Recent Developments in Viscoplastic flows

Andreas Alexandrou

Department of Mechanical and Manufacturing Engineering
University of Cyprus
andalexa@ucy.ac.cy

The interest in viscoplastic flows started with our involvement in the semisolid process. Semisolid slurries are mixtures of specially rounded solid particles in the melt of the same metal. The temperature dependence of the slurries produces properties that are a function of the volume fraction. For low volume fraction (high temperature) the slurry behaves as a dilute suspension where the solid is suspended freely in the bulk melt phase. At high volume fraction past the close-packing level (low temperature) the mixture behaves essentially as a solid and its processing resembles that of forging. In the mushy region (intermediate volume fraction) the solid particles form a solid network while maintaining enough melt in the mixture. This network imparts strength to the mixture known as ***yield stress*** and hence the suspensions behave as viscoplastic fluids.

While in the past our interest was directed to semisolid slurries this has changed in recent years since many other suspensions exhibit the same rheological behavior. Examples of such fluids are various food products (mayonnaise, ketchup), cosmetics (cold cream, make up, hair gel, shaving foam), pastes (toothpaste), emulsions, foams, polymer gels (e.g. carbopol), suspensions (oil drilling fluids), wet and dry sand, certain clays, certain paints and printing inks, coatings, quicksand, quick clay and self compacting concrete.

In most typical flowing suspensions of yield stress fluids, there coexist three types of forces: (a) those of colloidal origin; (b) the Brownian (thermal) randomizing force; and (c) the viscous forces acting on the particles due to fluid flow. The interplay between these forces and their balance are responsible for the formation of an internal structure which (i) has an inherit "strength", i.e. a yield stress and (ii) it can be altered by an externally applied shear during processing. In other more specialized suspensions, the mechanisms responsible for the internal structure and the yield stress may be entirely different. In semisolid suspensions, for instance, the yield stress is the combined effect of the solid network of connected particles and the dry friction between loose particles.

Given the nature of the internal structure and its "vulnerability" to an applied shear, most suspensions exhibit not only a strong non-linear viscoplastic behavior but also a time-dependent or thixotropic behavior. In semisolid slurries this time-dependent behavior is due to the breakage of solid bonds formed during prolonged rest between the particles. Other mechanisms responsible for thixotropy can be the disorganization of individual particles in granular materials, the deformation and disorganization of individual droplets changing in shape from spherical to elliptical in colloids (foams and emulsions), the orientation of polymer chains along the velocity field – as well as their breakage – in gels and the breaking of particle aggregates in suspensions. It is clear from the above that the yield stress and thixotropic effects are closely related and one cannot study one effect without the other.

In most suspensions there is a critical shear rate that determines the relative competition between what are known as aging and shear rejuvenation processes. In shear rejuvenation the structure breaks down resulting in decreasing viscosity with time. However, upon the reduction or the removal of shear aging occurs where the structure slowly rebuilds with a corresponding increase in the viscosity. At steady state, the rates of shear rejuvenation and aging are equal.

An interesting behavior exhibited by yield stress fluids in shearing flows is that of shear banding. At sufficiently low shear rates the flow domain is divided into two parts: (a) the yielded region close to the shearing wall and (b) the unyielded or solidlike region. In the unyielded region no flow is observed and the shear stress must essentially be lower than the yield value of the material while in the yielded region the shear stress should be higher than the yield stress. Now if the globally imposed shear rate increases, it is not the shear rate in the material in the yielded region that increases, but rather the extent of the sheared region which increases to fill the entire gap of the shear cell exactly at the critical shear rate. Obviously these results cast doubt on experimental data obtained in rotational rheometers when shear banding occurs within the gap of the rheometer.

The presentation will review the basic experimental results of the semisolid process, highlight the basic issues associated with the process and show the level of understanding gained through proper modeling. Following the review of the semisolid process the presentation will focus on thixotropy and its effects on the flow typical of a rotational rheometer, and (b) the classical problem of flow past a circular cylinder.

Implicit in the vast majority of the literature on viscoplastic flows is the assumption that the flow is always laminar. This may not be the case for fast suspension flows. Very recently we produced the first results on the transition from laminar to turbulent viscoplastic flow past a circular cylinder using DNS simulations. These results while preliminary in nature will be shared with the audience during the presentation. This work points to a new future direction in the study of viscoplastic flows in cases where the speed of the process is important.