Laser Compression of Nanocrystalline Tantalum

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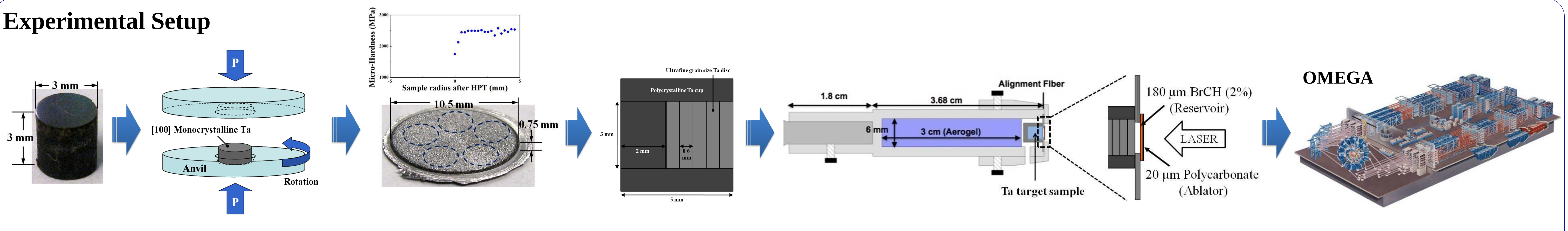
Research Objective

Using Tantalum as a model material, investigate the extreme dynamic response of BCC metals in the National Ignition Facility:

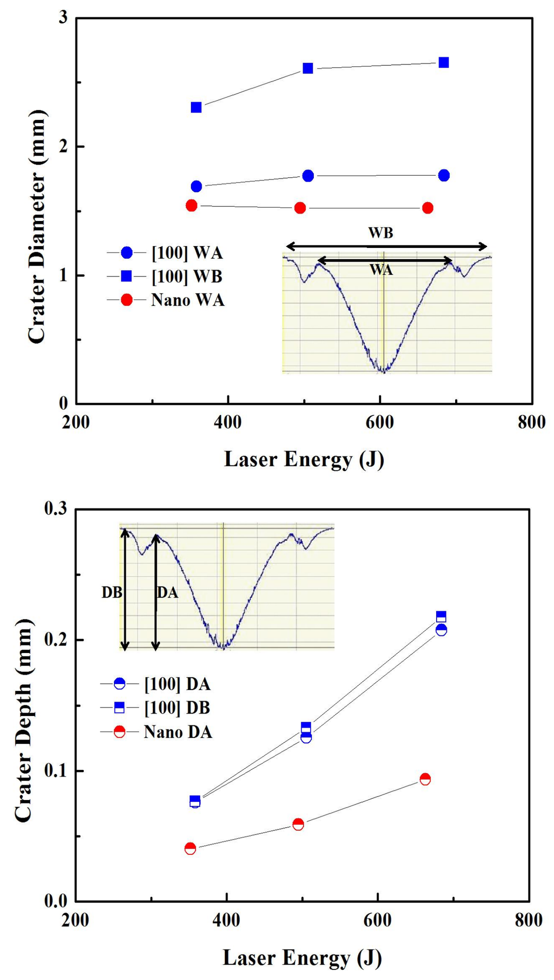
- dislocation configuration and density,
- transition pressure from slip to twinning,
- microstructure and micro-hardness of the target material.

Experimental Setup

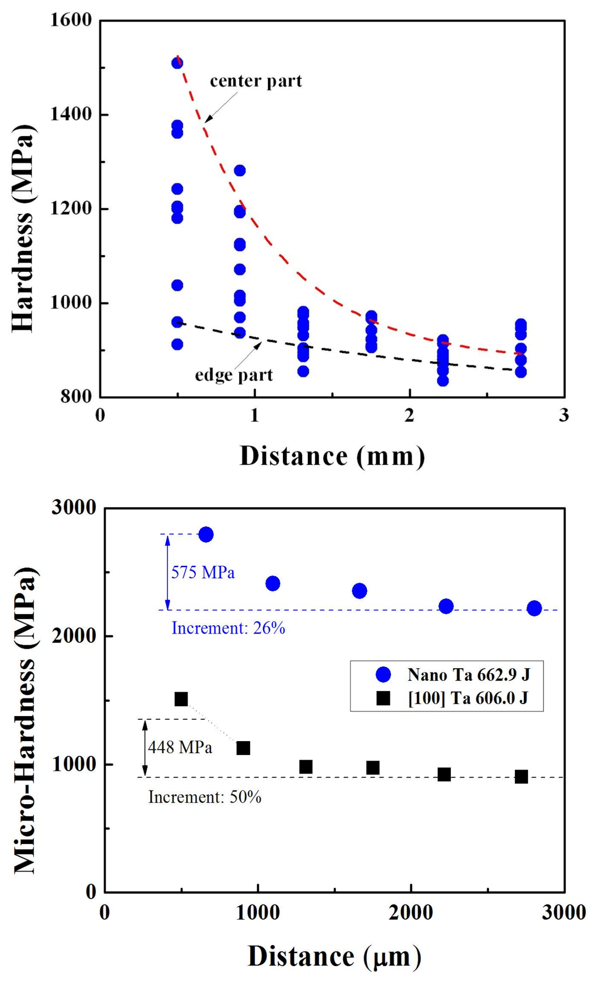


Characterization

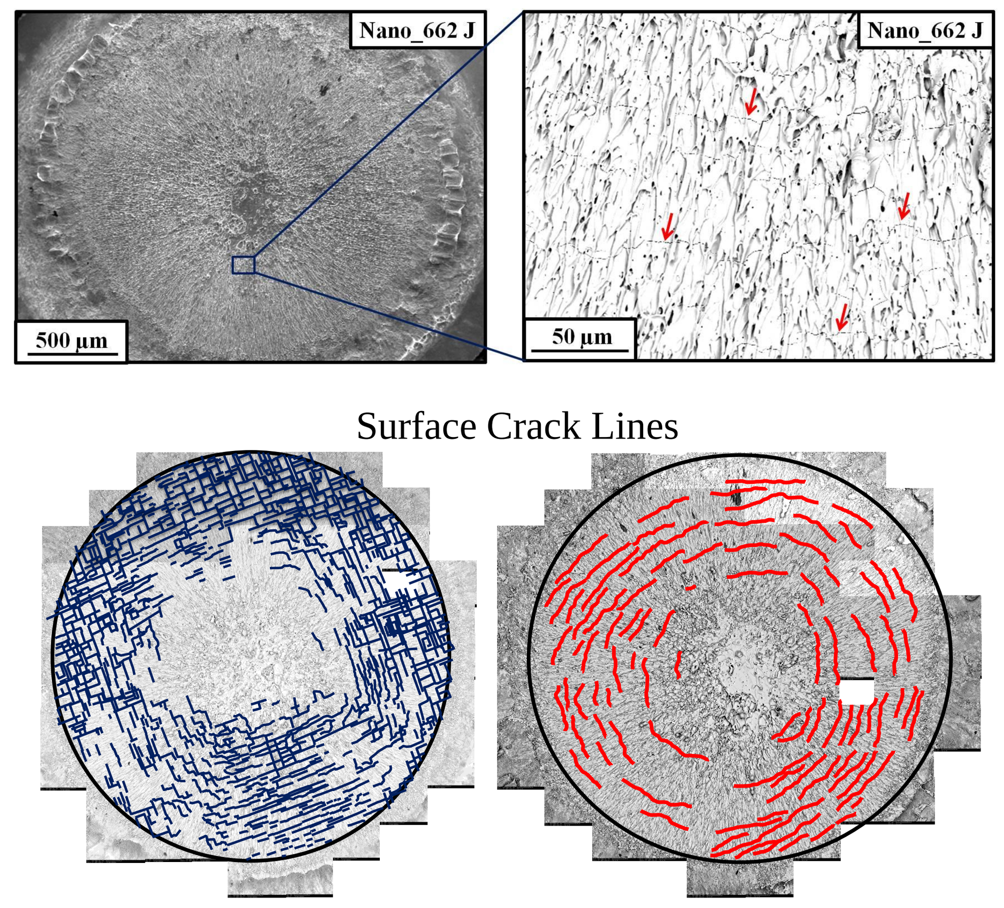
-Profilometry



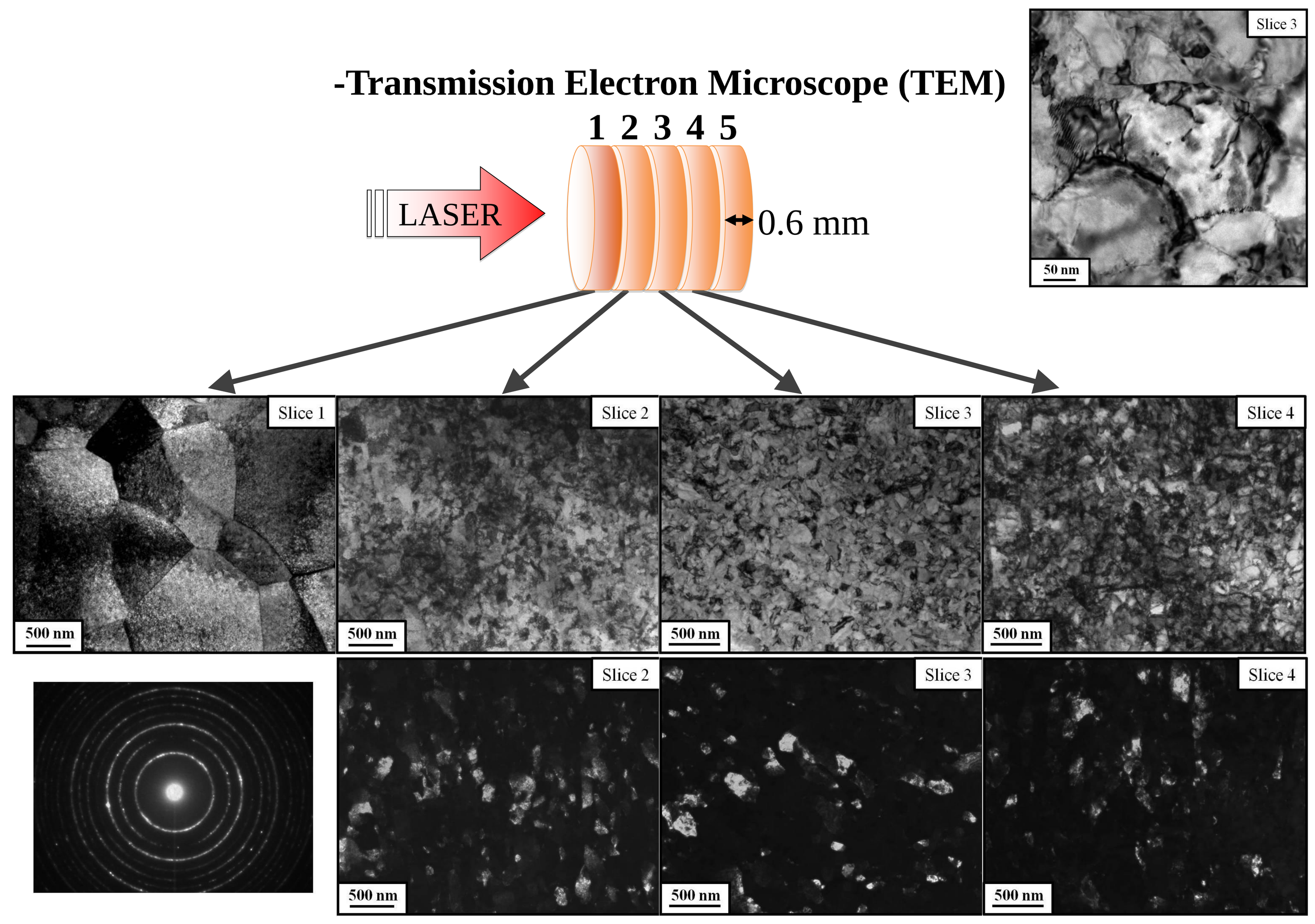
-Microhardness



-Scanning Electron Microscope (SEM)

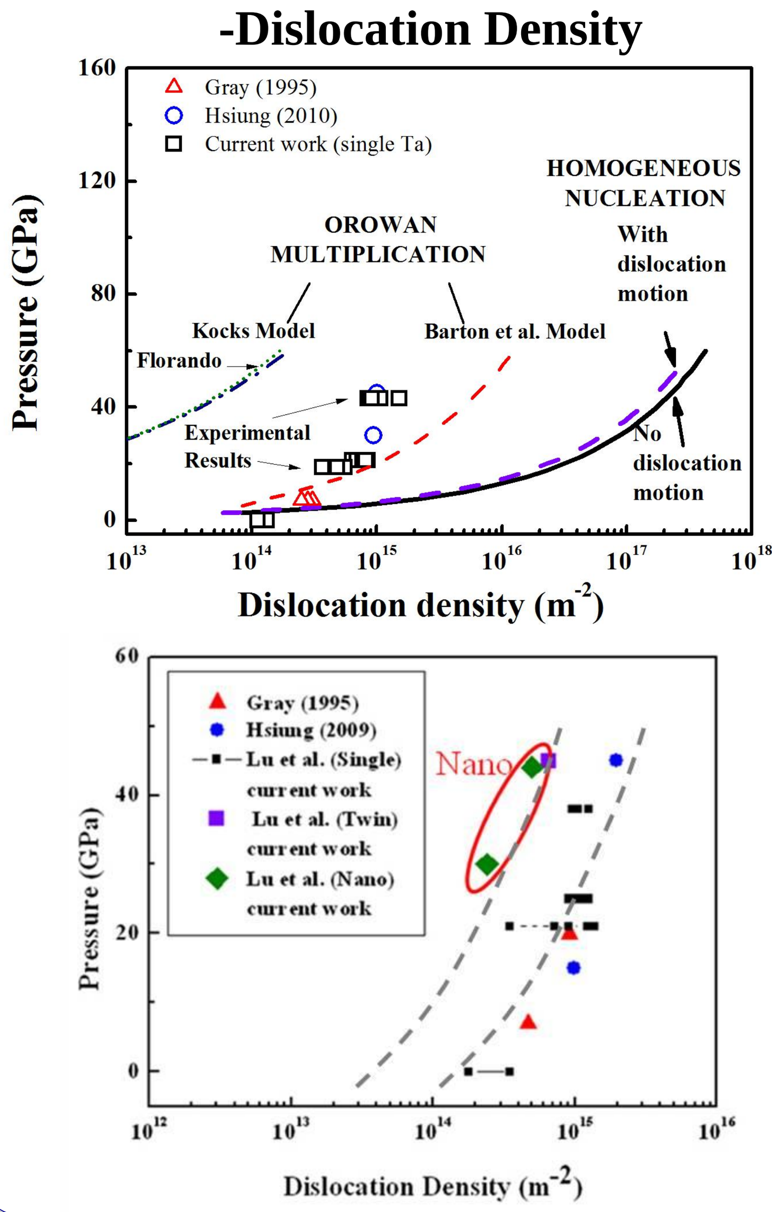


-Transmission Electron Microscope (TEM)



Modeling

-Dislocation Density



-Constitutive Response

Zerilli-Armstrong equation:

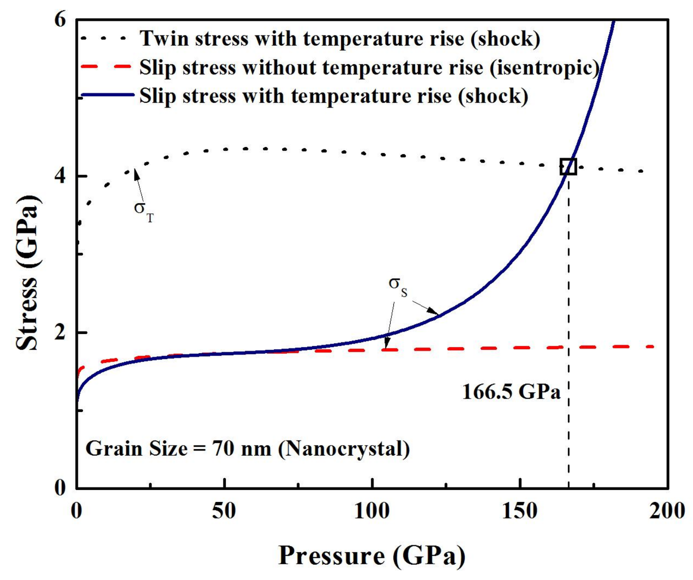
$$\sigma_S = \sigma_s^* + C_2 e^{-C_3 T} \dot{\varepsilon}^{C_4 T} + k_S d^{-1/2}$$

Armstrong-Worthington equation:

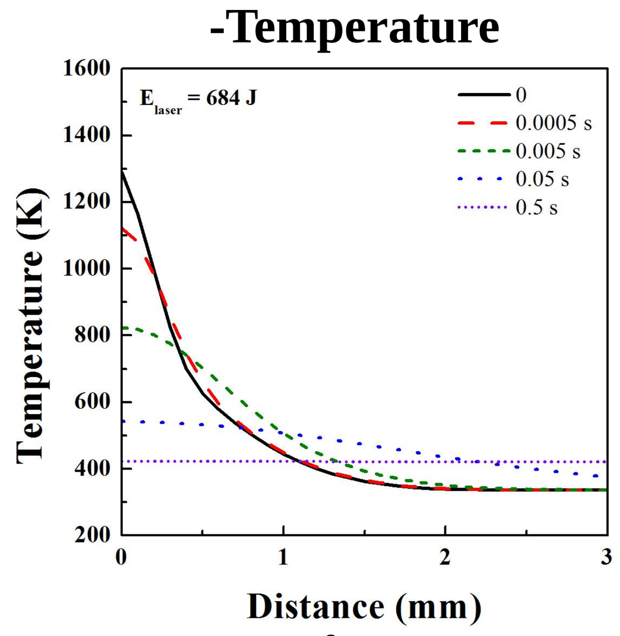
$$\sigma_T = \sigma_0 + m\left(\frac{G(P)b}{C_1}\right)^{1/2}\left[\frac{U^*}{RT}\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]^{1/q} d^{-1/2}$$

Swegle-Grady Relationship:

$$\dot{\varepsilon} = 27.34 P_{Shock}^4$$



-Temperature



Temperature rise function:

$$T_{Shock} = 1.007\times10^{-1} P_{Shock}^2 - 1.13 P_{Shock} + 294.8$$

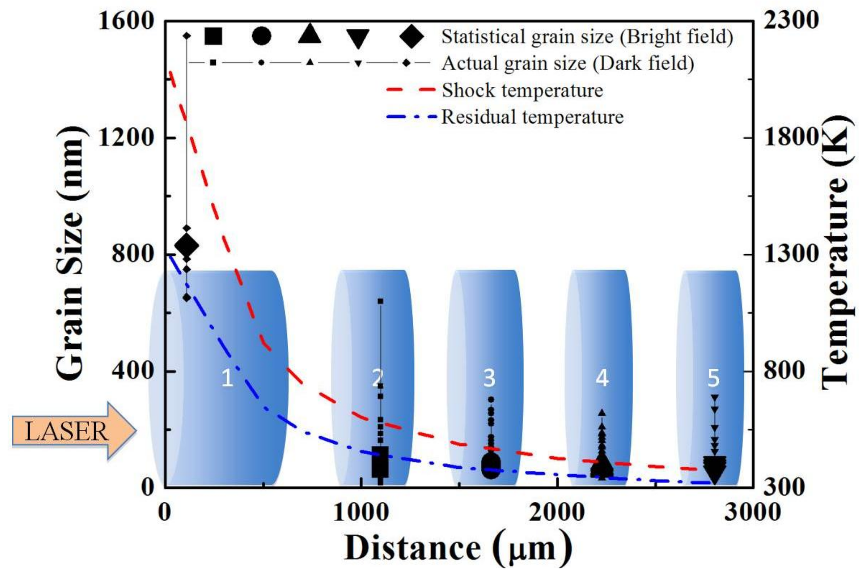
Shock temperature:

$$T_s = T_0 e^{\left(\frac{\gamma_0}{V_0}\right)(V_0 - V)} + \frac{(V_0 - V)}{2C_v}P + \frac{1}{2C_v} e^{\left(-\frac{\gamma_0}{V_0}\right)V} \int_{V_0}^{V} \left(\frac{C_0^2 (V_0 - V)}{[V_0 - S(V_0 - V)]^2}\right) e^{\left[\left(\frac{\gamma_0}{V_0}\right)V\right]} \cdot \left[2 - \left[\left(\frac{\gamma_0}{V_0}\right)(V_0 - V)\right]\right] dV$$

Residual temperature:

$$T_r = T_s \exp\left[\left(-\frac{\gamma_0}{V_0}\right)(V_0 - V)\right]$$

-Grain Size



Heat conduction:

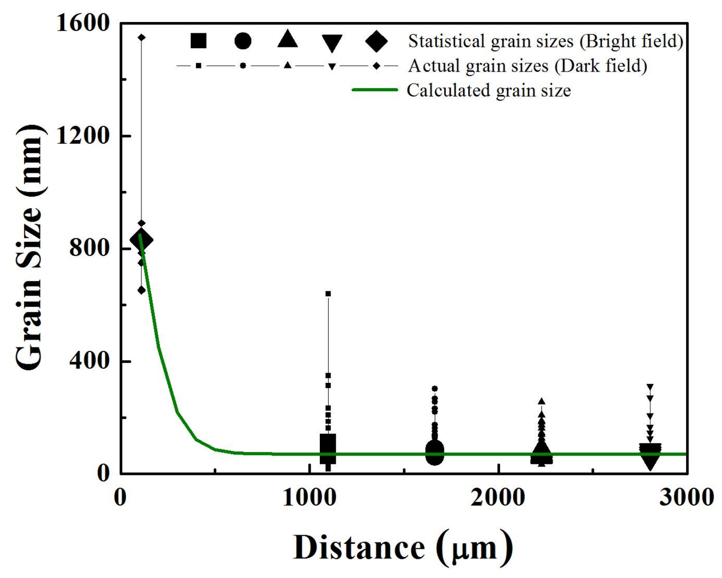
$$T_{i,m+1} = T_{i,m} + \frac{\Delta t}{\rho C \Delta x}\frac{k}{\Delta x}\left(T_{i+1,m} - 2T_{i,m} + T_{i-1,m}\right)$$

Hu-Rath equation:

$$v_{gb} = MF = M_0 \exp\left(-\frac{Q}{kT}\right)\cdot\frac{\gamma_{gb}}{R}$$

Grain size expression:

$$R_f = \left[2M_0\gamma_{gb}\int_0^{\infty}\exp\left(\frac{-Q}{kT(t)}\right)dt + R_0^2\right]^{1/2}$$



Conclusions

- Crater depth increases monotonically with laser energy. Crater depth depends on material strength.
- Surface cracks determined by crystal orientation (mono vs. nano).
- Laser hardening in Nano Ta follows same pattern as in Mono Ta.
- Twinning: present in [100] Mono Ta; absent in Nano Ta. Experiments and modeling agree.
- Dislocation densities in Nano Ta significantly lower than in Mono Ta: ubiquity of sinks in nano Ta (grain boundaries) is major factor.
- The grain size increases close to the energy deposition surface as a result of thermally induced growth: model successfully predicts effect.
- Dislocation activity decreases away from the impact surface in all cases and is in agreement with pressure decay and residual hardness.

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