



## Thermo-hydro-mechanical-chemical modeling of synthetic wet gouges sheared at experimental seismic slip under fluid drainage conditions

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Understanding dynamic weakening is of paramount importance because it involves thermally triggered physical-chemical processes that reduce the fault frictional resistance and facilitate earthquake propagation. Investigating the evolution of temperature ( $T$ ), pore fluid pressure ( $P_f$ ), and chemical reactions during slip therefore allows exploration of dynamic weakening mechanisms. However, direct in situ measurements of  $T$  and  $P_f$  within slip zones remain technologically challenging in laboratory high-velocity rotary shear experiments. Consequently, numerical simulations constrained by mechanical data are essential for inferring these critical parameters. We utilize a series of rotary-shear mechanical data on a combination of kaolinite and quartz. The experiments are conducted under undrained/drained conditions with thermocouples for temperature measurements. On the basis of these data, we develop a Thermo-Hydro-Mechanical-Chemical (THMC) modeling framework using COMSOL Multiphysics to estimate physical conditions within the Principal Slip Zone (PSZ) and to infer dynamic weakening mechanisms responsible for the observed frictional behavior. Under undrained conditions, the friction coefficient ( $\mu$ ) reaches a peak friction ( $\mu_p$ ) at  $\sim 0.28$  and undergoes abrupt weakening, followed by a steady-state low-friction ( $\mu_s$ ) at  $\sim 0.1$ . This behavior corresponds to a measured  $T$  stabilizing at  $320\text{--}360^\circ\text{C}$  and a simulated  $P_f$  rapidly increasing and is maintained at  $\sim 2.4$  MPa. It suggests that frictional heating induces pore water pressurization. Under drained conditions,  $\mu$  reaches a  $\mu_p \sim 0.3$  at  $0.7$  s and undergoes abrupt weakening during  $1.2\text{--}1.7$  s, maintains  $\mu_s \sim 0.17$  between  $2\text{--}4$  s and followed by a re-strengthening behavior at  $4$  s.  $\mu$  was accompanied by the changes of  $T$  and  $P_f$ .  $T$  increased to  $\sim 280^\circ\text{C}$  at  $1.2$  s, followed by a decrease to  $\sim 200^\circ\text{C}$ . Meanwhile, the simulated  $P_f$  achieved the highest value ( $\sim 1.9$  MPa) at  $1.2$  s and gradually decreased and reached a relatively lowest value ( $\sim 0.3$  MPa) at  $4$  s due to the pore fluid drainage. Whether  $P_f$  is present is corresponding to the weakening and re-strengthening times. In addition, microstructural and mineralogical observations show thermal decomposition of kaolinite. Because thermal decomposition is a strong endothermic reaction, the temperature decreases during the later stages of the process due to the thermal decomposition of kaolinite. We suggest that thermal pressurization operates as the dynamic weakening mechanism during the initial slip stage,

consistent with theoretical predictions and experimental documentation of thermal pressurization during rapid shear, as described by Rice (2006) and Ferri et al. (2010). Later, thermal pressurization ceases under drained conditions, resulting in complex frictional behavior. In general, our study provides essential insights into the dynamic weakening mechanism during experimental seismic slip. In addition, we suggest that drainage conditions may influence frictional behavior by affecting the generation and maintenance of pore fluid pressure during seismic slip.