CONSIDERATIONS ON THE RHEOLOGIC BEHAVIOUR OF SEMISOLID SLURRIES

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ABSTRACT:
This work presents some theoretical aspects concerning the rheology of semisolid slurries and it also highlights the importance of viscosity for the semisolid state processing technologies.
As a conclusion it presents the computation variations of the viscosity of semisolid slurries in steady state and transient state.

KEYWORDS:
semisolid, rheology, slurry, thixotropy

1. Introduction

Semisolid processing technologies are gaining attention both from scientists and from engineers due to their high potential to produce parts in an almost final state [1]. Two relatively new classes of the processing technologies are *thixoforming and rheocasting*, semisolid processing techniques for metals and metal alloys. Metals and metal alloys in a semisolid state and with a globular structure manifest thixotropic properties, which are dependant on time. Tixotropy is a term that defines the property of solution and suspension to gelatinate when they are in repose and to become fluid when they are shaken up. This phenomenon was first noticed in the year 1972 by David Spencer, a student at the Massachusetts Institute of Technology (MIT) and it lead to the development of a new technology for the processing of metal alloys (thixo-forming).

Semisolid metal slurries used for semisolid state processing may be divided in two categories, a liquid-like slurry which contains solid dispersed particles and behaves like a fluid under the action of external forces and a solid-like slurry which contains a solid interconnected stage and behaves like a solid, exposing a well defined yield strength. The metal semisolid slurry with a smaller fraction lower than 0.6 and with the globular structure of the solid particles usually exposes two unique rheologic properties: *thixotropy* and *pseudoplasticity* [2].

Thixotropy describes the dependence of the transient state viscosity in time at a given shear rate while pseudo-plasticity refers to the dependence between the shear rate and steady state viscosity. All semisolid processing techniques are based either on one of the two properties either on both of them within the same process. Therefore the development of semisolid processing technologies needs the understanding of the rheology of slurries.

2. Aspects concerning the semisolid slurries rheology

The first investigations on semisolid slurries rheology were done at the MIT (Cambridge, MA, USA) by Spencer [3] on a Sn-Pb alloy. They proved that a stirred semisolid slurry with a solid fraction higher than 0.2 behaves like a non-newtonian fluid with an apparent viscosity order of magnitude lower than in the case of non-stirred dendritic slurry. This is the first observation that initiated numerous studies about the

rheology of semisolid slurries. Joly and Mehrabian [3] also studied the Sn-Pb alloy and their work represents even today the basis of the knowledge related to the phenomena of stirred semisolid slurries.

The purpose of the majority of the rheologic models following the work of the two researchers is to reproduce the main properties which they experimentally observed. After Joly and Mehrabian the rheologic phenomenon in the stirred semisolid slurries may be divided into three categories:

❑ *The continuous cooling behaviour* – it describes the evolution of viscosity during continuous cooling at a constant cooling and shear rate;
❑ *The pseudoplastic behaviour* – describing the dependence relation between the steady state viscosity and the shear rate; or shear thinning behaviour;
❑ *The thixotropic behaviour* – describing the dependence of the transient state viscosity in time.

The continuous cooling behaviour offers the first information about the influence of the solid fraction, the shear rate and the cooling rate on the rheologic behaviour of semisolid slurries. Due to the complexity of the experiments related to the continuous cooling the modelling of this aspect was very much limited.
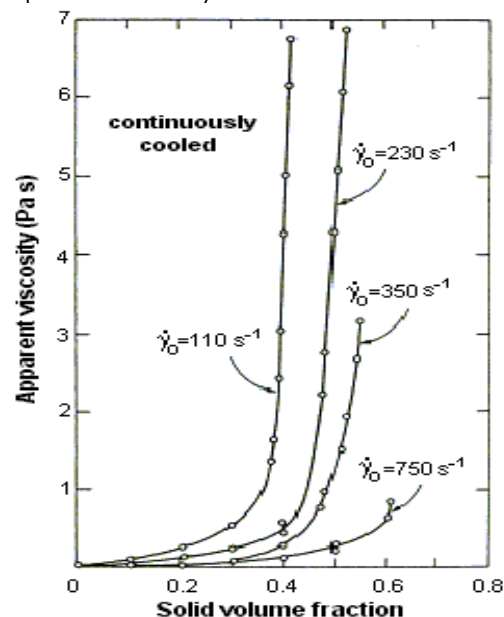

Figure 1. Apparent viscosity versus solid fraction f_S of Sn-15Pb alloy sheared continuously and cooled at 0.33 K/min at different shear rates $\dot{\gamma}_o$ [1]

Figure 1 shows an example of the results obtained by Joly and Mehrabian [2] at the continuous cooling experiments on the Sn-15Pb alloy. Generally, for a known cooling and share rate the apparently measured viscosity increases with the increase of the solid fraction, slowly in the case of low fractions and rapidly in the case of high solid fractions. At a given solid fraction the apparent viscosity decreases with the increase of the share rate and the decrease of the cooling speed. This phenomenon occurs due to the fact that the increase of the share rate and the decrease of the cooling rate lead to the obtaining of spherical particles.

Isothermal steady state tests lead to a more precise rheologic characterization; thus Joly and Mehrabian proved that the Sn-15Pb alloy manifests a pseudoplastic behaviour (thinning at shearing) where the apparent viscosity of the stationary regime decreases with the increase of the share rate. This pseudoplastic behaviour was confirmed in many other alloy systems.

It is generally accepted that the steady state viscosity at a given share rate depends on the degree of agglomeration among the solid particles which in its turn is the result of the dynamic equilibrium between the agglomeration and deagglomeration processes.

As the kinetics of the agglomeration and deagglomeration process is insufficiently known, efforts were carried out to develop experimental procedures involving a sudden increase or decrease of the share rate. It was thus discovered that the agglomeration process predominates after a sudden decrease of the shear rate while the deagglomeration process predominates after a sudden increase of the shear rate. The degree of agglomeration of the semisolid slurries uses a structural scalar parameter *s* which has values in the 0 and 1 interval. The completely agglomerated state corresponds to the s=1 point while the deagglomerated state corresponds to the final stationary regime at a given shear rate.

The objective of the thixotropic modelling is to deduce the time evolution of the structural s parameter.

As Brown and other researchers highlighted, rheologic models should be connected to micro-structural parameters measurable metalographically because such models coupled with the experimental investigations may allow a better understanding of the agglomeration and deagglomeration mechanisms.

3. The viscosity of semisolid slurries

The main purpose of rheology-related research was to understand how slurries behave in different flowing conditions. Thus the property which dictates the answer of the fluid to the deformation rate is viscosity. Although slurries are made up of two stages they are generally treated as homogenous fluids and thus they were attributed an apparent viscosity.

The semisolid slurry is usually a system containing many different sizes agglomerates. For simplification it is supposed that the semisolid slurry contains an average of same size agglomerates. At a certain time moment *t* the system contains *M* spherical agglomerates of the same *n* dimension. No matter the size of the agglomerates they shall catch a certain quantity of liquid inside. The volume of the fraction of the liquid entrapped inside the agglomerates in noted with ϕ_{fl}. Under the action of the deformation forces provoking the flowing of the semisolid material the entrapped liquid behaves just like the solid. Therefore the consequence of the agglomeration phenomenon is the increase of the solid fraction of the slurry from its original value ϕ to ϕ_{ef}, where ϕ_{ef} is the actual solid fraction and it is defined through the relation:

$$\phi_{ef} = \phi + \phi_{fl} \tag{1}$$

Initially we take a very diluted slurry with the solid fraction ϕ <0.1. The viscosity of these diluted slurries was theoretically determined by Einstein [4] and is obtained with the following relation:

$$\eta = \eta_0\left(1 + \frac{5}{2}\phi\right) \tag{2}$$

where: η_0 - is the viscosity of the liquid which does not contain a solid fraction;

η - is the viscosity of the slurry.

The Quemada researcher considered the formation of the agglomerates in the semisolid slurries and the behaviour of the liquid entrapped in the agglomerates and thus he replaced the solid fraction ϕ from the relation (2) with the actual solid fraction ϕ_{ef}; the following equation resulted:

$$\eta = \eta_0\left(1 + \frac{5}{2}\phi_{ef}\right) \tag{3}$$

To extend the use of the equation (3) to the semisolid slurries with a big solid fraction, too they adopted Brinkmans's and Roscoe's approximation models. The diluted semisolid slurry with an actual solid fraction ϕ_{ef} is considered a continuous environment whose viscosity is $\eta(\phi_{ef})$ and the obtaining of a new slurry is done by adding a small

quantity of particles at the diluted slurry (the $\Delta\phi_{ef}$ volume) per volume unit. By making the mathematical calculations the following relation is obtained:

$$\eta = \eta_0\left(1 - \phi_{ef}\right)^{-5/2} \tag{4}$$

According to equation (4) it is noticed that the viscosity of the semisolid slurry depends directly on the viscosity of the liquid matrix and of the volume of the actual solid fraction; viscosity is affected also by the flowing conditions but only indirectly through the modification of the actual solid fraction. These concepts are in accordance with the results of the experiments obtained by Ito [5] who discovered that the steady state viscosity is a function depending on the actual solid fraction.

To calculate the viscosity of slurry under specified external conditions the theoretic computation of the actual solid fraction is essential. Thus the relation used to calculate the actual solid fraction is:

$$\phi_{ef} = \left(1 - \frac{n-1}{n}\cdot A\right)\phi \tag{5}$$

where: A – is the parameter related to the packing mode

n – average size of the agglomerates.

The equation (4) may be applied to slurries with a solid fraction higher than equation (2). However, due to the suppositions performed by the equation (4) it may be applied until that volume of the actual solid fraction where the particles form a tri-dimensional network. In practice, the value of the solid fraction is of ϕ=0.6 for spherical particles and much less for dendritic particles. Moreover, the fact that this equation applies not only for obtaining steady state viscosity but also for determining the transient state viscosity must be stressed down.

4. Conclusions

Thixoforming and rheocasting are thw most often used semisolid state processing techniques for metals and metal alloys. They are based on the time-depending thixotropic properties which metals and metal alloys in a semisolid state and with a globular structure manifest.

The rheologic phenomenon in the semisolid slurries may be divided into three categories: continuous cooling behaviour, pseudo-plastic behaviour and thixotropic behaviour. Thus, in the case of continuous cooling, for known values of the cooling and shear rate the apparent measured viscosity increases with the increase of the solid fraction, slowly in the case low solid fractions and rapidly in the case of high solid fractions. At a given solid fraction the apparent viscosity decreases with the increase of the shear rate and the decrease of the cooling speed. This phenomenon is produced because the increase of the shear rate and the decrease of the cooling rate lead to the creation of spherical particles.

So it may be said that viscosity is one of the most important properties of the slurries and it depends directly of the viscosity of the liquid matrix and of the volume of the actual solid fraction and indirectly on the flowing conditions through the modification of the actual solid fraction.

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