Deformation Twinning Mechanism in Magnesium at High Temperature and High Strain Rates during compression/tension loading at the Micron Scale

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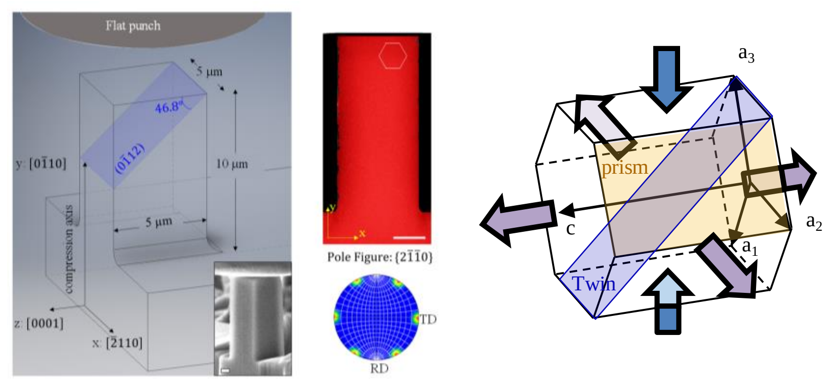
Goal of the study

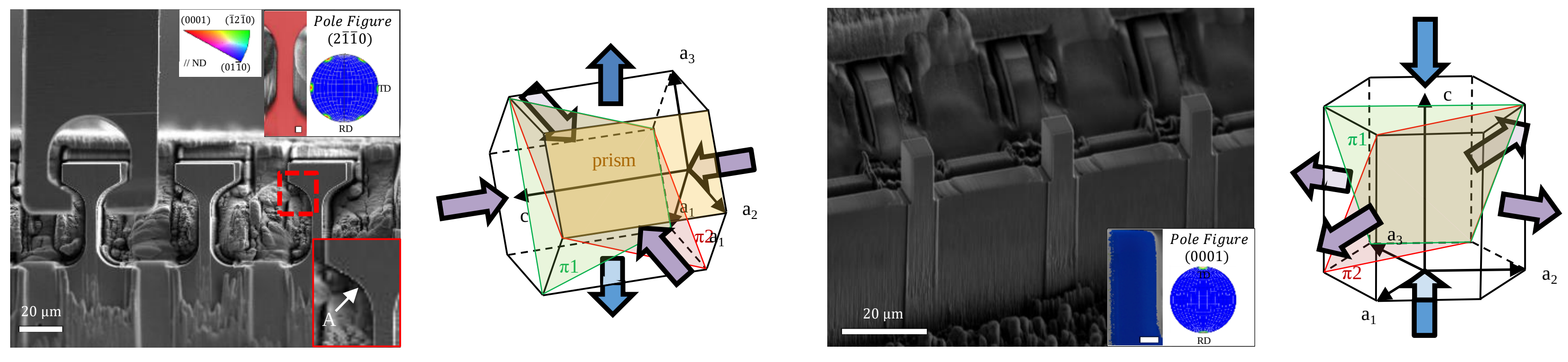
- By investigating differently oriented single crystalline microstructures, the present work shows how plasticity is accommodated in pure Mg at various temperatures (T) and high strain rate ($\dot{\varepsilon}$), broadening the understanding of the strain rate and temperature sensitivities of two activated deformation modes in Mg: extension twinning and prismatic slip. The ranges of T and $\dot{\varepsilon}$ covered are 293 - 573 K and 10^{-3} s^{-1} – 500 s^{-1}, respectively.
- Due to the lower strain rate sensitivity of twinning compared to slip, the nucleation of twins with higher critical resolved shear stress is suspected and investigated under shock c-axis compression/contraction.

Crystal orientations and corresponding testing mode: High Temperature and High Strain Rate

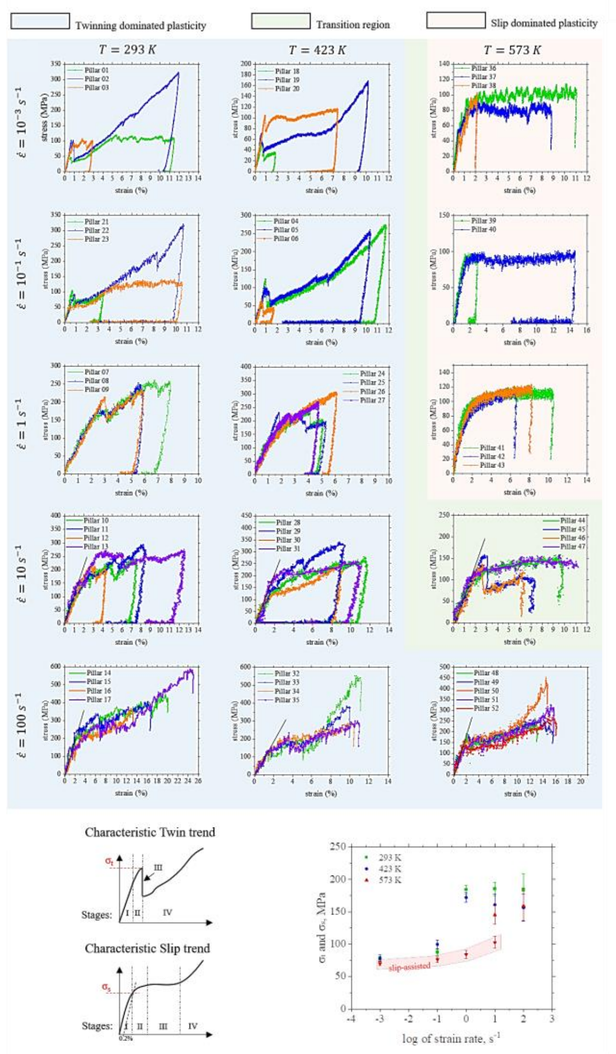
1st work Pillar compressions under HT and HSR conditions

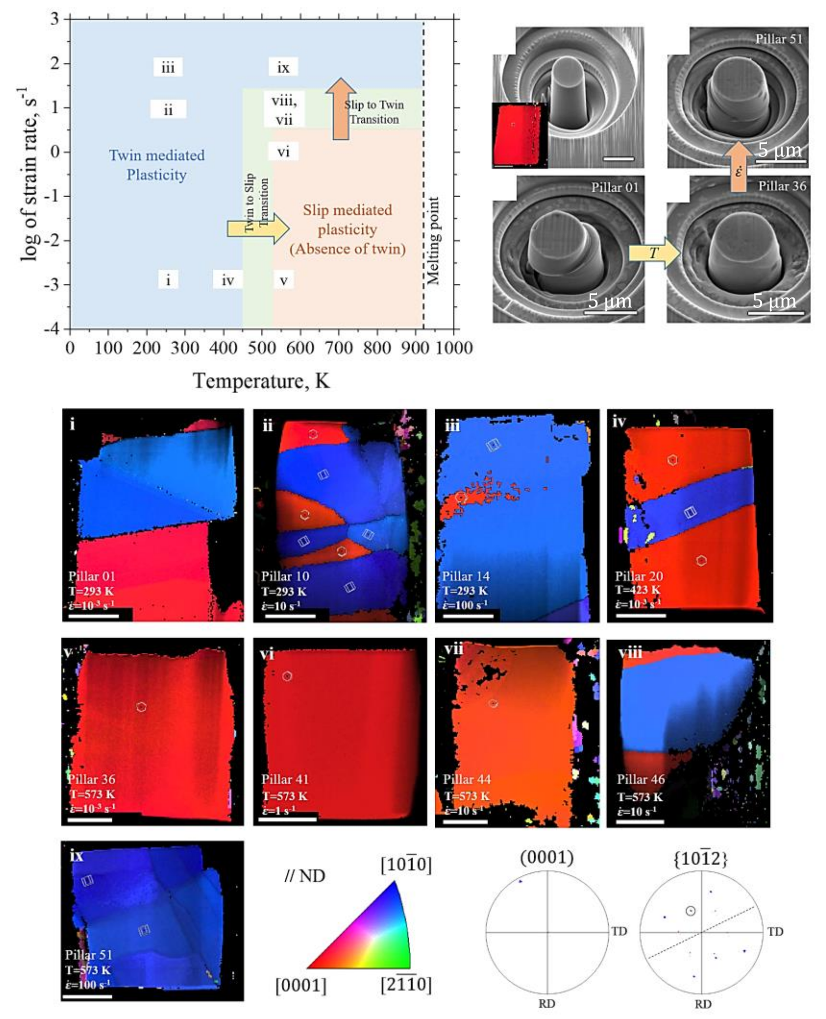


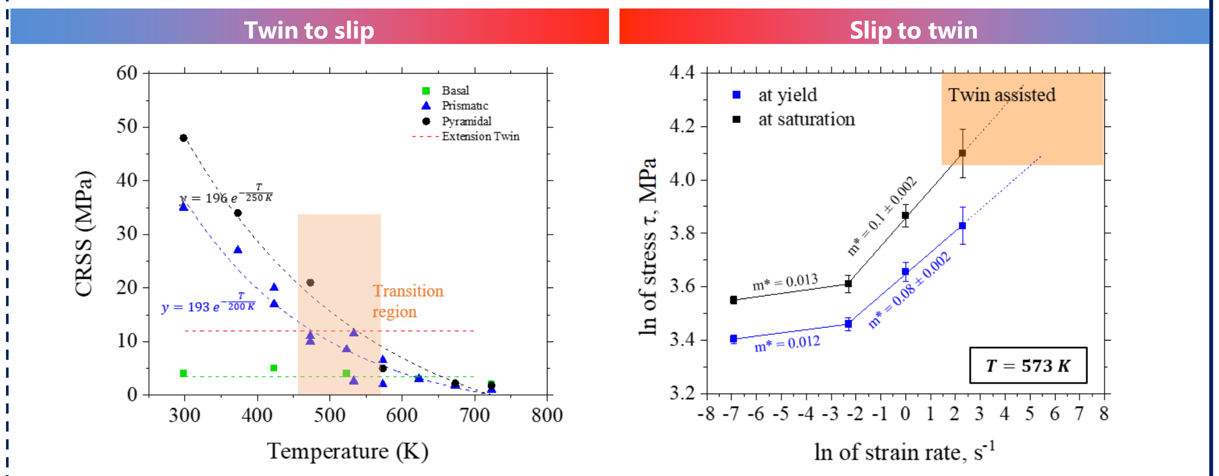
2nd work Tensile bar extensions and pillar compressions under HSR conditions



1st work — Slip to twin and twin to slip transition points







Flow stress model in slip-assisted plasticity

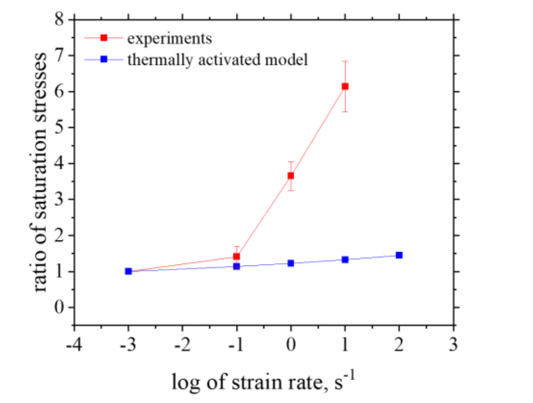
$$\frac{d\rho}{d\gamma} = k_1\sqrt{\rho} - k_2(\dot{\varepsilon},T)\,\rho$$

$$\frac{d\rho^{\alpha}}{d\gamma^{\alpha}} = 0, \qquad \rho_{sat}(\dot{\varepsilon},T) = \left(\frac{k_1}{k_2(\dot{\varepsilon},T)}\right)^2$$

$$\frac{k_2(\dot{\varepsilon},T)}{k_1} = \frac{\chi b G}{\tau_{sat}(\dot{\varepsilon},T)} \qquad \frac{k_2(\dot{\varepsilon}_1)}{k_2(\dot{\varepsilon})} = \frac{\tau_{sat}(\dot{\varepsilon})}{\tau_{sat}(\dot{\varepsilon}_1)}$$

$$\frac{k_2(\dot{\varepsilon},T)}{k_1} = \frac{\chi b}{g}\left(1 - \frac{kT}{Db^3}\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)$$

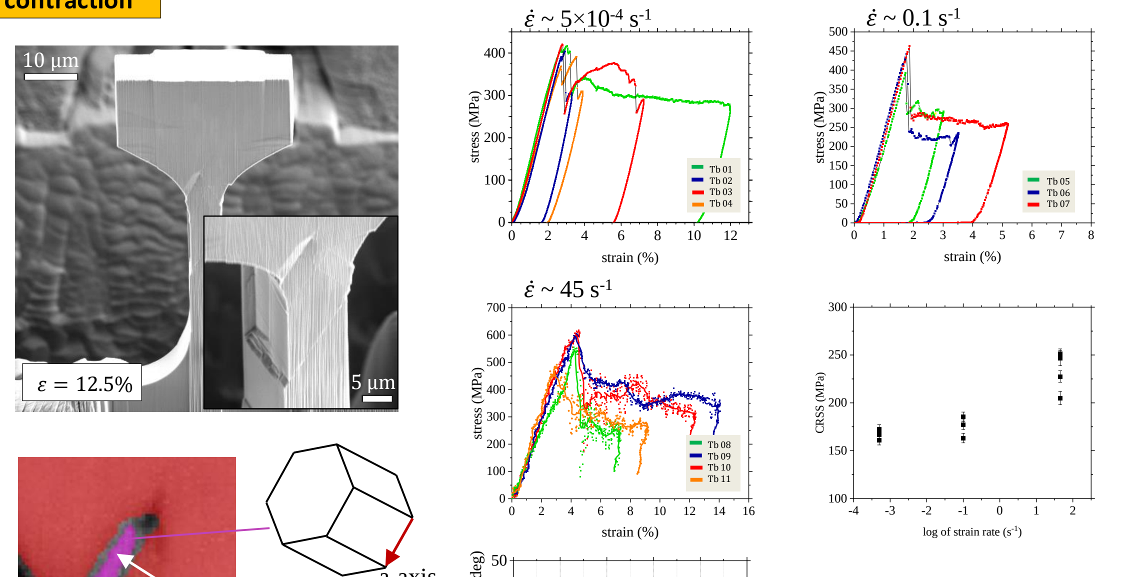
$$\frac{k_2(\dot{\varepsilon}_1)}{k_2(\dot{\varepsilon})} = \frac{\left(1 - \frac{kT}{Db^3}\ln\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_0}\right)\right)}{\left(1 - \frac{kT}{Db^3}\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)} = \frac{\tau_{sat}(\dot{\varepsilon})}{\tau_{sat}(\dot{\varepsilon}_1)}$$

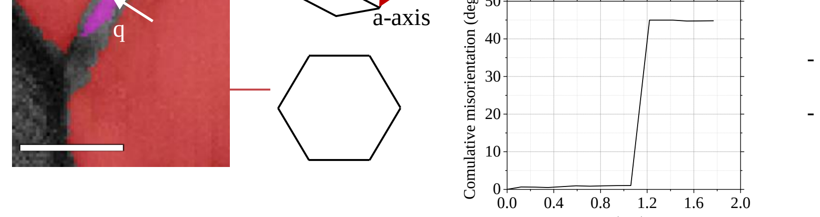


$$k_1(\dot{\varepsilon}) \propto \frac{1}{d(\dot{\varepsilon})} \qquad \tau'_{sat}(\dot{\varepsilon},T) = \frac{k_1(\dot{\varepsilon})}{k_1}\tau_{sat}(\dot{\varepsilon},T)$$

2nd work — C-axis contraction and compression during high strain rate loading

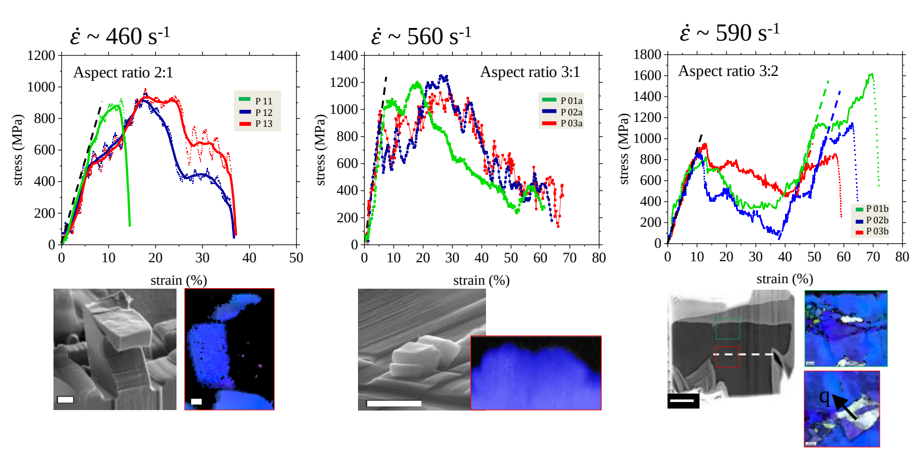
contraction



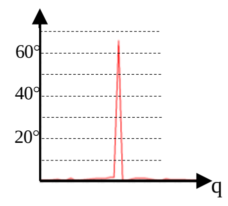


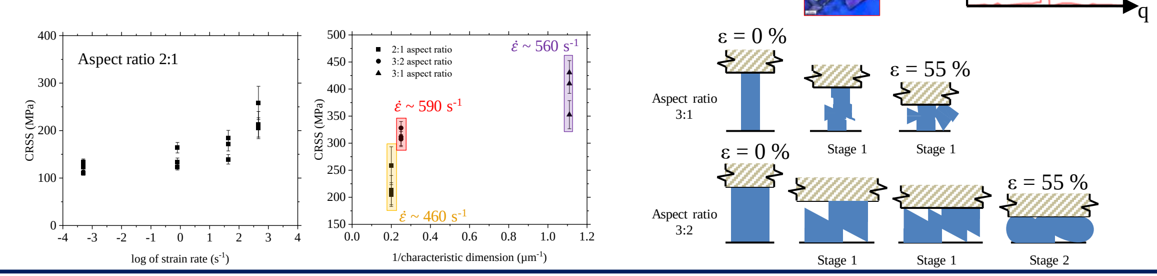
- Prismatic slip-assisted plastic deformation
- New grain formation at high strain rate

compression



- Pyramidal slip-assisted plastic deformation
- New grain formation during biaxial straining

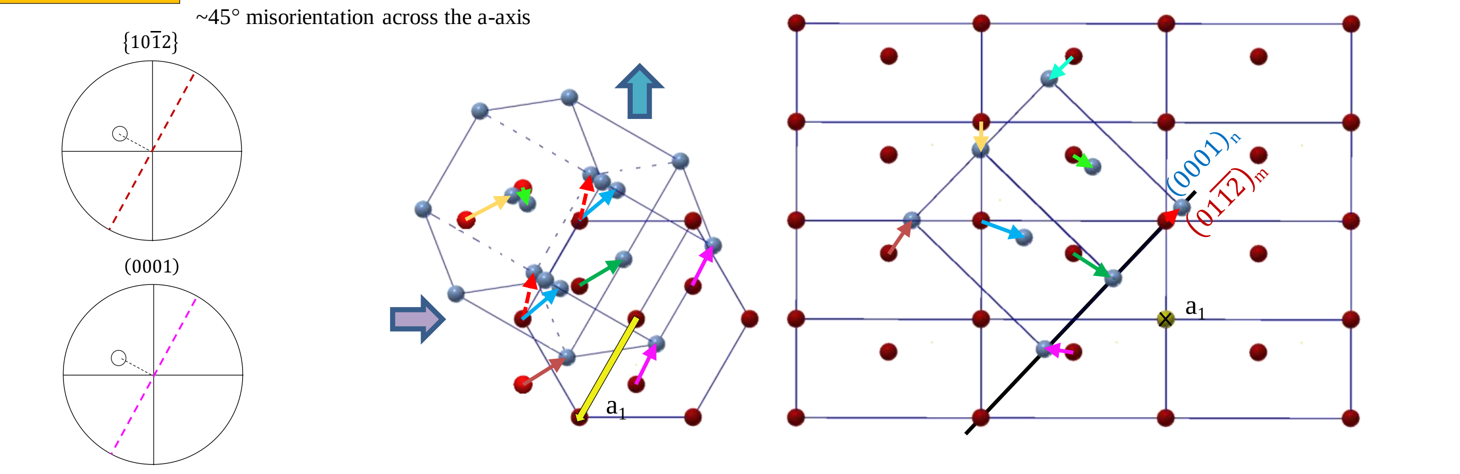




Twinning or simply new grains?

contraction Pyramidal II to Basal plane transformation

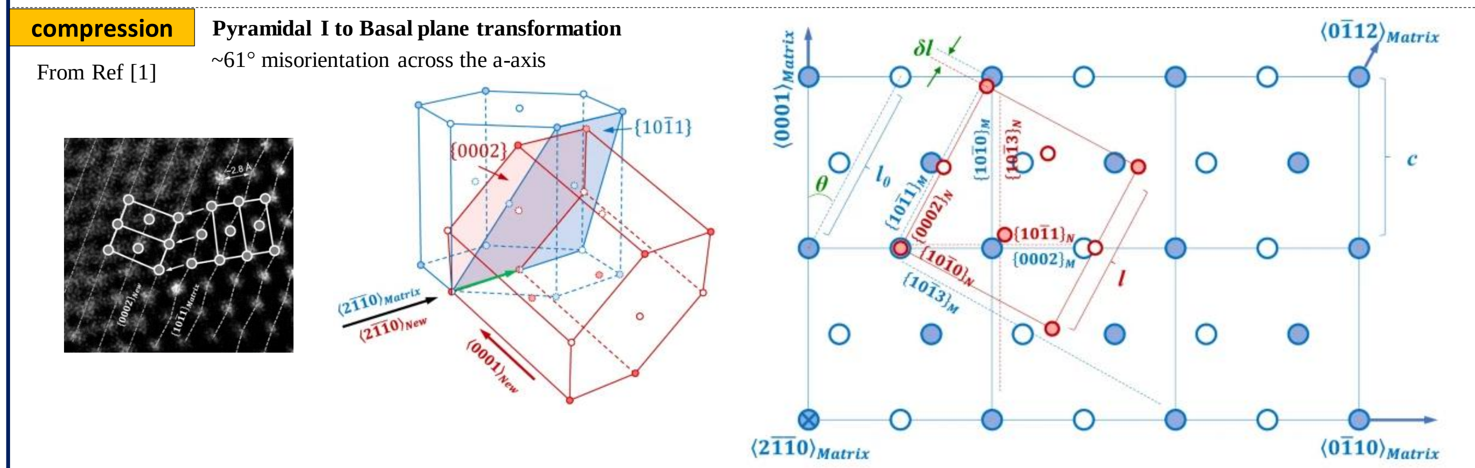
~45° misorientation across the a-axis



compression Pyramidal I to Basal plane transformation

From Ref [1]

~61° misorientation across the a-axis



Conclusions

1st Work

- For T ≤ 423 K, twinning accommodates the plastic deformation and the material response shows a decrease in work hardening with temperature at given strain rate as well as an increase with strain rate for given temperature.
- For T > 423 K, for $\dot{\varepsilon}$ ≤ 10 s^{-1}, twinning is absent and the governing deformation mechanism is dominated by prismatic slip.
- For T > 423 K, for $\dot{\varepsilon}$ > 10 s^{-1}, the higher local stresses that build throughout the loading at higher deformation rate re-establish deformation twinning to be the primary way of accommodating the plasticity.

Deviations between the simulated and experimentally calculated flow stress values are observed at higher $\dot{\varepsilon}$, and can be explained by the changes in dislocation kinetics induced during high strain rate loadings at the microscale where dislocation generation and annihilation rate are influenced mostly by the structural size effect.

2nd Work

The strain rate sensitivities of prismatic and pyramidal slip have been assessed at the microscale.

The nucleation of new grains not attributable to classical twin modes have been found under shock compressions, revealing that dislocation-free mechanisms such as pure atomic shuffling can accommodate the deformation in magnesium in high stress regions.

References

[1] Liu B.Y. et al., Rejuvenation of plasticity via deformation graining in magnesium, Nat Comm. 13 (2022).

Note: all undefined scale bars correspond to 2 μm

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