THE COMPETITION BETWEEN GRAIN MELTING AND SOLIDIFICATION DURING SHEAR HEATING IN SIMULATED FAULTS

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Summary Pseudotachylyte formation has been found to be associated of frictional melting, ductile deformation, overprinted at a later stage by a new generation of pseudotachylytes. We connect these cycles to earthquake dynamics using a development of discrete element model with solid grains that can melt during frictional heating and viscous melts that can bond through solidification during cooling. A new earthquake episode initiates with the crushing of bonded clusters once the bond strength is exceeded, with frictional shear heating being activated again. We explore the competitions between melting and solidification in terms of phase transitions using scaling laws dependent on the characteristic times for melting, thermal diffusion, and loading rates.

INTRODUCTION

Melts produced within localized shear zones during faulting can become critical for fault dynamics [1, 2]. Once formed, melts can act either as a coseismic fault lubricant or as a viscous brake to the earthquakes [3]. Faults present rheology that strongly varies with depth. In that respect, faults with evidence of melted material in the form of pseudotachylytes may be a reliable indicator for ancient seismic activities in exhumed faults. Two types of pseudotachylyte rocks have been distinguished, including pseudotachylytes associated to cataclasites and mylonites [2]. Pseudotachylytes associated to cataclasites support the model by Sibson[1], which describes transition from elasto-frictional solids to viscous-plastic shear zones. The presence of mylonite-associated pseudotachylytes favors an alternative model [2] describing the nucleation of ductile instabilities that allow the transition from unstable to stable flow in crustal rocks. Here we develop a micromechanical approach to construct a general phase diagram dependent on the characteristic times for melting, thermal diffusion, and loading rates, at this stage without accounting for crystal-plastic deformations that possibly dominate in deeper faults. The development of melt associated with pseudotachylytes can be lead to critical weakening factors. Such factors have been studied at the scale of laboratory tests [4, 3]. Using theoretical studies with the consideration of the rate and state friction law, fault weakening was associated with either flash heating involving localized asperity melts and global melting [5, 6]. Finally, numerical models using the discrete element method (DEM) have been used to study fault localizations with a focus given to comminution, stick-slip driven by local force chain buckling between the grains, and the thermal convection arising from the dispersed granular motions and temperatures within the fault [7]. Here the method is extended with added details accounting for the melting of the grain surfaces, melt viscosity, solidification of melts, and deboning of the solidified melts. In this 'Meltable-DEM' model, heat generation comes from intergranular viscous damping and most importantly from intergranular friction.

METHOD AND RESULTS

Conventional DEM comes to describe the motion of grains using Newton's law, while their interactions are represented using mechanical contact laws, and heat transfer between grains by a simple Fourier law of conduction. We extend this method to develop Meltable-DEM, starting by adding the heat generation from friction and viscous mechanical dissipation effects. We capture transitions from solid to melt and vice versa by partitioning the grains into separate molten and solid phases; the geometries and time evolution of these distinct phases are simplified to describe a spherical solid core and a shell-like flash-melt layer. Contact dynamics between meltable grains is considered by adding the contribution of melt viscosity to the overall mechanical interaction. Melting or solidification of isolated grains evolves either by increasing or decreasing the shell thickness, respectively. Solidification can further develop a bond between two grains if they have melt-layers coming in contact, which results in clustering; such bond clusters can degrade either through de-bonding or re-melting. A three-dimensional representative volume element containing 5,000 grains has been subjected to loading conditions that enable to reproduce a stick-slip response. Consistent with Spray[4], slip initiates through comminution of clustered 'super-particles' (that are naturally let to be formed during previous stick episodes via melt-solidification). As a result of the thermo-mechanical contact rheology, those super-particles are left to develop individual geometries: each having a unique agglomerated shape that may comprise as many spherical units as the local thermodynamics dictate.

Each of these three simulations in Fig. 1(a) belongs to a different phase regime with responses that are clearly distinguishable. Those three phases represent: (i) a fully melting regime, where the grains are not able to cool down and solidify between two consequent slip events; (ii) a cyclic melting regime, where the average temperature is rising sufficiently to cause for grain melting during slip and form new intergranular bonds between the slips; and (iii) a non-melting regime, with a typical stick-slip behavior without any grain reaching the melting point, and therefore without introducing any form of solidification. Furthermore, these three phase regimes reveal totally distinguishable modes of motion: (i) the fully melting regime involves viscous dominated motion; (ii) the cyclic melting regime develops high-magnitude stick-slip motions;

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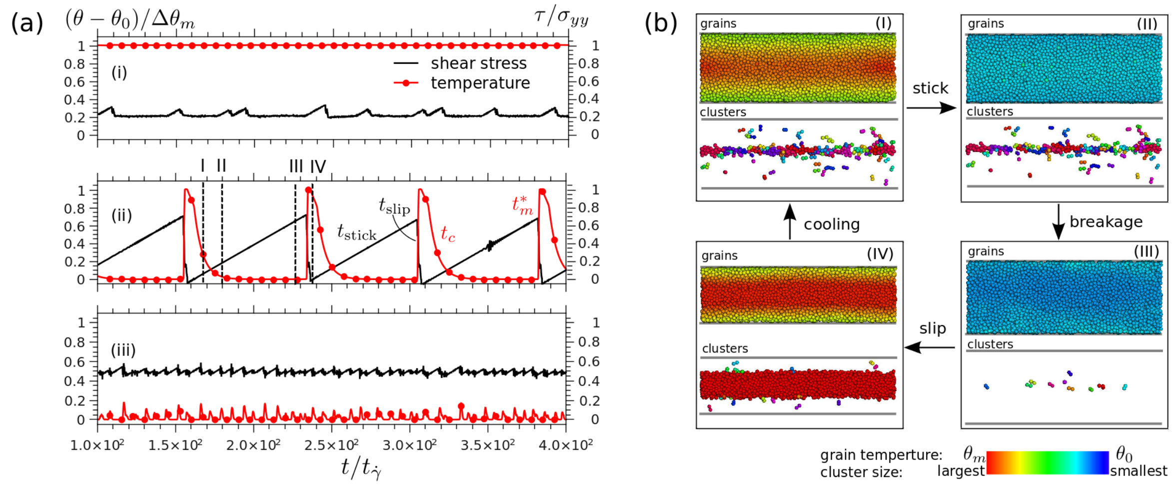

Figure 1. (a) Time evolutions (t) of the normalized average fault core temperature, $(\theta - \theta_0)/\Delta\theta_m$, and shear stresses, τ/σ_{yy}, from three typical simulations, representing distinguishable dynamic regimes. (b) Stages from a typical Meltable-DEM simulation belonging to the cyclic melting regime, shown in the right figure (b-ii).

and (iii) the non-melting regime also with stick-slip motion but with much smaller magnitudes. Most interestingly, in the cyclic melting regime, the average fault temperature θ during the slips (i.e. over time denoted in the figure as $t_{\rm slip}$) rapidly reaches the melting temperature θ_m (i.e. mostly over a shorter time denoted in the figure as $t^*_{\rm m}$). In return, a stick phase develops over a time $t_{\rm stick}$, associated with the rise of the shear stress, which is mostly longer than the thermal diffusion time, $t_{\rm c}$. In those cases $t_{\rm c} \geq t_{\rm stick}$, i.e. solidification evolves after slip but with the cooling time not sufficiently long to reduce the average fault temperature towards the ambient temperature before the next slip event. Fig. 1(b) shows the four typical stages corresponding to simulation case (ii) in Fig. 1(a). Each stage is represented by two subfigures. The first subfigure shows all grains within the fault with color denoting their temperatures. The second subfigure shows only those grains belonging to super-particles. A single super-particle includes the agglomerate of all unit spheres inter-connected via solidified bonds; this super-particle is distinguished from the others in Fig. 1(b) using a color dependent on the number of spherical units it contains. These four typical stages are repeatedly found during the simulated faults in the cyclic melting regime, and represent: (I) a cooling stage subsequent to a slip event, (II) a stick stage where the overall shear stress increases gradually, but without much topological change to the super-particles, (III) a comminution stage at higher shear stresses that includes the rapid breakage of the super-particles, and (IV) a slip stage where the amount of energy released raises temperatures towards the melting temperature, followed by a cooling stage already described as stage (I).

CONCLUSIONS

A meltable DEM was proposed that extends previous models including thermal diffusion between grain contacts. Major to our proposed Meltable-DEM were details provided on how to include grain melting, melt solidification, bonds creation and breakage. The Meltable-DEM was then adopted to explore pseudotachylyte formation and cyclic melting of faults. The marked transitions between various observed fault responses and formations have been identified, and understood by comparing theoretical characteristic times requiring to stay in the so-called cyclic melting regime. This regime is extremely relevant to earthquake studies, as it targets a fundamental stick-slip process that involves the melt-solidification phase changes of grains.

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