Semisolid Metal Processing

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ABSTRACT

Processing of metal alloys in their mushy state represent a new trend in metal processing. The process produces components with low porosity, high crack resistance, fine microstructure, and better mechanical properties than those produced by casting and comparable to those of forged alloys. In the present work, a summary of the current understanding on the rheology of semisolid slurries, different mathematical models that describe the experimentally observed behavior of the material, and salient numerical results including die filling are presented.

SINOPSIS

El procesamiento de aleaciones metálicas en su fase semisólida representa una nueva tendencia en el procesamiento de metales. El proceso produce componentes con baja porosidad, alta resistencia a las grietas, microestructura fina y con mejores propiedades mecánicas que aquellas producidas por fundición, y son comparables a las producidas por aleaciones forjadas. En este trabajo se presenta un resumen del conocimiento actual en la reología de suspensiones de semisólidos, además de diferentes modelos matemáticos que describen el comportamiento observado experimentalmente del material y resultados numéricos que incluyen el proceso de llenado en un molde.

I- INTRODUCTION

For years, metallurgists and scientists are looking for a process that produces parts with better mechanical properties or looking for new alloys with improved characteristics. However, the discovering of processing metal alloys in their semisolid state was almost accidentally. In the early 70's, Flemings and co-workers at MIT, while working on the hot tearing in alloy castings [1], envisioned that the rheological properties of vigorously stirred tin-lead slurries offered potential advantages over processing metal alloys in liquid phase. In the last few years, the interest in the process has increased rapidly. This is evidenced by the incidence of five bi-annual international conferences devoted to the subject in the last eight years. Currently, a number of automotive components are being produced using semisolid metal (SSM) processing technology.

II- THE SSM PROCESS

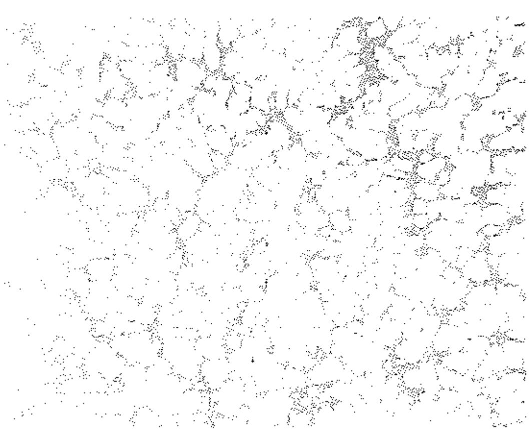
The processing of metal alloys in semisolid state can be divided into two steps: preprocessing and processing. During preprocessing, the raw material is melted and allowed to cool while growing dendrites are broken up using mechanical or electromagnetic stirring (MHD). The resultant slurry has an equiaxed microstructure made up of round, rosette-like crystals mixed in eutectic liquid. The specially preprocessed material is either immediately injected into a die (rheocasting) or solidified in billet forms for later processing (thixoforming). In the last process, the billets are reheated to a temperature in the mushy zone, and then injected into a die (thixocasting) or shaped between closed dies (thixoforging). The process is called rheocasting in that the melt is rheologically manipulated during the liquid solid transformation.

In thixoforming, the preprocessing of the raw material can be alternatively performed using a process called Strain Induced Melt Activated (SIMA). This consists in deforming the billet at a temperature above the recrystallization temperature (hot working) followed by cold work at room temperature.

The preprocessing of the raw material plays a very important role. Figure 1 shows the microstructure of an A357 aluminum alloy obtained by classical casting and by electromagnetic stirring. In conventional casting, the nuclei formed during solidification grow and become coarse, heavily branched dendrites as depicted in Figure 1a. In contrast, when continuous electromagnetic stirring is used, the microstructure is extremely fine, composed of coarsened dendrite fragments as shown in Figure 1b.

The desired morphology in the solid phase is obtained only after reheating the billet into the semisolid state just before injection. Figure 2 shows that the microstructure of the electromagnetically stirred alloy, after a holding time of 10 min at 580°C, evolves to a more spheroidal microstructure. The reheating time is long enough to allow a minimum degree of spheroidization, but it has to be limited to avoid excessive ripening for thin section castability.

(a)



(b)

Figure 1: *Dendritic and equiaxed microstructure*

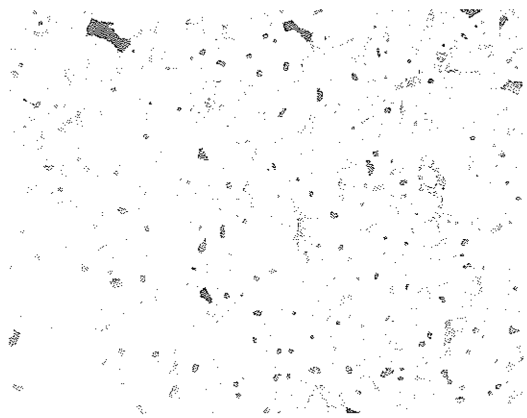


Figure 2: *Microstructure of MHD A356 aluminum alloy after reheating to 580 °C and 10 min holding time*

III- ADVANTAGES OF THE PROCESS

The processing of materials in semisolid state offers distinct advantages over other near-net shape manufacturing processes. Upon reheating the semisolid billet to the mushy zone, the material exhibits solid-like and liquid-like behavior. It maintains its structural integrity and it can be easily handled. And due to its higher than liquid viscosity, the flow remains mostly laminar minimizing the possibility for gas entrapment, thus allowing heat treatment to obtain superior mechanical properties.

The process can be used to produce parts with complicated geometry and close dimensional tolerances. The process is performed at a lower temperature, resulting in shorter solidification times, less shrinkage and increased productivity. The lower temperature also results in longer die life, and lower energy requirement than in other traditional casting methods. Products made using the process also have high strength and integrity with improved surface finish

IV- RHEOLOGY OF SSM

The theoretical understanding of SSM materials during shape making operations is still under development. Most systematic studies of SSM relate to equilibrium steady-state shear flow experiments [1, 2, 3, 4, 5, 6 and 7]. In these experiments, the SSM samples were cooled continuously to a given solid fraction while sheared at a constant shear-rate. Under these conditions, SSM's behave as shear thinning (pseudoplastic) fluids with effective viscosity decreasing with increasing shear rate. However, available experimental data on transient flows show a shear-thickening behavior, i.e., increasing effective viscosity with increasing shear rate [7, 8, 9]. In constant shear-rate experiments, the structure of the material is allowed to evolve to a new steady state corresponding to the imposed shear field. On the other hand, in rapid transients, the structure of the material does not have enough time to adjust to the new conditions. Additionally, experimental results show that these materials resist finite shear stresses before deformation begins, thus behaving like Bingham fluids [7].

The difference in behavior under steady and unsteady deformation is due to the complex rheology of the slurry. In the mushy state, the slurry is a dense suspension made up of eutectic liquid and alpha phase particles. The average solid volume fraction is a function of the bulk temperature of the suspension that as the temperature varies from the liquidus to the solidus limits, changes from zero to unity. During processing, the applied forces are transmitted throughout the bulk of the mixture, thus squeezing the liquid out of the solid matrix. As the liquid is squeezed out, and the local volume fraction changes, the viscosity of the mixture also varies.

The kinetic nature of the skeleton, breakdown/restoration process, is manifested in step-shear-rate experiments. It was found that he breakdown of the network formed by the solid metal particles in the slurry is faster than the restructuring [7, 9, 10, 11]. The characteristic time for the stress evolution was estimated to be about 10 s. Also, from hysteresis-loop tests for the Sn-15%Pb SSM and shear-rate step experiments after different rest times, it was concluded that SSM's are thixotropic [11, 12]. The most plausible explanation for this behavior is that at high solid fractions, the particles form a skeleton, and the apparent mechanical behavior of the system is determined primarily by the structure and properties of the skeleton. The structure is almost never at equilibrium, it depends on the mechanical and thermal history of the material, and its evolution is governed by a number of kinetic phenomena of different characteristic time-scales. As a result of these kinetic processes, the rheological properties of the material, such as effective viscosity and yield stress, decrease with structure breakdown and increase with its development.

The dynamic response of the material under net-shape forming conditions is the result of the combined effects of liquid-solid and solid-solid interactions. Unlike most conventional materials, the geometry of the flow also affects the rheological behavior of the slurry: solid walls and geometric details of the die can induce relative motion between the solid matrix and the liquid phase, thus leading to phase separation and particle crowding. Moreover, the material response is different depending on the nature of the applied forces. For instance, pure shear can cause particle migration that produces variable density. The material under extensional shear conditions however, results in a more uniform microstructure. It is important to note that most real flows are a combination of the above two extremes. The resultant material microstructure and its response to processing variables are needless to say complicated.

Figure 2 summarizes the current understanding of the behavior of semisolid slurries: (a) under steady shear conditions the micro-structure evolves exhibiting shear-thinning behavior, (b) under rapid transients the material structure remains constant thus exhibiting shear thickening behavior, (c) at low shear rates the material shows a finite yield stress. This implies that the material will not deform unless a stress level is exceeded. Note, also that the above behavior depends also on time and temperature.

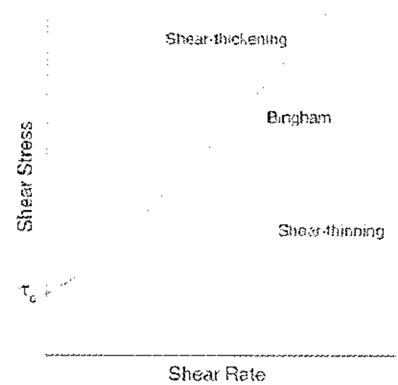


Figure 3: *Behavior of SSM: shear thinning in steady flow and shear thickening in rapid transient flow.*

Given the complex rheology of the SSM slurries, i.e. nonlinear stress-shear rate relationship, finite yield stress, thixotropic behavior, and temperature and shear rate dependent properties, the filling of complex geometries is significantly different from that of liquid casting of melt aluminum. In order to develop a better understanding of the process and to optimize the operation, it is important to gain a deep insight into the underlying theoretical and physical concepts associated with this novel family of materials. Mathematical and computational models then are essential tools for the further development and application of the process.

V- MODELING SSM

A- BULK MODELS

Semisolid materials are two-phase mixtures of liquid and solid particles. Therefore, a complete mathematical model should involve a complete description of both phases. However, it is possible to capture the bulk behavior of the slurry by using average models.

1- Model with constant structure

Bulk models that ignore the evolution of the microstructure attempt to reproduce the experimentally observed behavior that SSM slurries exhibit shear-thinning and shear-thickening behaviors under steady-shear and rapid transients, respectively. Therefore, the majority of such constitutive models are based on power-law type fluid models [5]. These models are valid to the extent of the underlying assumptions, i.e. shear thinning models are only valid for steady processes (not representative of fast filling processes). Similarly, shear-thickening models are valid under the assumption of constant microstructure, characteristic of rapid transient response. Alexandrou [13] used a phenomenological constitutive equation based on a Herschel-Bulkley fluid that fits both shear-thinning and shear-thickening behaviors. The finite yield stress implicit in the model accounts for the existence of finite yield stress,

$$\tau = \tau_o + K\dot{\gamma}^n \tag{1}$$

where τ is the shear stress tensor, $\dot{\gamma}$ the shear rate tensor, τ_o the yield stress, K the consistency index, and n the power law index. Indeed, numerical results in a sudden 3-D square expansion show that this model predicts the time evolution of yielded/unyielded regions (Figure 4) [14]. In unyielded zones, the material does not deform, and hence it remains stagnant or flows like a solid body.

2- Model with variable structure

The time-dependent rheological behavior is modeled using a non-dimensional structural parameter λ, similar to the one introduced by Mada and Ajersch [10] and Kumar et al. [7]. This parameter characterizes the state of the structure of the solid particles in the slurry. In a fully structured state i.e. when all the particles are connected, λ is assumed to be unity. In a fully broken state, when none of the particles are connected, λ is assumed to be zero. The evolution of this structural parameter

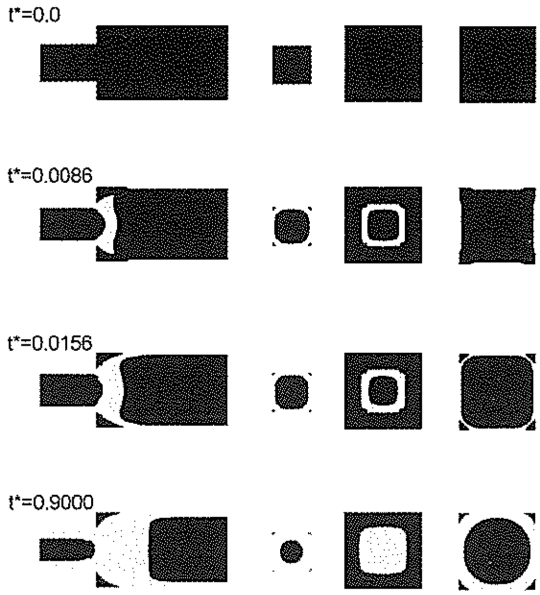


Figure 4: *Evolution of yielded (gray) and unyielded zones (black) in a sudden 3-D square expansion [14].*

is defined by a first-order rate equation, similar to the approach in chemical reaction kinetics [15]. Typically, it is assumed that the rate of breakdown depends on the fraction of links existing at any instant and on the deformation rate. Similarly, the rate of build-up is assumed to be proportional to the fraction of links remained to be formed,

$$\frac{\partial \lambda}{\partial t} + u \cdot \nabla \lambda = a(1-\lambda) - b\lambda|\dot{\gamma}|e^{c|\dot{\gamma}|} \tag{2}$$

where the recovery parameter a, and the breakdown parameters b and c are empirical constants. $|\dot{\gamma}|$ is the second invariant of the rate of strain tensor. The exponential dependence on the deformation rate, in the rate of break-down term of Equation (2) is included to account for the fact that the shear stress evolution for the shear-rate step-up experiment is faster than for the step-down case [10, 11, 16]. At equilibrium, the rate of breakdown is the same as the rate of recovery.

Consistent with the experimental evidence, the rheological constants are assumed to depend on λ and volume fraction s (hence, temperature),

$$= \;_o(\;, s) + K(\;, s)\dot{\gamma}^{n(\lambda, s)} \tag{3}$$

Experimental data then are analyzed for the actual dependence of the material parameters by using various assumptions concerning the initial state of the microstructure. For instance, it can be assumed that, starting from the same steady state shear stress, immediately after the shear-rate step-up and step-down experiments the structure remain the same (and hence λ) [17]. The assumption is based on the fact that in shear-rate step experiments, there is not enough time for the structure to change. Currently, complete sets of such experimental data are not available to determine the material properties and therefore, more experimental data is needed.

The constitutive model presented above is used to simulate the filling of a tensile bar cavity against gravity. This simple cavity is chosen in order to demonstrate the importance of the thixotropic behavior of SSM slurries. The evolution of the filling process with a gate velocity equal to 1 m/s is presented in Figure 5. The corresponding Reynolds and Bingham numbers are respectively, Re = 195 and Bi = 0.12. For the simulated conditions, the middle section is filled first, and then, the two end sections. A back-flow pattern in the lower section is generated due to the stepped change in cross section. High shear rates are generated close to the walls and specially in the lower end section of the tensile bar due to the change in direction of the flow. In these regions a breakdown of the structure is predicted. Only a small core region penetrating the bar remains almost undeformed at the end of the filling process.

3- Two-Phase Model

In a two-phase model based on transport phenomena ideas [17, 18], the deformation of the solid matrix was assumed to follow the behavior of an incompressible Herschel-Bulkley fluid while the liquid phase is assumed to behave as a Newtonian fluid. Numerical simulations [19, 20] predicted relative motion and particle crowding. The development of conservation laws for such two-phase theory is rather straightforward; however, the main issues are the appropriate constitutive models and material parameters that must be obtained through extensive experiments.

Figure 6 shows the distribution of solid fraction at the sudden expansion section of a 3-D square expansion. Di-agglomeration of solid particles are predicted close to the inlet channel wall due to the high shear rates encountered in this region while particle crowding is predicted at the corners.

VI- CONCLUSIONS

Processing metal alloys in their semisolid state has distinct advantages over similar near-net shape manufacturing processes. The process can be used

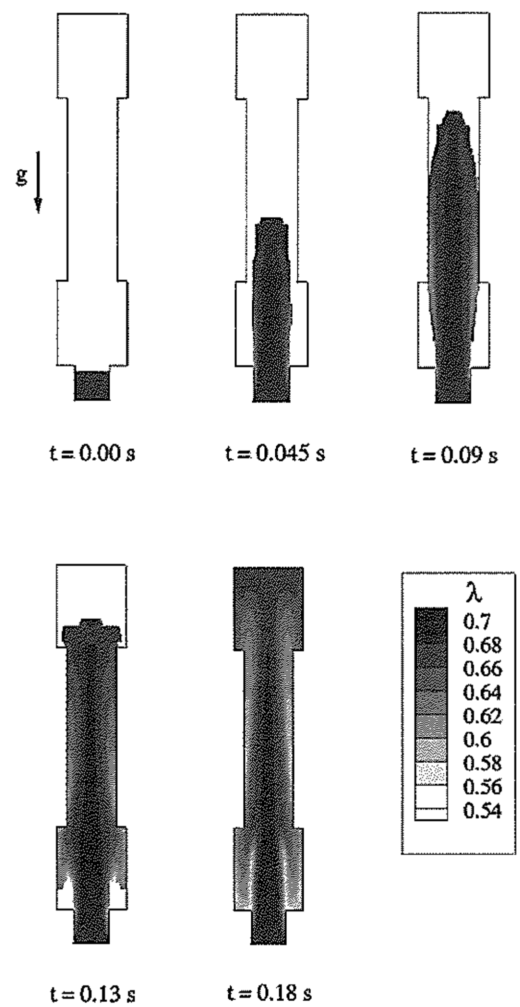


Figure 5: *Evolution of the structural parameter λ in the filling of a tensile bar cavity in the direction of gravity (Re =195, Bi = 0.12)*

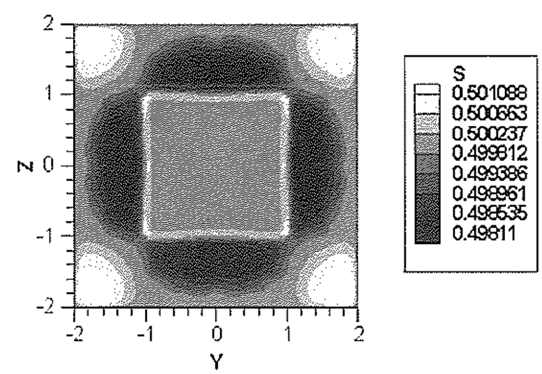


Figure 6: *Solid fraction distribution at the sudden expansion section of a 3-D square expansion*

to produce parts with improved mechanical properties compared to parts produced by conventional processes. However, the effective use of the process requires a good understanding of the physics of the process. Several issues remain to be understood before the potential of the process can be fully realized such as: (a) the effect of processing pre-history on microstructure development, (b) the re-heating of the material, (c) the rheology during processing, (d) solid/liquid phase separation etc. A complete understanding of the process can be achieved through simultaneous experimentation and mathematical/numerical modeling.

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