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Length scale of interface heterogeneities selects propagation mechanism of frictional slip fronts

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ABSTRACT

We present three-dimensional finite-element simulations showing the propagation of slip fronts at striped heterogeneous interfaces. The heterogeneous area consists of alternating stripes of weaker and stronger frictional properties, which is equivalent to a lower and higher fracture energy, respectively. By comparing the slip front propagation at interfaces that differ solely by the length scale of the heterogeneous pattern, we illustrate that two different propagation regimes exist. Interfaces with wide stripes present slip fronts with propagation speeds that transition from sub-Rayleigh to inter-sonic. Thinner stripes are, however, characterized by the propagation of sub-Rayleigh slip fronts, which are preceded by slip pulses of negligible slip in the weaker stripes. From a macroscopic point of view, an interface with a smaller heterogeneous pattern appears to be stronger than the equivalent coarser interface even though both have the same average properties. The numerical results as well as a theoretical approach based on fracture-mechanics considerations suggest that the origin of these two distinct propagation mechanisms lies in the interaction between the length scales of the cohesive zone and the heterogeneous configuration. We further show by estimating the relevant length scales that the occurring propagation mechanism is influenced by the friction weakening rate of the interface as well as the shear modulus of the bulk material.

1. Introduction

The propagation of slip fronts at frictional interfaces as well as classic shear cracks at weak interfaces has, in the past, often been modeled in two-dimensional systems. Neglecting the third dimension enables the use of plane-strain or plane-stress approximations and reduces the interface to a one-dimensional line. This simplifies the theoretical description of interface ruptures and decreases significantly computational cost of numerical simulations. Nevertheless, the propagation of ruptures along two-dimensional interfaces presents interesting additional aspects. The effect of non-homogeneous interfaces, for instance, is of great importance for earthquake science (because faults are not homogeneous) and engineering (with the use of “designed” materials such as composites). Most ruptures propagate along interfaces that present different types of heterogeneities at various scales. Examples are non-uniform loading, such as areas of higher or lower pre-stress, and heterogeneous interface properties, such as zones of stronger/weaker strength or rate-strengthening/weakening friction. All these types of heterogeneities affect the rupture propagation, but become particularly interesting for fronts of at

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least two dimensions because areas that are less easily broken can simply be circumvented (or partially circumvented and broken with delay). Even though early theoretical work (Gao and Rice, 1989) showed that a first-order perturbation analysis describes well the curved shape of a static crack around slightly tougher interface obstacles, the dynamic aspects of rupture propagation on interfaces with significant heterogeneities remain elusive.

The experimental observation of slip events at frictional interfaces is challenging and only few results of two-dimensional fronts have been reported so far. Brörmann et al. (2013) and Romero et al. (2014) showed on interfaces with discrete contacts (pillars and spherical caps, respectively) that the transition from sticking to sliding is characterized by slip fronts propagating along the interface, similar to the observations of Rubinstein et al. (2004) but at a two-dimensional interface. Latour et al. (2013) studied experimentally the effect of interface barriers on frictional slip. They showed, using different configurations of barriers, that heterogeneities can cause rupture arrest/delay as well as increase/decrease of the rupture speed. However, no systematic prediction can be provided because the behavior of a sequence of ruptures is complex and memory effects potentially cause inter-dependence of subsequent ruptures.

More experimental observations showing the effects of heterogeneities have been reported for Mode I (decohesion) ruptures. Natural heterogeneities of the interface (Måløy et al., 2006) and the bulk material (Ponson, 2009) were observed to affect the propagation speed. Måløy et al. (2006) analyzed local velocity fluctuations of an interface crack along a heterogeneous weak plane and showed that local velocities larger than the average front speed present a power law distribution. Ponson (2009) observed a depinning transition of a crack in a heterogeneous sandstone. Theoretical studies of planar (tensile) cracks in heterogeneous media suggested that elastic wave propagation is a key component to explain the observed roughness of the fracture (Ramanathan et al., 1997; Ramanathan and Fisher, 1997, 1998; Bouchaud et al., 2002). Other experiments applied artificial heterogeneities in order to study their influence on the rupture fronts. Mower and Argon (1995) performed crack-trapping experiments showing a locally bowed configuration of a quasi-static crack between two obstacles with higher interface strength. Dalmas et al. (2009) and Chopin et al. (2011) described the shape of quasi-static and dynamic decohesion fronts, respectively, observed at interfaces with stripes of different fracture energy. Xia et al. (2012) showed in thin-film experiments that the macroscopic peel force depends on the shape of the interface heterogeneities and can vary despite having the same cumulative area.

In addition to experimental observations, some numerical studies of the propagation of frictional shear ruptures at weak interfaces have been conducted. This includes one-dimensional as well as two-dimensional interfaces with heterogeneities due to changed pre-stresses or modified frictional properties of the interface. The number of simulations with two-dimensional interfaces is limited because a set-up with a rupture far from the edges (to avoid the influence of wave reflection), with a small process zone compared to the rupture length, and with a sufficient fine discretization is computationally challenging. Early work by Day (1982) showed that the rupture speed presents large changes during the propagation along an interface with zones of higher and lower pre-stresses. Fukuyama and Olsen (2002) and Dunham et al. (2003) demonstrated with numerical simulations of two-dimensional interfaces that a circular heterogeneity of higher pre-stress or higher fracture energy can provoke a transition from sub-Rayleigh to (temporary) super-shear propagation. Three-dimensional simulations provided also the opportunity to study differences in the near-source ground motion of earthquakes when an interface rupture propagates through an area of higher strength or higher pre-stress (Page et al., 2005). Other simulations were used to study earthquake mechanisms at faults with velocity-weakening patches surrounded by velocity-strengthening areas (Rice, 1993; Ben-Zion and Rice, 1997; Madariaga and Olsen, 2000; Kaneko et al., 2008; Ariyoshi et al., 2009, 2012; Kaneko and Ampuero, 2011). In these set-ups, the velocity-strengthening zone is continuously sliding and causes an energy accumulation in the system, which eventually leads to dynamic ruptures (earthquakes) propagating mostly within the velocity-weakening zones. The dynamic propagation of ruptures at two-dimensional interfaces was also numerically modeled with heterogeneous initial stresses mimicking a realistic state of a fault (Andrews, 2005; Brietzke et al., 2009).

Even though the effect of heterogeneities on the propagation of slip fronts is different at one-dimensional interfaces, such simulations are still important tools to help understand the underlying mechanisms. Das and Aki (1977) showed that ruptures at one-dimensional interfaces can propagate through areas of higher strength with and without breaking the heterogeneity. In a different set-up with a weakening and a strengthening zone, Voisin et al. (2002) studied the arrest of frictional slip at the border of the areas of different properties and showed the presence of a self-healing slip pulse that penetrates the strong area. In a detailed study of the transition from sub-Rayleigh to inter-sonic propagation at a one-dimensional interface, Liu and Lapusta (2008) demonstrated that a single favorable heterogeneity leads to a secondary crack which accelerates to inter-sonic speeds with an abrupt jump from the Rayleigh wave speed to an inter-sonic speed. The emergence and evolution of increased pre-stress heterogeneities due to the arrest of preceding slip fronts was studied by Radiguet et al. (2013, 2015).

In this work, we focus on the dynamic aspects of frictional in-plane shear ruptures within a heterogeneous zone of a two-dimensional interface (in contrast to studies of ruptures beyond a single interface heterogeneity (Dunham et al., 2003; Liu and Lapusta, 2008)). We present three-dimensional finite-element simulations of a slip-front propagation along an interface with heterogeneous friction properties. We will show that two different propagation mechanisms (sub-Rayleigh and inter-sonic speed) exist in this configuration and that the propagation regime is selected by the interplay of two length-scales: size of heterogeneity vs. process-zone size. The studied set-up consists of a semi-infinite interface with a homogeneous area used as an establishing zone and an area with stripes of different slip-weakening properties (which reduces essentially to a difference in fracture energy).