MODELING MECHANICAL RESPONSE OF METALS AT LARGE DEFORMATION AND HIGH STRAIN RATE

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BACKGROUND

In 2009, Los Alamos National Laboratory introduced the DTE - Dynamic Tensile Extrusion - to test materials at very high strain rates - large strain in order to make more evident the role of the microstructure on the dynamic material response. Surprisingly, tests on fully annealed 99.97% OFHC copper revealed that the smaller the grain size the larger is the ductility. In this work, advanced constitutive modeling incorporating microstructure evolution was used to simulate the material deformation occurring in the DTE test. Numerical simulations were carried out using implicit finite element code. To support simulation work, additional tests have been performed at the light gas-gun testing facility of the University of Cassino.

CONSTITUTIVE MODEL

Strength model

Modified Voce-Johnson-Cook law

$$\sigma_y\left(\varepsilon_p,\dot{\varepsilon},T\right)=\left[\sigma_y+R_{\infty}\left(1-\exp\left(-b\varepsilon_p\right)\right)\right]\left(1+C\ln\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)\right)\left(1-T^{*m}\right)$$

Damage model

Bonora damage model (1997)

$$dD=\alpha\cdot\frac{D_{cr}^{\frac{1}{\alpha}}}{\ln(\varepsilon_f/\varepsilon_{th})}\cdot R_{\upsilon}\cdot\left(D_{cr}-D\right)^{\frac{\alpha-1}{\alpha}}\cdot\frac{dp}{p}$$

Microstructure model

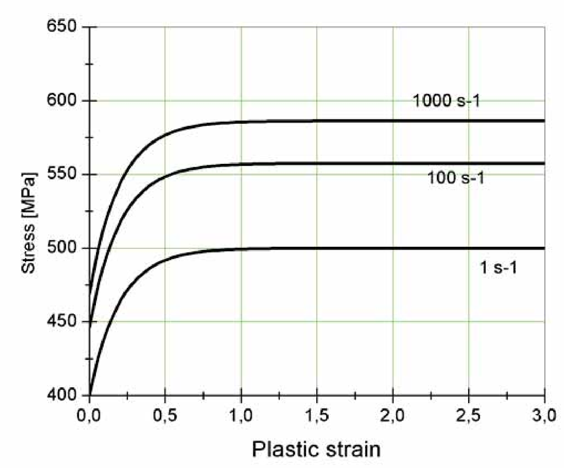
Modified Lin-Liu recrystallization model

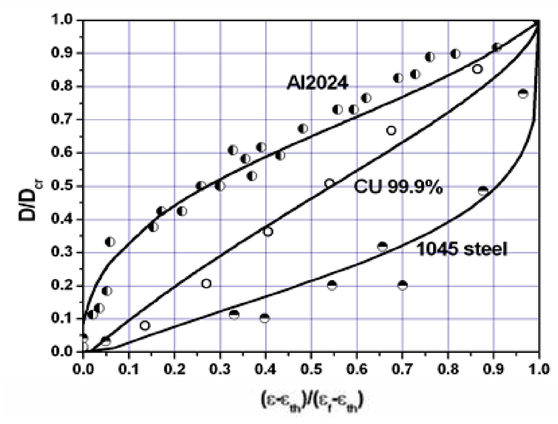
$$\dot{\bar{\rho}}=\left(\frac{d}{d_0}\right)(1-\bar{\rho})\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}-c_1\bar{\rho}^{c_2}-\exp\left(\frac{c_3\bar{\rho}}{1-S}\right)\dot{S}$$ Normalized dislocation density

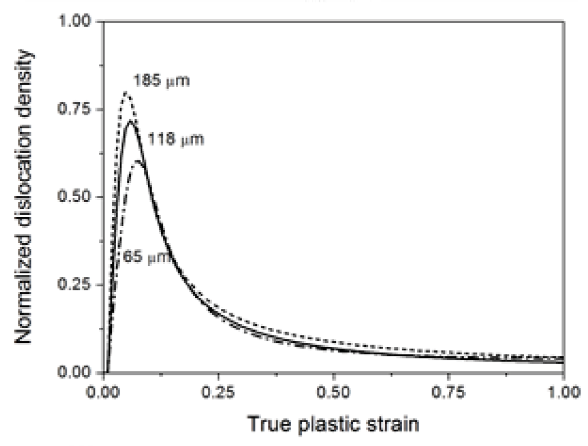
$$\dot{d}=\alpha_0 d^{-\gamma_0}+\alpha_1\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}d^{-\gamma_1}-\alpha_3^m(d-d_f)m\cdot S^{m-1}\cdot\dot{S}$$ Average grain size

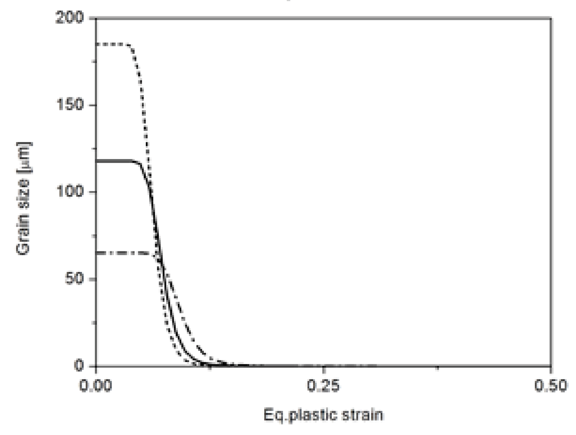
$$\dot{x}=A_0\cdot\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}(1-x)\bar{\rho}$$ Activation term

$$\dot{S}=Q_0\cdot\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\left[x\cdot\bar{\rho}-\bar{\rho}_c\left(1-S\right)\right]\left(1-S\right)^{N_q}$$ Recrystallized volume fraction









Continuum-microstructure coupling

Hall-Petch: yield stress function of grain size

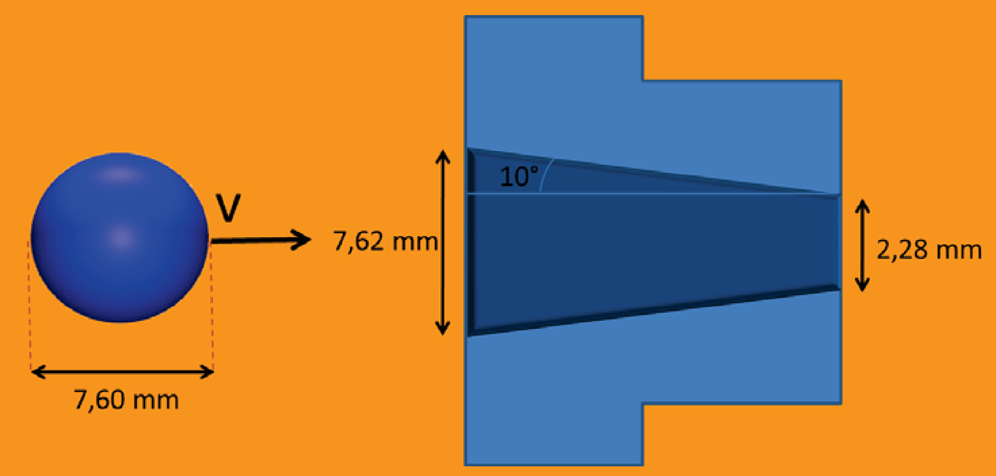
$$\sigma_y=\sigma^*+\frac{\lambda}{\sqrt{d}}$$

Zhao-Li-Jiang: melting temperature function of grain size

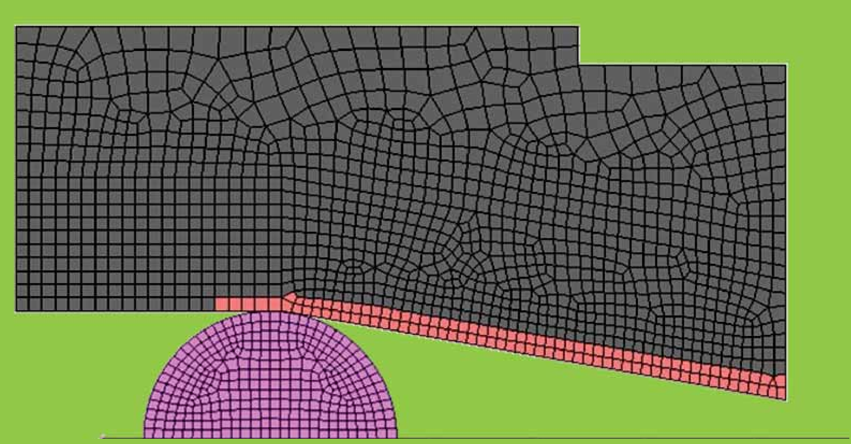
$$\frac{T_m(d)}{T_{m_0}}=\exp\left(-\frac{2}{3}\frac{S_{vib}/R}{d/d_c-1}\right)$$

TEST CONFIGURATION

DTE test consists in launching at high speed a sphere into a conical dime. During the travel, the projectile is subjected to strong pressure and shear waves. As a result, the material is stretched, extruded and ejected while recrystallization occurs reducing the grain size down to the nanoscale. Since the tip is travelling faster than the rear, the jet of material breaks in fragments.

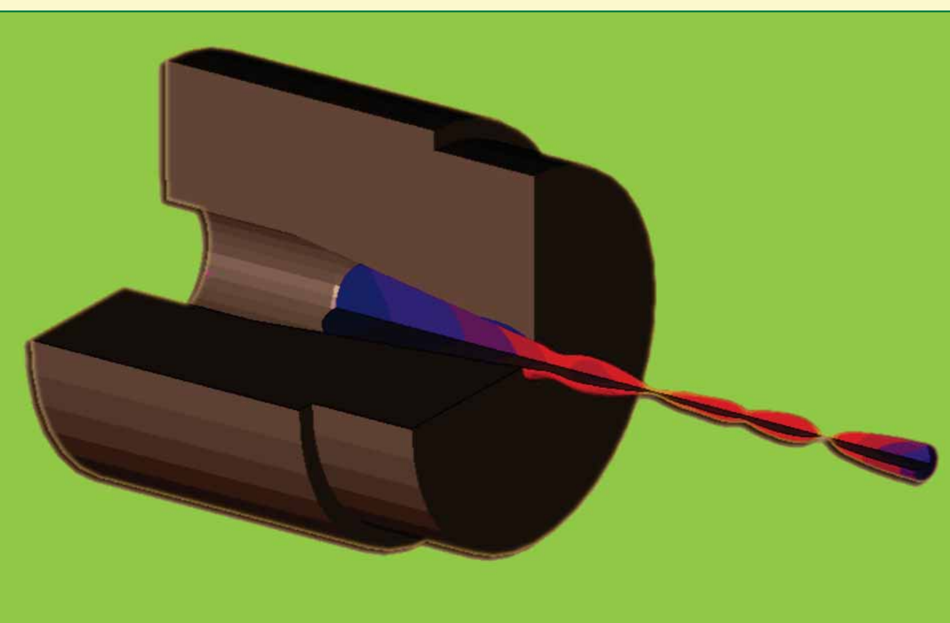


NUMERICAL SIMULATION



FEM model

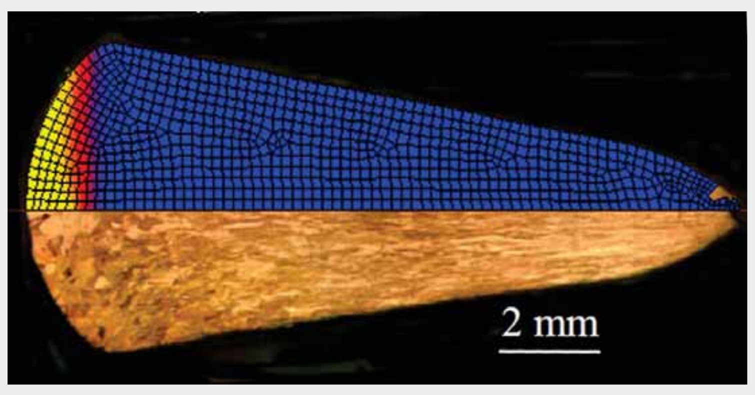
Finite element analyses were performed with MSC.MARC running coupled thermo-mechanical dynamic transient in axisymmetric configuration, with large displacement, finite strain, lagrangian updating. Both the projectile and the dime were simulated as deformable bodies. Dynamic transient was simulated using direct integration solving scheme (Houbolt Operator). Automatic global remeshing was used to avoid excessive element distorsion. Material failure was simulated using element removal technique. Parametric investigation varying the impact velocity and initial grain size in the projectile.



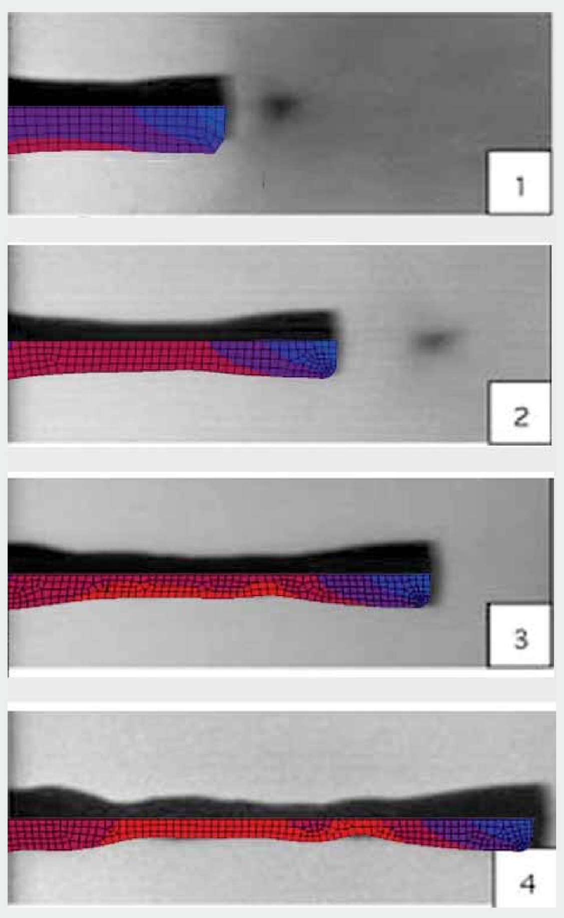
Material Jet formation at the exit of the dime

RESULTS

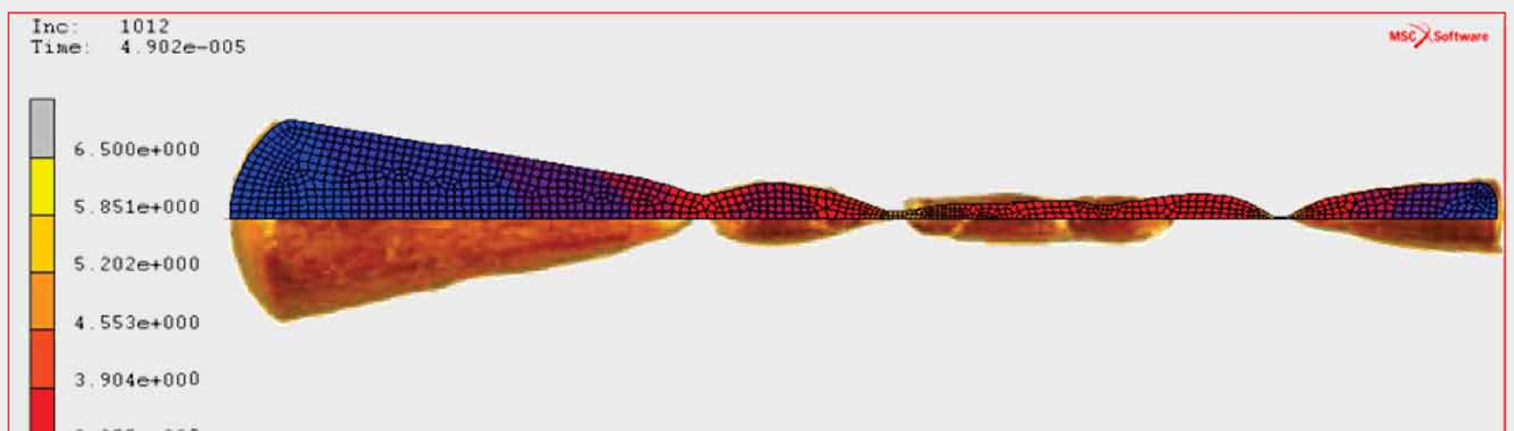
- Very good correlation in terms of time resolved jet shape and final number of fragments and size.
- Accurate prediction of ductility as a function of initial grain size.
- Good agreement of calculated grain size distribution in the deformed fragment remaining into the dime.
- Same good agreement with different projectile geometry (bullet type).



Grain size distribution and model prediction



Comparison of time resolved jet shape. Each frame every 5 μs



Grain size [μm]	Elongation (TEST) [mm]	Elongation (FEM) [mm]	Number of segments (TEST)	Number of segments (FEM)
65	39	40.6	5	5
118	37	37.6	5	5
185	34	35.0	4*	5

Predicted fragment number , size and shape for different initial grain size

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