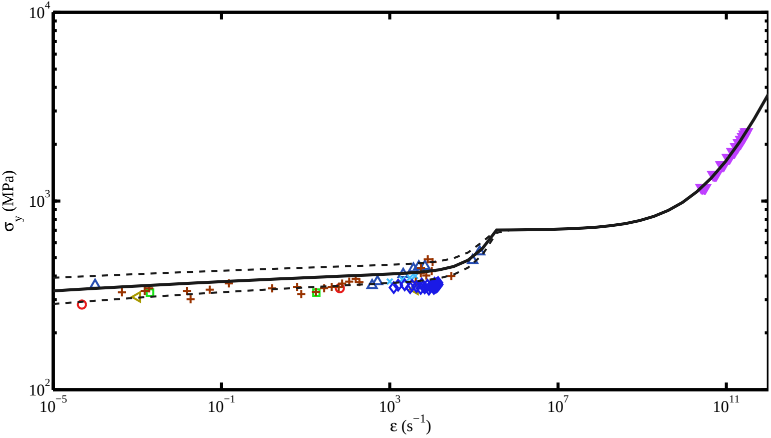
Strain-Rate = 0.001 /s.



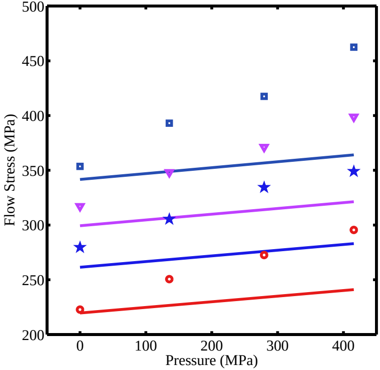
Strain-Rate = 1000 /s.



Strain Rate Dependence

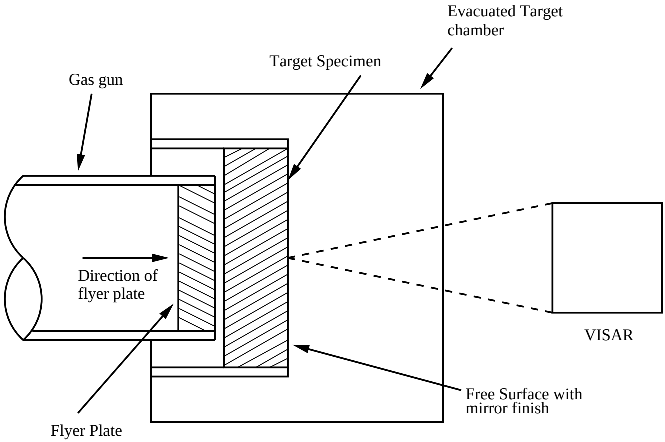


Pressure Dependence



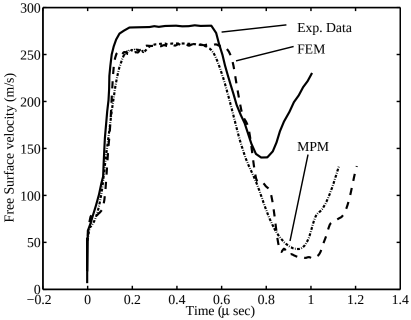
Numerical validation of the model

Flyer Plate Impact

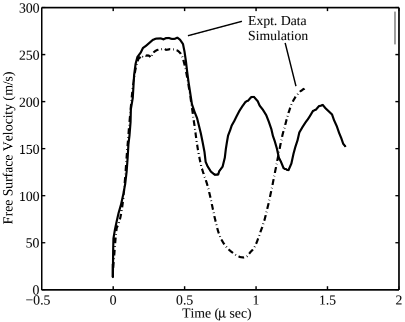


Flyer Plate Simulations

h_i = 1.879 mm, h_f = 3.124 mm, v_0 = 270 m/s.

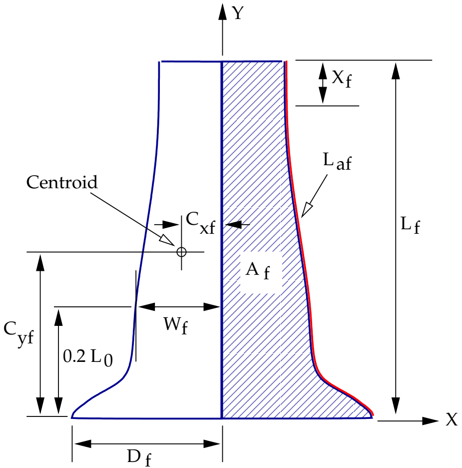


h_i = 1.600 mm, h_f = 3.073 mm, v_0 = 265 m/s.

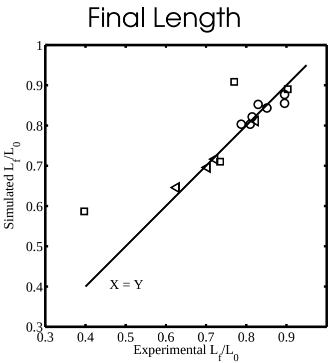


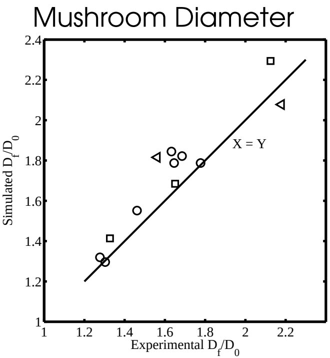
Experimental data from Isbell (2005).

Taylor Impact Tests



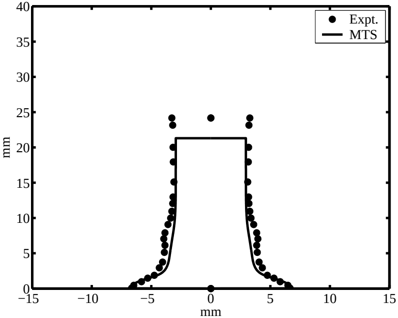
Comparison of Metrics



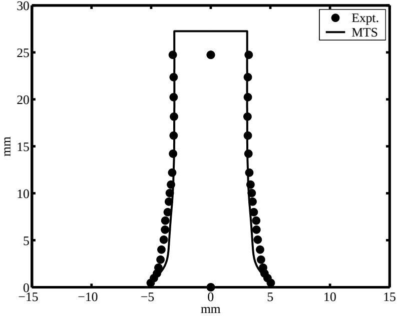


Comparison of Profiles

l_0 = 30.00 mm, l_0 = 6.00 mm, l_0 = 358 m/s, T_0 = 295 K



l_0 = 30.00 mm, d_0 = 6.00 mm, v_0 = 194 m/s, T_0 = 635 K



Experimental data from Gust (1982).

Summary

- Improved high temperature prediction.
- Improved strain rate dependence at high rates.
- Pressure dependence cannot be solely from shear modulus.

For Further Reading I

B. Banerjee and A. Bhawalkar.
An extended Mechanical Threshold Stress plasticity model: modeling 6061-T6 aluminum alloy.
under review, 2007.

A. Bhawalkar,
The Mechanical Threshold Stress Plasticity Model for 6061-T6 aluminum alloy and its numerical validation
M.S. Thesis, University of Utah, 2006.