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A one phase thermomechanical model for the numerical simulation of semi-solid material behavior. Application to thixoforming

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ABSTRACT

This work deals with the development of an appropriate constitutive model for semi-solid thixoforming processes of metallic alloys. These processes rely on a very specific material behavior called thixotropy that can be displayed by some metallic alloys heated up to their semi-solid state. It is a particular evolutionary behavior which is characterized by a solid-like behavior at rest and a liquid flow during shearing, thus by a decrease of the viscosity and of the resistance to deformation while sheared.

An original one-phase thermo-elasto-viscoplastic constitutive model has been developed. The basic idea is to extend the classical isotropic hardening and viscosity models beyond the solid state by considering two more non-dimensional internal scalar parameters. The semi-solid state is treated as a particular case, and one of the main features of the proposed constitutive model is that it remains valid over a wide range of temperatures, starting from room temperature to above the liquidus in a continuous manner, thus allowing a continuous transition between classical solid and fluid behavior.

Another feature is that, after the forming step, it is possible to simulate the cooling down of the component back to room temperature using the elastic–viscoplastic model. So it is possible to estimate residual stresses, something that is definitely impossible while using a fluid-like model or a rigid viscoplastic approach.

The presented model is illustrated and validated by means of representative numerical applications, as two different extrusion tests are carried out and the computed predictions are compared to experimental results.

1. Introduction

Semi-solid thixoforming relies on a particular material behavior that can be exhibited by some semi-solid metallic alloys. These materials display thixotropy, which is characterized by a solid-like behavior at rest and a liquid-like flow when submitted to shear. This behavior is illustrated in Fig. 1 where the metal can be cut and spread as easily as butter.

The key point of semi-solid forming processes is the thixotropy of metallic alloys at the semi-solid state which can appear between solidus and liquidus temperatures of the alloy. Thus, semi-solid forming processes can be seen as an intermediate family of processes between casting and forging.

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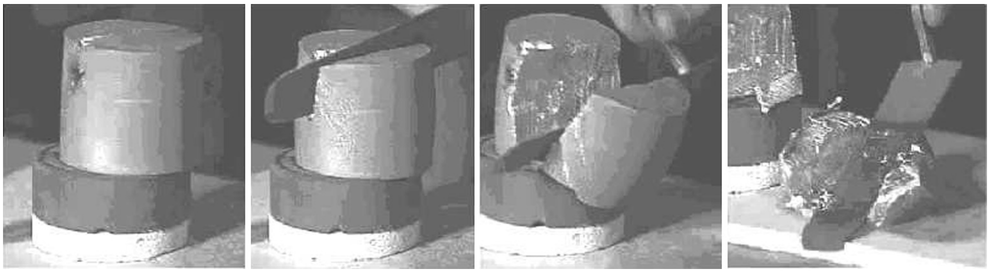

Fig. 1. Photographic sequence illustrating the thixotropic behavior of a semi-solid alloy slug (Atkinson, 2005).

As a consequence, a family of innovative manufacturing methods based on this thixotropic behavior presents the potential to gather the advantages of both casting and forging while trying to avoid their respective drawbacks: On the one hand, casting allows to produce a large variety of complex geometries, most notably thin-wall components that allow the manufacturing of lighter parts. However, during solidification, the material tends to shrink, and this inevitably leads to porosity that weakens the mechanical properties of the final product. On the other hand, forging can offer a very good level of mechanical properties but is limited to simpler geometrical designs than with casting. The waste of material is also higher than in casting.

Semi-solid material processes have already proved to be efficient in several application fields, such as military, aerospace and most notably automotive industries. However, the range of metallic alloys that are suitable for thixoforming is still limited and a lot of efforts is currently being put into broadening it. In this context, simulation techniques exhibit great potential to gain a better understanding of these semi-solid manufacturing routes and may be very helpful in the development of the process.

Therefore, the present work lies within the scope of the numerical simulation of thixoforming processes. More precisely, the goal of this work was the development of constitutive laws to model the thixotropic behavior. The resulting constitutive model has been integrated into the object oriented finite element code Metafor (Ponthot, 2013).

The paper is structured as follows. First, the specificities of the thixotropic behavior that have been observed experimentally and that need to be inserted in the models are detailed. In other words, the background rheology and mathematical theories of thixotropy are reviewed in order to develop proper constitutive models and to simulate thixoforming processes by means of, for example, the finite element method. In essence, thixotropic materials are highly temperature dependent and rate sensitive so that computational modeling must include non steady-states as well as thermomechanical effects.

All constitutive models that are studied here are one-phase models based on a solid thermo-elasto-viscoplastic formulation with isotropic hardening. The choice of this specific framework is motivated by the following arguments.

Versus two-phase models see e.g., Zavaliangos and Lawley (1995), Kang and Yoon (1997), Ko et al. (2000), Petera et al. (2004), and Petera (2006, 2008) one phase models appear to be much simpler and thus lighter in terms of material parameters involved, and associated identification, as well as in terms of implementation and CPU costs. As long as macrosegregation (Atkinson, 2005; Koeune, 2011; Koeune and Ponthot, 2010a) is not a big concern, the consideration of such a complex two-fields calculation that is required by two-phase models is not necessary.

As the central issue of this work, the focus is then put on the development of the constitutive modeling. It is established in the frame of the solid thermo-elasto-viscoplastic formalism, and is extended here in a continuous way in order to be able to simulate fluid flows therefore allowing a continuous transition between solid and fluid behavior. The key concept of the proposed models, beyond J2 large deformation thermo-elasto-viscoplastic model, relies on two additional internal parameters to reproduce the material behavior. The first one introduces the effect of the evolution of the microstructure of the material and the other one manages the transition between the solid and the liquid state. Step by step, the different features of the model are introduced and discussed. The motivations that have lead to the proposition of each of these features are also explained.

Finally, to validate the proposed constitutive laws and analyze the ability of these models to predict the thixotropic behavior, the numerical simulations of several bench tests are conducted. The computed results are described, analyzed, and compared to experimental data. Two forming processes are numerically represented. They are based on the experimental campaign that has been conducted at the University of Liège by Pierret (2009), Vaneetveld (2009), and Pierret et al. (2010).

2. Rheological aspects

This section aims at giving a brief review about the thixotropic behavior in order to derive constitutive relations by structural considerations.

First, it is worth mentioning that thixotropic behavior is not restricted to metallic alloys, but also appears in polymer materials. For thixotropic behavior of polymeric materials, the interested reader can, among others, refer to Drozdov and