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Endao Han

Transient Dynamics of Concentrated Particulate Suspensions Under Shear

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Doctoral Thesis accepted by the University of Chicago, IL, USA

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To my family

The greatest obstacle to discovery is not ignorance—it is the illusion of knowledge.

—Daniel J. Boorstin

Supervisor's Foreword

How does the flow of a simple liquid change when particles are added to it? This was calculated by Albert Einstein in his PhD thesis over 100 years ago for small volume fractions of particles and subsequently extended by others to increasingly larger fractions. The result is that the suspension's resistance to applied shear, i.e., its viscosity, rises rapidly as more and more particles are added, to the point where all flow becomes arrested and the suspension's viscosity diverges. Underlying this divergence is the mechanism of jamming: beyond some critical volume fraction there simply is no longer room for neighboring particles to move with respect to one another and the whole suspension turns rigid, exhibiting a solid-like yield stress. Exactly when the jamming transition will occur, i.e., what value the critical volume fraction for jamming will assume, depends on details of the particle–particle interactions, which in turn is controlled by aspects such as the particles' shape and their surface properties. This type of isotropic jamming transition, controlled only by the particle density, describes the response to applied shear when the suspension is at rest. There is, however, another possibility to induce jamming, namely by driving an initially fluid suspension into a rigid state. This type of dynamic jamming occurs without any overall change in the volume fraction of particles. Instead, it is a consequence of the fact that shear reorganizes particles into anisotropic configurations. These configurations can establish load-carrying force chains as long as the particle volume fraction is not too low and the particle–particle contacts are sufficiently frictional. This thesis demonstrates how suspensions provide a model system for investigating such jamming by shear and it describes some of the remarkable consequences of the associated dynamic transformation that converts a fluid into a solid in a fully reversible manner.

A key aspect of jamming by shear in suspensions is that the process proceeds along rapidly moving fronts. Ahead of a front the suspension is still in its initial, fluid state, while behind the front the suspension has been transformed into a solid-like state. The thesis breaks new ground in establishing a constitutive framework that relates the properties of shear-jamming fronts, such as their propagation speed, to the applied shear stress and strain. In treating the dynamic, effectively transient conversion of fluid into solid, this significantly extends prior work on jamming phase transitions, which only considered steady-state conditions. As the thesis shows, the local shear stress in the front region is set by the external stress applied at the boundary of the suspension. This enables a completely new way of performing stress-controlled experiments: by using the jamming fronts to generate conditions of controllable local stress, a method is introduced that overcomes a critical limitation of standard steady-state rheology, which cannot establish spatially uniform stress conditions in the interior of a concentrated suspension as jamming is approached. Finally, the thesis introduces high-speed ultrasound imaging as a powerful experimental technique to image propagating shear jamming fronts and extract the associated flow field.

As a whole, the work described here has significantly advanced our understanding of how jamming by shear can reversibly solidify a dense suspension and how this transformation depends on both the suspension properties and the kind of forcing that is applied. In concert with the powerful experimental techniques that are introduced, this opens up exciting new avenues for further research.

Chicago, IL, USA
January 29, 2020

Heinrich Jaeger

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