中国工程物理研究院
流体物理研究所

Investigation of the Temperature Dependence of the Dynamic Yield Stress of BCC Metals Subjected to Shock Loading

Songlin Yao, Xiaoyang Pei, Jidong Yu,

Yuying Yu, Qiang Wu

Institute of Fluid Physics, CAEP

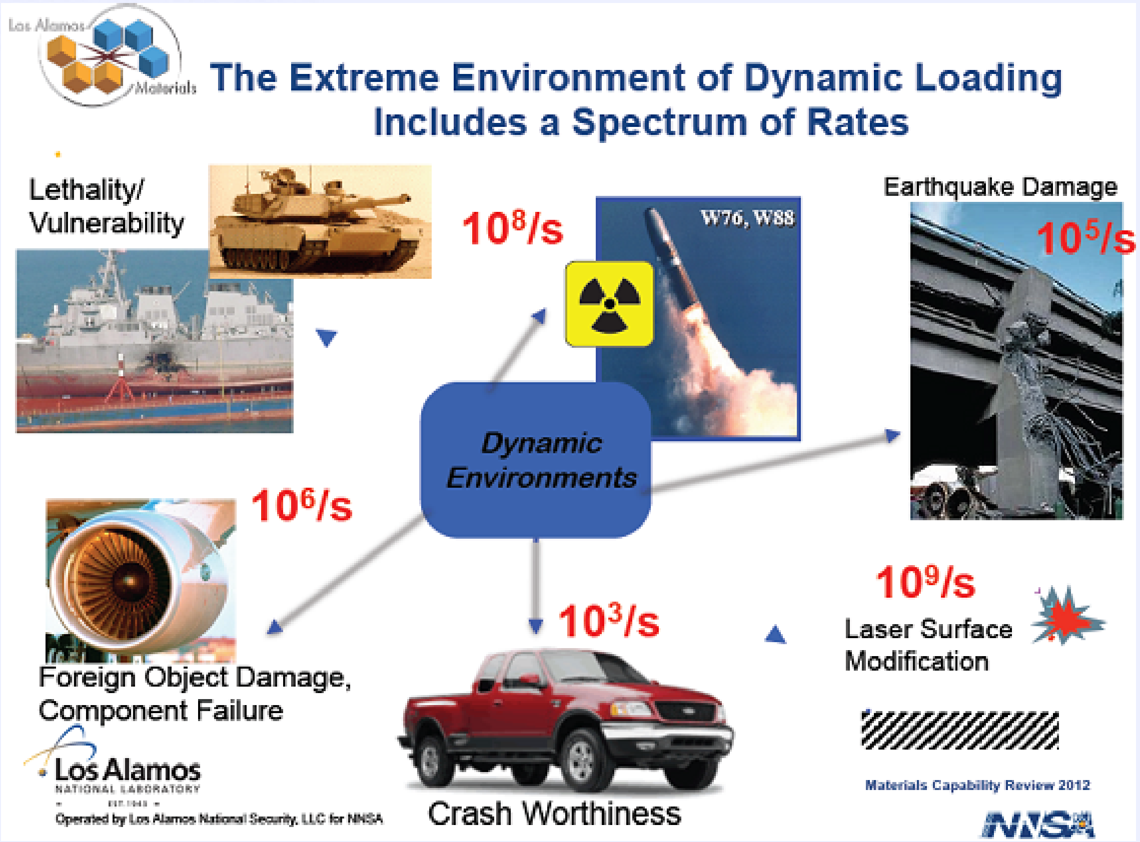
18-22, March, 2019

Outline

- Background
- Dislocation based constitutive model
- Results and Discussions
- Conclusions

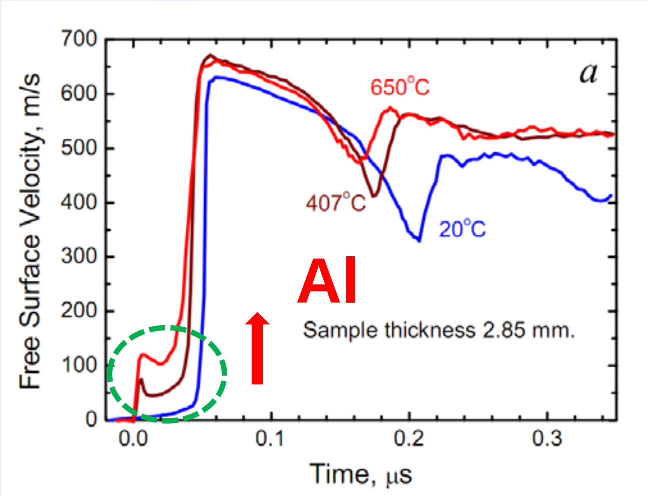
- Background
- Dislocation based constitutive model
- Results and Discussions
- Conclusions

Background

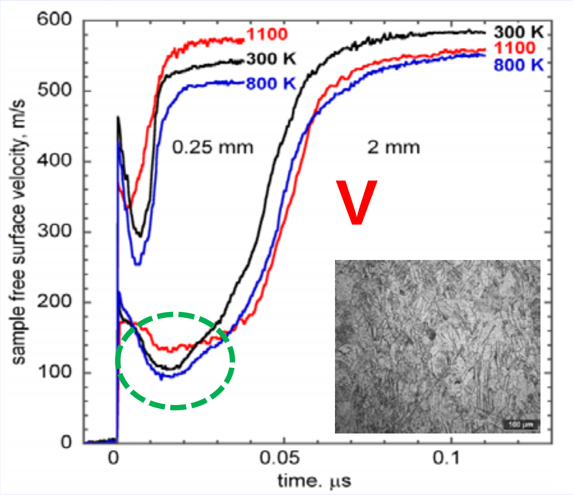


- Study of the dynamic strength of metals plays a central role on shock wave physics research ;
- Dynamic strength is influenced by an amount of factors, including strain rate, **temperature**, and deformation routines etc.

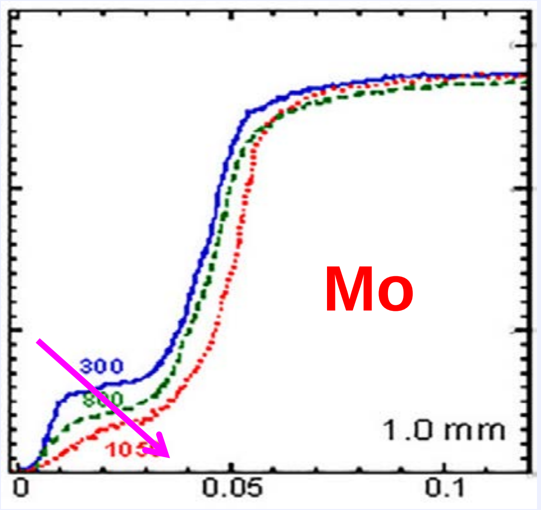
Dynamic strength at elevated temperature



Kanel, JAP, 2001



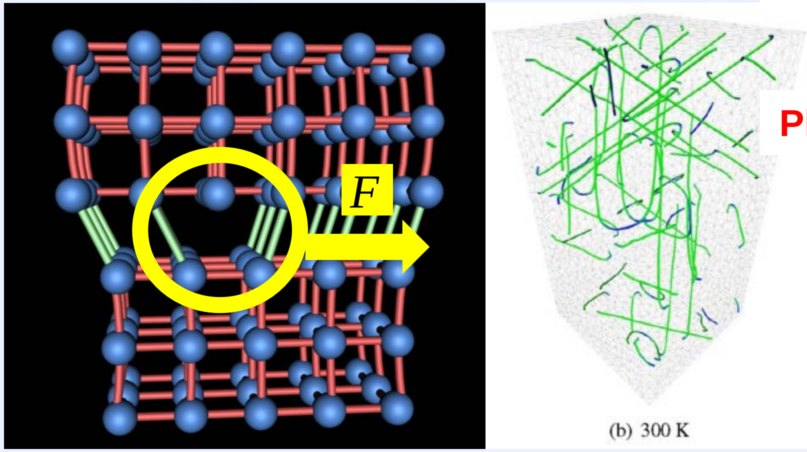
Zaretsky, JAP, 2014

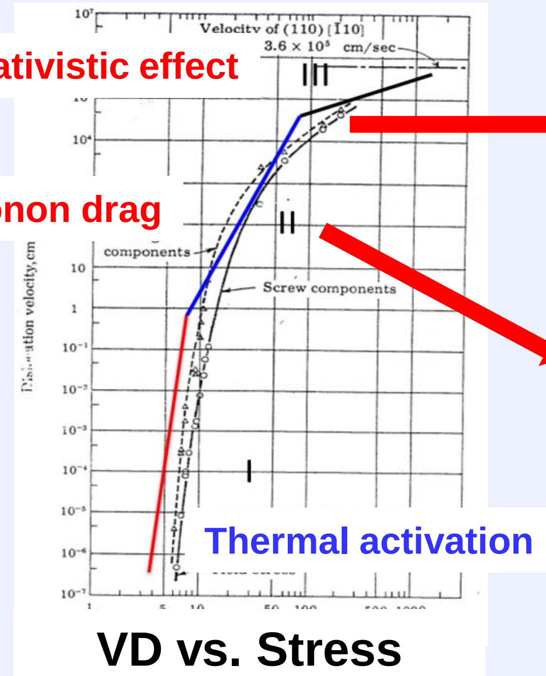


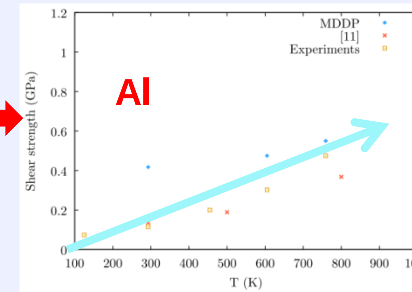
Zaretsky, JAP, 2016

- ☐ Dynamic yield stress of FCC metals increases with increasing temperature;
- ☐ Most BCC metals under shock loading still present thermal softening behaviors except iron and vanadium.

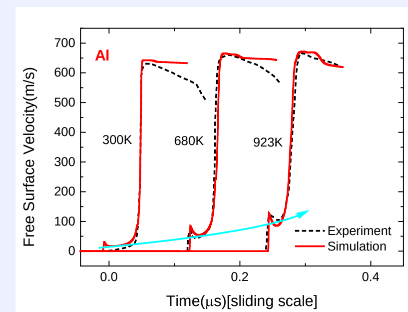
Fundamental origin of strength







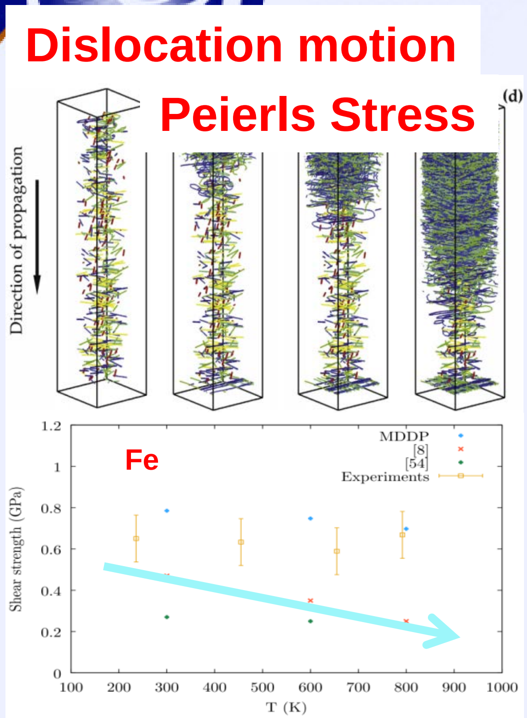
Benat Gurrutxaga-Lerma, IJP, 2017



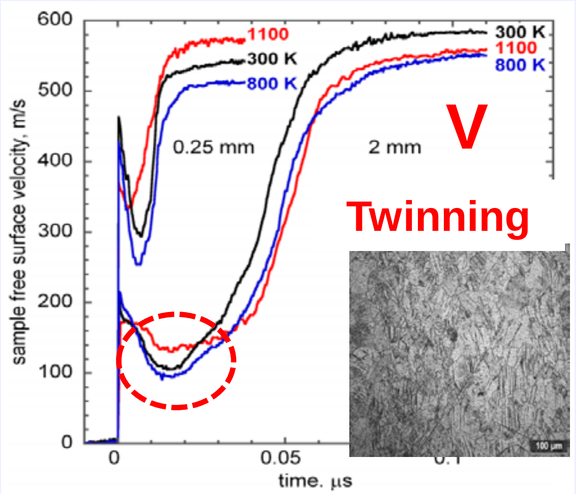
Krasnikov, IJP, 2011

- Fundamental origin of plasticity: Dislocation motion, creation, annihilation, and evolution of twinning;
- Usually, the physical principle of dynamic strength is unravel from the viewpoint of dislocation motion, such as (Krasnikov and Mayer) and (Gurrutxaga-Lerma) .

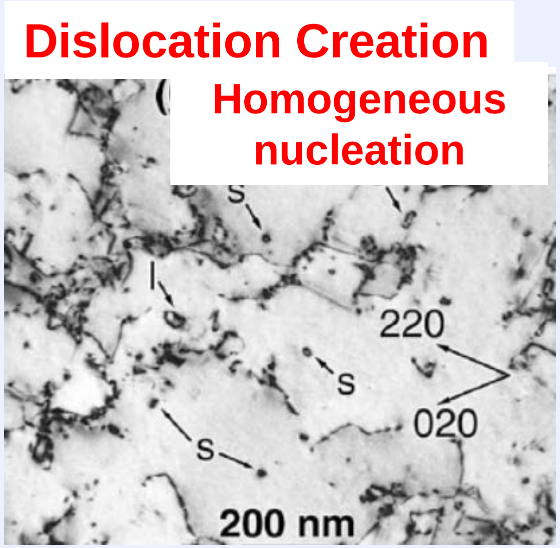
Dynamic strength of BCC metals



Gurrutxaga-Lerma, IJP, 2017



Zaretsky, JAP, 2014

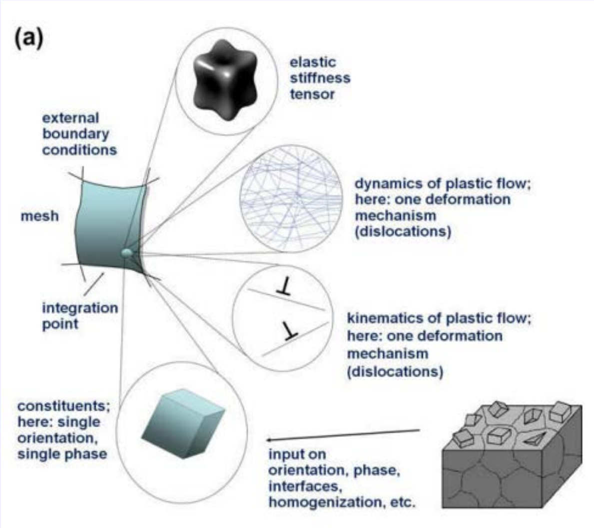


Meyers, 2003, Acta Mater.

- Gurrutxaga-Lerma: Dynamic strength of iron is determined by Peierls stress;
- What about the thermal hardening behavior of vanadium?
- **Twinning and Homogeneous nucleation is not considered in a constitutive model for BCC metals.**
- **Which mechanism dominates the dynamic strength of BCC metals?**

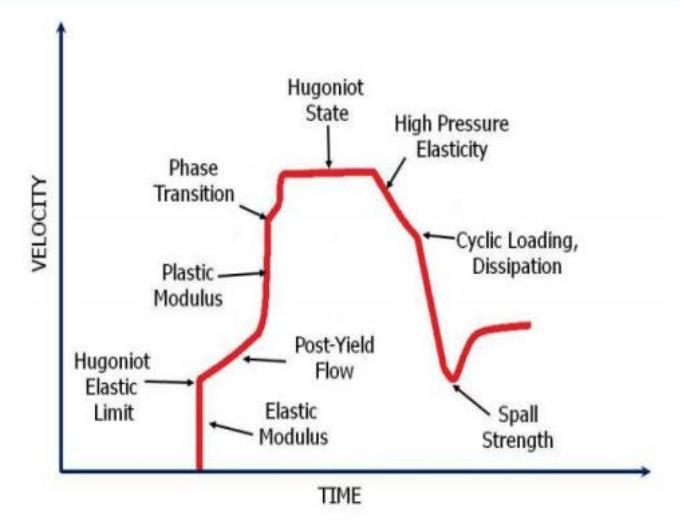
- Background
- Dislocation based constitutive model
- Results and Discussions
- Conclusions

CPFEM



$$\Delta S = 2G\left(\dot{\gamma}_e - \dot{\gamma}_p\right)$$

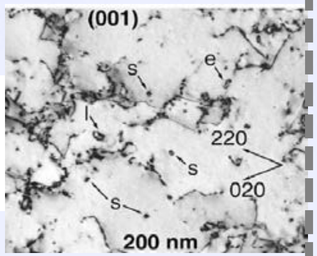
$$\dot{\gamma}_p = \rho_M b V_D + \dot{\rho}_{IM} b \bar{l}$$



- CPFEM can couple the behaviors of dislocations and twinning on meso-scales with the mechanical response on macro-scales.

Dislocation based model

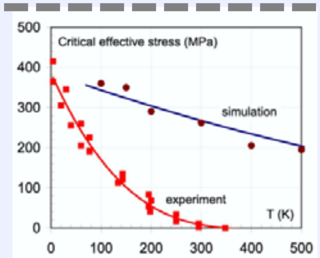
Homogeneous nucleation

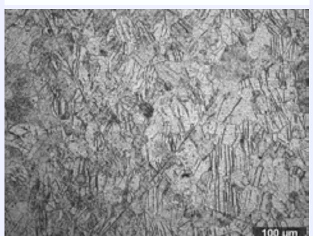


Peierls Stress

Viscosity

Twinning





Dislocation motion

$$V_D = \frac{(\tau - \tau_c)b}{B(T) + B_{vis}} \qquad \tau_c = \tau_p + \tau_{int}, \quad A_I G b \sqrt{\rho_I}$$

Dislocation Density

$$\begin{cases} \dot{\rho}_m = \chi \dot{\rho}_{HN} + \dot{\rho}_{mult} - \dot{\rho}_{anni} - \dot{\rho}_{trap} \\ \dot{\rho}_{im} = (1-\chi)\dot{\rho}_{HN} + \dot{\rho}_{trap} - \dot{\rho}_{anni} \end{cases}$$

Twinning

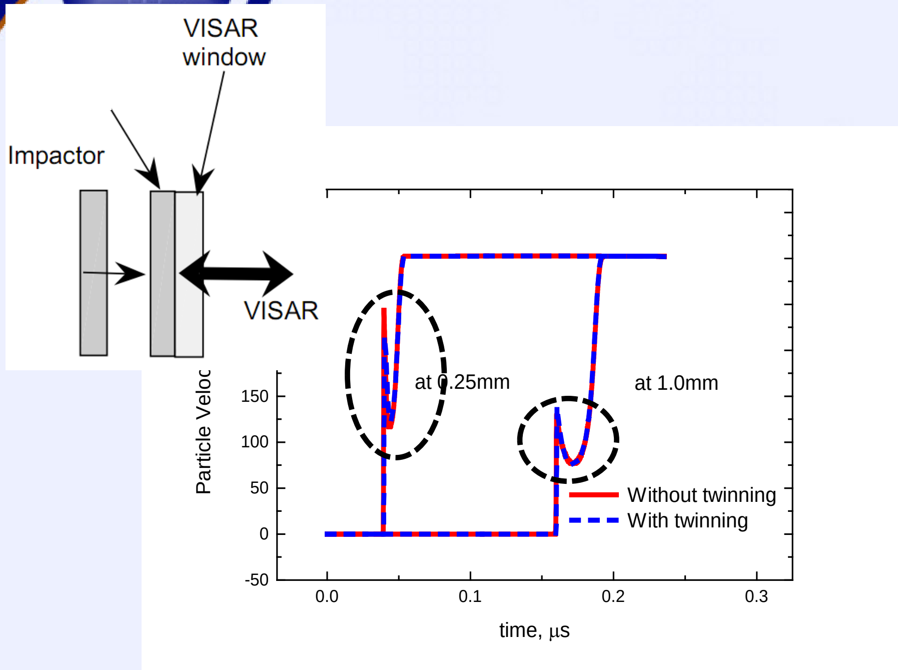
$$\dot{\gamma}_{tw}^{\beta} = \begin{cases} \dot{\gamma}_{tw}^{0} \left(\frac{\tau^{\beta}}{\tau_{tw}} \right)^{1/r}, \tau > \tau_{tw} \\ 0, \tau < \tau_{tw} \end{cases}$$

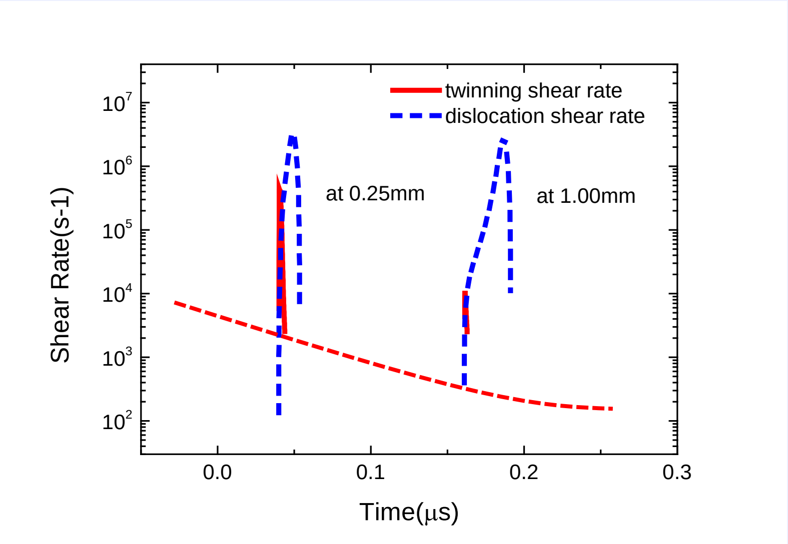
$$\Delta S = -2G\dot{\gamma}_p \Delta t = 2G(\rho_m b V_D + \dot{\rho}_{DK} b \bar{l} + \dot{\gamma}_{tw})\Delta t$$

- To describe the shock loading response, homogeneous nucleation is considered;
- To describe the response of BCC metals, Peierls stress、twinning、 viscosity are considered;
- To unravel the fundamental origin of the dynamic strength: dislocations or twinning, dislocation creation or dislocation motion?

- Background
- Dislocation based constitutive model
- **Results and Discussions**
- Conclusions

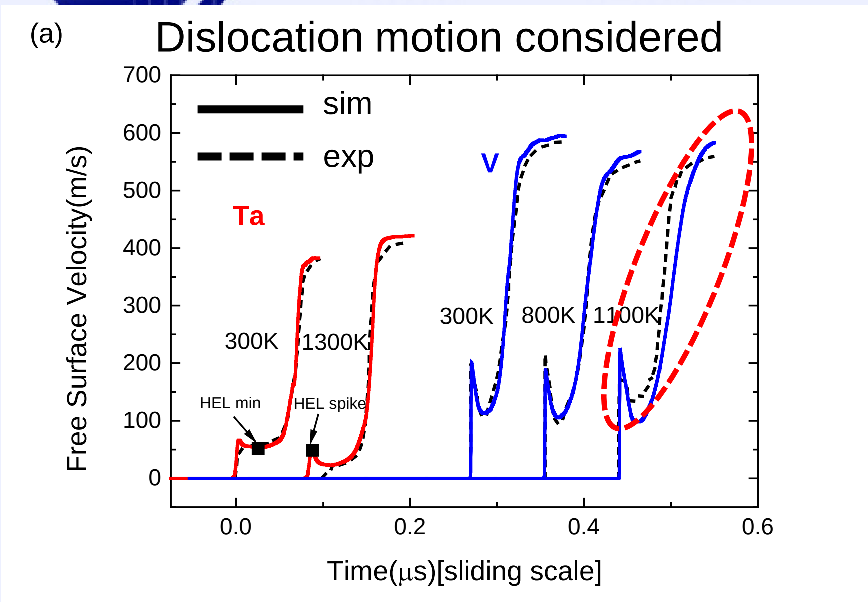
Twinning

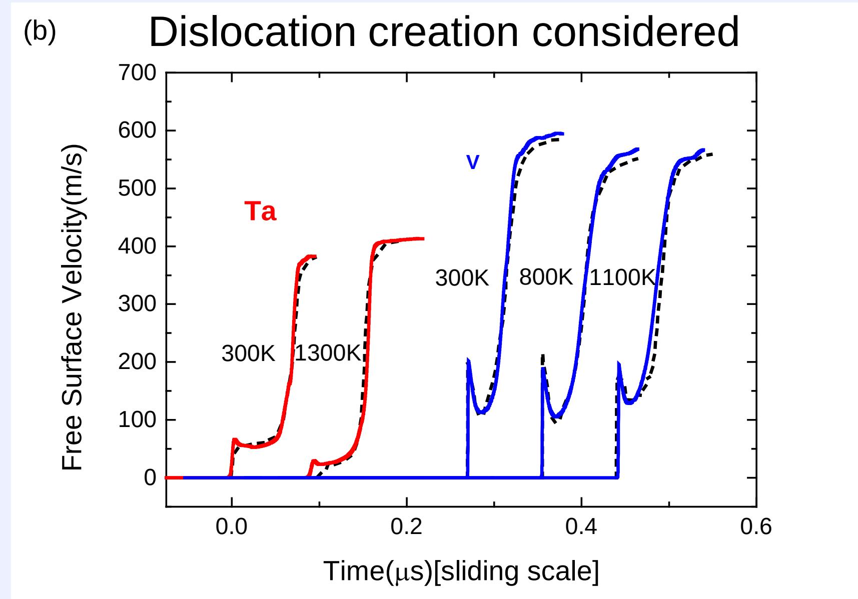




- Twinning shear rate drops sharply with distance, and influence the dynamic yield stress near the impact surface more significantly;
- The experimentally observed strength behaviors are obtained from thicker samples. Thus, the behaviors of dynamic strength are attributed to dislocation creation and dislocation motion.

Dislocation motion or creation

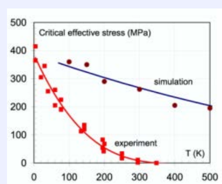




Peierls Stress

$$V_D = \frac{(\tau - \tau_c) b}{B(T) + B_{vis}}$$

Phonon Drag

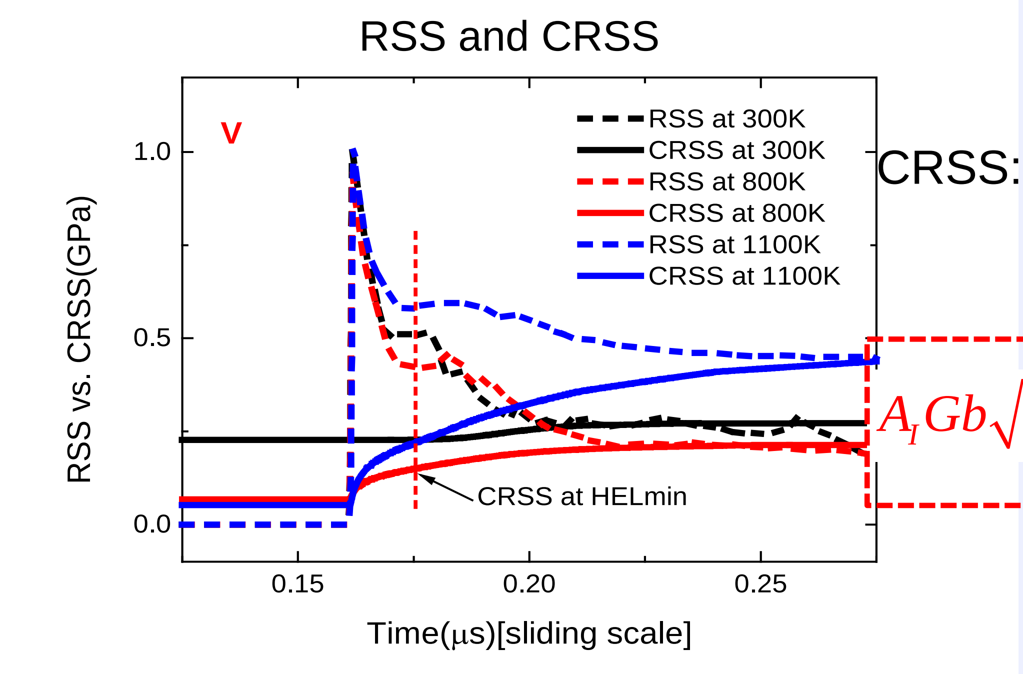


Homogeneous nucleation

$$\dot{\rho}_{\mathrm{HN}} = \alpha \exp\left(-\frac{\Delta G}{k_B T}\right)$$

- The thermal softening behaviors result from Peierls stress;
- **TA-HN contributes to the plastic dissipation, and the thermal hardening behavior of vanadium.**

Forest hardening



CRSS:

$$\tau_c = \tau_p(\mathrm{T}) + \tau_{\mathrm{int}}$$

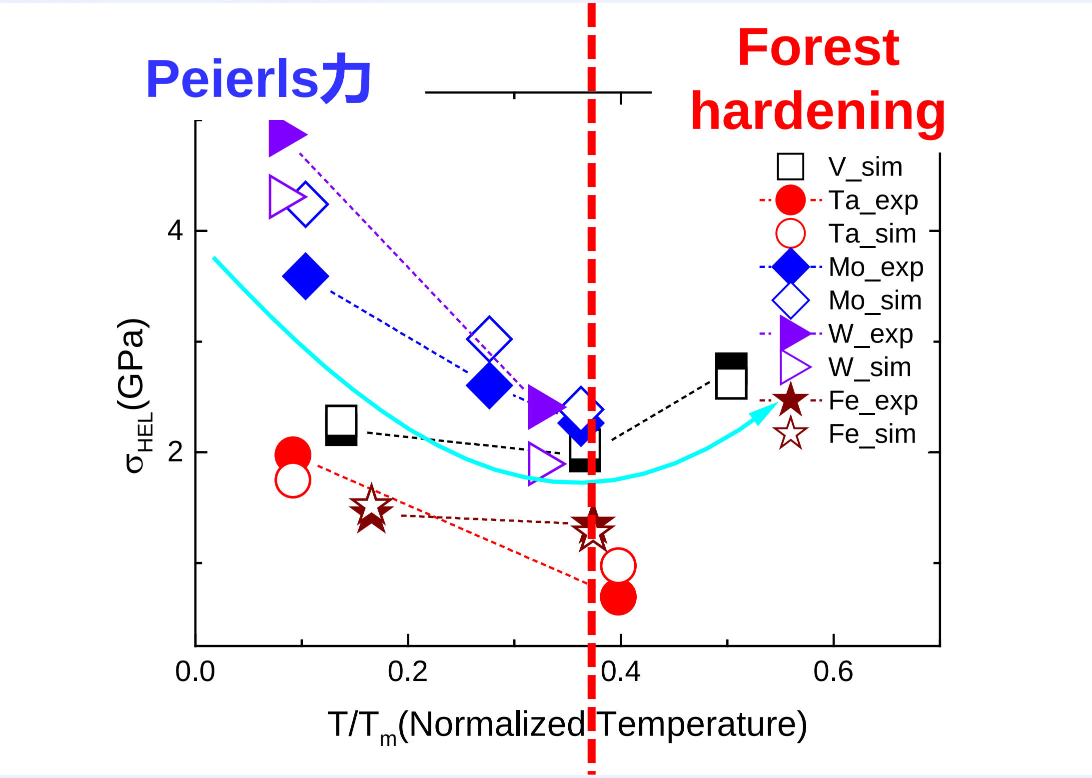
$$A_I G b \sqrt{\rho_I}$$

$$\dot{\rho}_{\mathrm{HN}} = \alpha \exp\left(-\frac{\Delta G}{k_B T}\right)$$

Thermal hardening

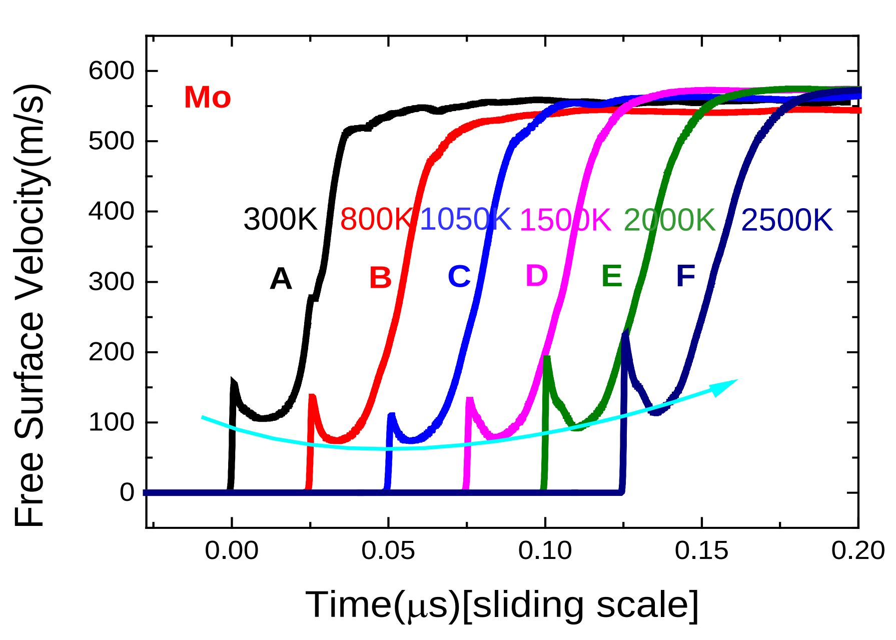
- Newly generated dislocation not only participate in plastic dissipation, but also obstruct the motion of other dislocations due to forest hardening;
- TA-HN strengthen the forest hardening effect at higher temperature, which counterbalances the thermal softening behaviors of Peierls stress, and results in the thermal hardening behavior of vanadium.

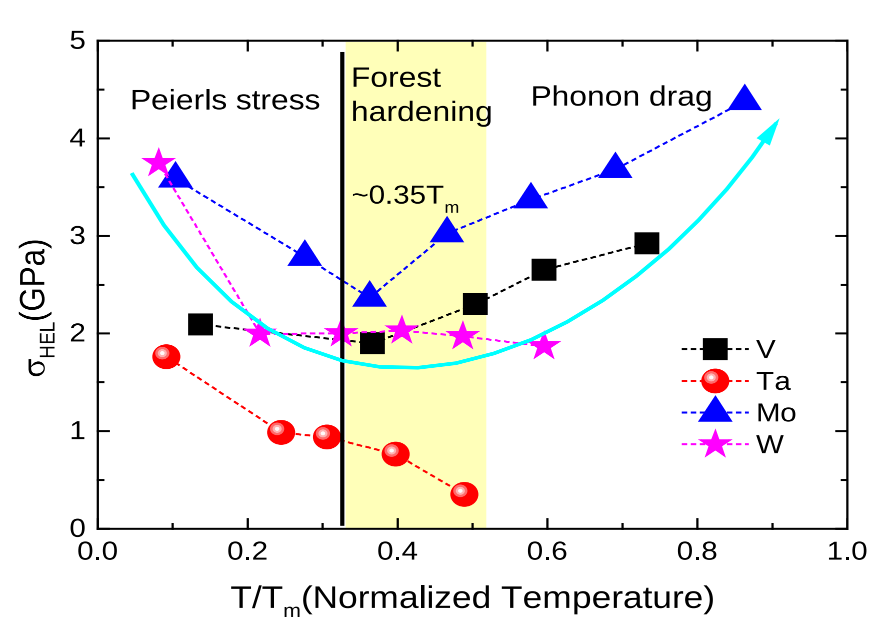
How about other BCC metals?



- **Peierls** stress contributes to the thermal softening behavior, while **forest hardening** contributes to the thermal hardening behaviors;
- Will other BCC metals present thermal hardening behaviors at higher temperature?

How about other BCC metals?





- Three regions according to temperature:

Temperature	Mechanism	Strength
$T<0.35T_m$	Peierls stress	Thermal softening
$0.35T_m<T<0.50T_m$	Forest hardening	Thermal hardening
$0.5T_m<T$	Phonon drag	Thermal hardening

- Background
- Dislocation based constitutive model
- Results and Discussions
- **Conclusions**

Conclusions

- A dislocation based constitutive model is established;
- Unraveling the fundamental origin of dynamic strength of BCC metals;
- A new thermal hardening mechanism is proposed, i.e. forest hardening induced by TA-HN;
- Predicting the thermal hardening behavior of other BCC metals at higher temperature.

Thanks for your attention!