The shear rupture nucleation: Horizons broadened by high-resolution laboratory experiments

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This paper reviews our recent studies on the shear rupture nucleation. Once shear rupture instability occurs in the brittle regime, the rupture propagates dynamically at a high speed close to sonic velocities. Physically, however, shear rupture cannot begin to propagate abruptly at speeds close to sonic velocities immediately after the instability is attained, when the constitutive property of the fault is inhomogeneous. Shear rupture nucleates at a local point of the lowest resistance of rupture growth on the fault, and as a consequence of fault heterogeneities, unstable, high-speed rupture is preceded by stable, quasi-static rupture growth in a localized zone. The nucleation process is defined as the transition process from stable, quasi-static rupture growth to the phase of unstable, high speed rupture in a localized zone on the fault.

During the shear rupture, slip displacement proceeds on the rupturing surfaces in the breakdown zone behind the propagating front of rupture, and hence the rupturing surfaces are in mutual contact and interacting throughout the breakdown process. This suggests that the shear rupture process may be severely affected by geometric irregularities on the rupturing surfaces, and that the size of the breakdown zone over which the shear strength degrades transitionally to a residual friction stress level with ongoing slip may be greatly influenced by these geometric irregularities. This leads to the speculation that geometric irregularities on the rupturing surfaces will be a key factor in scaling the size scale and duration of the shear rupture process.

A series of systematic, high-resolution laboratory experiments have been performed on the propagating frictional slip failure (stick-slip) on preexisting faults having different surface roughnesses, to reveal the entire picture of the nucleation process, and to demonstrate how severely the length scale of shear rupture nucleation and its duration are affected by geometric irregularities on the rupturing surfaces. On the basis of the experimental results, we also discuss theoretically how the critical length of the nucleation zone and its duration are scaled consistently in terms of the governing constitutive law.

Fault surface topographies or roughnesses in general exhibit band-limited self-similarity. In this case, the relation between the topographical length $L(r)$ and the ruler length r can be expressed by the power law:

$$L(r) = A_i r^{-a_i} (\lambda_{ci-1} < r < \lambda_{ci}) \quad ,$$

where A_i and a_i are constants in a bandwidth bounded by lower corner length λ_{ci-1} and upper corner length λ_{ci} $(i = 1, 2, ..., k)$. The corner length λ_{ci} that separates the neighboring two bands with different segment slopes a_i and a_{i+1} is a characteristic length representing geometric irregularity of the fault surfaces. Thus, the fault surface topographies or roughnesses with band-limited self-similarity are quantified and characterized in terms of the two parameters λ_{ci} and a_i. Of these two parameters, only the corner length λ_{ci} straightforwardly represents a characteristic length scale in the slip direction on the fault.

The high-resolution laboratory experiments have led to a conclusive result that the nucleation process consists of two phases: an initial, quasi-static phase (phase I), and a subsequent accelerating phase (phase II). In phase I, the rupture grows at a slow, steady speed, and the rupture growth rate is independent of the rupture growth length. In contrast, during phase II, the rupture develops at accelerating speeds, and it has been found that the rupture growth rate V increases with an increase in the rupture growth length L, obeying a power law $V \propto L^n$. The experiments also led to a conclusive result that the nucleation process is severely affected by geometric irregularity on the rupturing surfaces; that is, the nucleation zone size and its duration both depend greatly on geometric irregularity of the rupturing surfaces, and it has been found that both the nucleation zone size and its duration scale with λ_c. Combining the above two results leads to a power law of the form:

$$\frac{V}{V_S} = \alpha \left(\frac{L}{\lambda_c} \right)^n \quad ,$$

for the relation between the rupture growth rate V and the rupture growth length L during phase II. In the above equation, V_S is the shear wave velocity, λ_c is the characteristic length representing geometric irregularity of the rupturing surfaces in the slip direction, and α and n are non-dimensional constants ($\alpha = 8.87 \times 10^{-29}$ and $n = 7.31$).

The above experimental results are treated quantitatively in terms of the governing constitutive law if the constitutive law is formulated as a slip-dependent law. The critical size of the nucleation zone L_c is expressed theoretically in terms of the constitutive law parameters $\Delta\tau_b$ (breakdown stress drop) and D_c (critical slip displacement) as:

$$L_c = \frac{1}{k} \frac{\mu}{\Delta\tau_b} D_c \quad ,$$

where k is a non-dimensional parameter depending on the rupture growth rate V, and μ is the rigidity. Recent experiments on fracture of intact rock and frictional slip failure have led to a new finding that the constitutive law parameters, $\Delta\tau_b$, τ_p, and D_c, are mutually not independent, but are related to one another by the following universal relation:

$$\frac{\Delta\tau_b}{\tau_p} = \beta \left(\frac{D_c}{\lambda_c} \right)^M \quad ,$$

where β and M are non-dimensional constants. These two equations lead to the following relation between L_c and λ_c:

$$L_c = \frac{1}{k} \left(\frac{1}{\beta} \right)^{\frac{1}{M}} \frac{\mu}{\Delta\tau_b} \left(\frac{\Delta\tau_b}{\tau_p} \right)^{\frac{1}{M}} \lambda_c \quad .$$

The time t_c needed for shear rupture to grow from a stage of the rupture growth length L in phase II to the critical length L_c beyond which the rupture propagates at a fast speed V_c close to sonic velocities is also given by

$$t_c = \frac{\lambda_c}{V_S} f\left(\frac{V}{V_S}, \frac{V_c}{V_S}\right) \quad ,$$

where

$$f\left(\frac{V}{V_S}, \frac{V_c}{V_S}\right) = \frac{\alpha^{-1/n}}{n-1}\left(\frac{V_c}{V_S}\right)^{(-n+1)/n}\left[\left(\frac{V/V_S}{V_c/V_S}\right)^{(-n+1)/n} - 1\right] \quad .$$

The above theoretical relations show that both L_c and t_c scale with λ_c, which has been demonstrated with the present series of laboratory experiments. The scale dependency of L_c and t_c provides an important implication for predicting the onset of dynamic high-speed rupture, because the run-up distance and time are short to attain the fast-speed rupture on smooth fault surfaces, and because a long run-up is necessary for reaching the same speed on rough, irregular fault surfaces. The slip-weakening process during nucleation is less stable and more dynamic on a smoother fault. Since the characteristic length λ_c representing geometric irregularity of a fault whose surfaces exhibit band-limited self-similarity in general increases with an increase in the fault size for natural earthquakes, it is concluded from the above results that the nucleation zone size and its duration are necessarily size-scale dependent.