A CONTINUOUS FLUID/SOLID TRANSITION MODEL FOR SEMI-SOLID MATERIAL MODELING.

APPLICATION TO THIXOFORGING

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Abstract This paper deals with the simulation of two extrusion tests by thixoforming: a non stationary extrusion test and a double-cup extrusion test. The simulations are based on a thermo-mechanical one-phase constitutive law that has been presented in details in several previous papers. A campaign of experimental extrusion testing has been conducted on a steel alloy and the comparison between the numerical and experimental results will validate the model under study. A new feature that has been added to the model is also discussed: the introduction of the phase change thermal effects such as the fusion latent heat and the contraction of the material.

Keywords: Finite Element Method (FEM), Thixoforging, Semi-solid, Thermo-mechanical coupling, Arbitrary Lagrangian Eulerian formulation

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1 Introduction

The semi-solid forming of steels reveals high potential to reduce material as well as energy consumption compared to conventional process technologies. Simulation techniques exhibit a great potential to acquire a good understanding of the semi-solid material process. Therefore, the goal of this research was to validate the constitutive law presented in a previous work [1]. This study focuses on thixoforging working at low liquid fractions.

First of all, a new feature has been introduced in the model and is presented in section 2.

Then, sections 3 and 4 present the simulations of two extrusion tests of steel alloy. The computed results have been compared to experimental data [2,3].

2 Phase change thermal effects

This section focuses on heat conduction problems with phase change. In the present work, the thermal calculation is based on a weak formulation of the energy equation, and does not track the interface between the phases but consider the material as homogeneous (as it is done for the one-phase constitutive law). Thus, it can not represent the temperature gradient discontinuity at the interface.

The thermal energy conservation equation can be written as:

$$\frac{\partial h}{\partial T}\dot{T} = -\nabla(\lambda\nabla\mathbf{T}) + Q$$

(1)

where h is the enthalpy, T the temperature, λ the thermal conductivity and Q the volume heat sources power.

J. Petera[4] assumes there exists a unique relationship between enthalpy and temperature and proposes the following equation including phase change:

$$h(T) = \int_{T_{ref}}^{T} \rho c_s dT + f_l \int_{T_s}^{T} (\rho c_l - \rho c_s) dT + f_l L \quad (2)$$

where $\rho c_{s,l}$ are the volume heat capacity of the solid or the liquid phase respectively, f_l is the liquid fraction, L is the phase change latent heat, T_{ref} is a reference temperature and T_s is the solidus.

Thus, we have:

$$\frac{\partial h}{\partial T} = \underbrace{\rho c_s + f_l(\rho c_l - \rho c_s) + \frac{\partial f_l}{\partial T}\int_{T_s}^{T}(\rho c_l - \rho c_s)dT}_{\rho c_p} + \frac{\partial f_l}{\partial T}L \quad (3)$$

$$= \rho c_{eq}$$

Here, the method of equivalent heat capacity is adopted and Eq.(1) is rewritten as:

$$\rho c_{eq}(T)\dot{T} = -\nabla(\lambda \nabla \mathbf{T}) + Q$$

(4)

We can see in Eq.(3) that the function $\rho c_{eq}(T)$ is a continuous function only if the function $f_l(T)$ is continuously differentiable, which is not the case of the Scheil equation adopted in this work (see[1]):

$$f_l = \begin{cases} 0 & \text{if } T \le T_s \\ \left(\dfrac{T - T_s}{T_l - T_s}\right)^{\frac{1}{r-1}} & \text{if } T_s < T < T \\ 1 & \text{if } T \ge T_l \end{cases}$$

(5)

$$\Rightarrow \frac{df_l}{dT} = \begin{cases} 0 & \text{if } T \le T_s \\ \dfrac{f_l^{\,2-r}}{(r-1)(T_l - T_s)} & \text{if } T_s < T < T_l \\ 0 & \text{if } T \ge T_l \end{cases} \quad (6)$$

Taking a closer look to Eq.(6), it can be seen that the derivative of the liquid fraction is well continuous around the solidus (as long as we keep r<2). It is not the case at the liquidus. This fact is illustrated in Fig.1 where the different heat capacities are plotted in terms of the temperature.

This discontinuity in the equivalent heat capacity can cause numerical problems at temperatures near the liquidus. However, this is not a concern in the present framework, which is focused on thixoforging and where liquid fractions remain low.

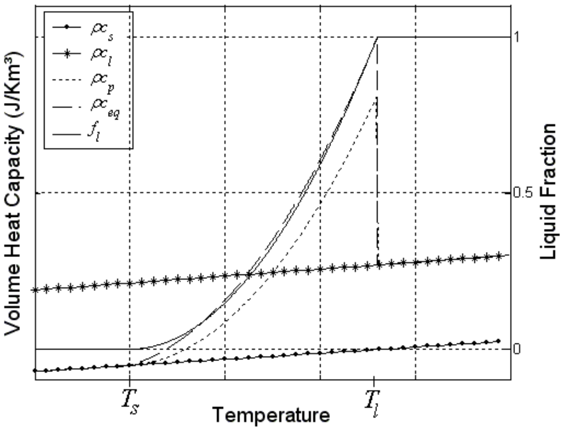

Fig.1 Heat capacities evolution with temperature

Eq. (3) shows that the equivalent volume heat capacity ρc_{eq} has got two contributions: ρc_p , which introduces the effect of material properties modifications and contraction with phase change and a term that includes the phase change latent heat. This last term of latent heat has the effect to increase the apparent heat capacity of the material and, following Eq.(4), it will thus tend to decrease the temperature rate $\dot{T}$. This means that, when temperature is increasing, the phase change (fusion) consumes heat which slows down the temperature elevation. On the contrary, when temperature is decreasing there is some heat dissipation due to solidification.

To illustrate the introduction of phase change effects on heat conduction, several simulations of the compression test detailed in [1] have been conducted.

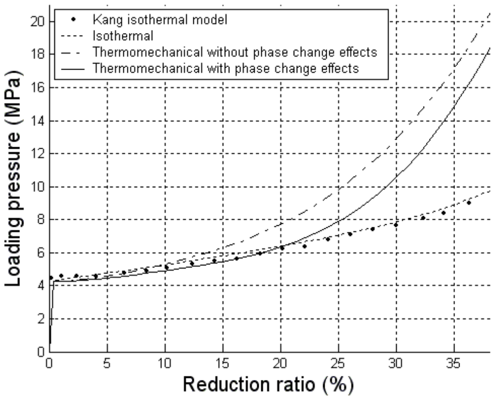

Fig.2 Comparison of different models on a compression test

Fig.2 compares results in terms of loading pressure for different models: If we take Kang's isothermal model[5] as a reference, we can see that the model proposed in[1] shows good agreement under isothermal conditions. When introducing thermomechanical effects in the model, the contact with the colder die causes some solidification which increases the loading forces. Finally, it can be seen that taking into account the phase change effects on the thermal calculation counteracts this fact, the results being closer to the isothermal case. This is coherent with the comment made above saying that phase change effects go against temperature variations.

3 Non stationary extrusion test

Now, we will focus on numerical simulations and the validation of the proposed model.

The extrusion process consists in pushing a billet through a pattern. This method results to long products of different shapes. A campaign of experimental cylindrical extrusion testing [2] has been conducted on a steel alloy that was modified for thixoforming properties (see Fig. 3a).

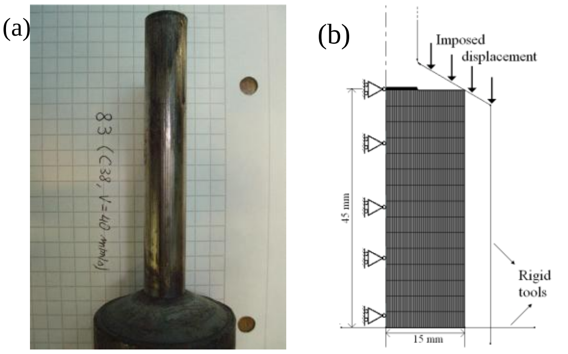

Fig.3 Description of the non stationary extrusion experiment (a) and simulation (b)

The experiment can be reduced to the 2D axisymmetric test described in Fig. 3b. The billet is 45mm high and has a radius of 15mm. One section is discretized using a 15 by 30 mesh, and the calculation uses an "Augmented Lagrangien Eulerian" (ALE) [6] formalism to deal with the high deformations occurring into the piece. In general, the die velocity V_{die} is 100mm/s. The friction coefficient is 0.05 and the initial temperature T_0 is 1440°C. The billet is made of a modified C38 steel alloy for which we know most common material parameters. Some material parameters, specific to the original constitutive model under study, are chosen to best fit the experiments so far. The choice of the material parameters is detailed in Table 1.

Table 1 Material parameters for steel alloy C38

Young modulus: $E = 207 - 0.1T$ (GPa)	Shear modulus: $G = \frac{E}{2.6}$	
Equilibrium partition ratio: $r = 1.5$	Solidus: T_s =1350 ($^\circ$C)	Liquidus: T_l = 1480 ($^\circ$C)
Cohesion degree: $a = 0.035$ (1/s); $b = 0.15$; $c = 1.5$ (s); $d = 0.001$; $\lambda_{initial} = 1$; $f_c = 0.6$		
Viscosity: $k_1 = 0.45$ (Pa); $k_2 = 0.1$; $k_3 = 12.173$; - *Original model*: $m_1 = 1$; $m_2 = 0.1$; $m_3 = m_4 = 0$		
Hardening: $h_1 = 6.87$ (MPa) ; $h_2 = 2.5$; σ_y^0 =10.13 (MPa)		

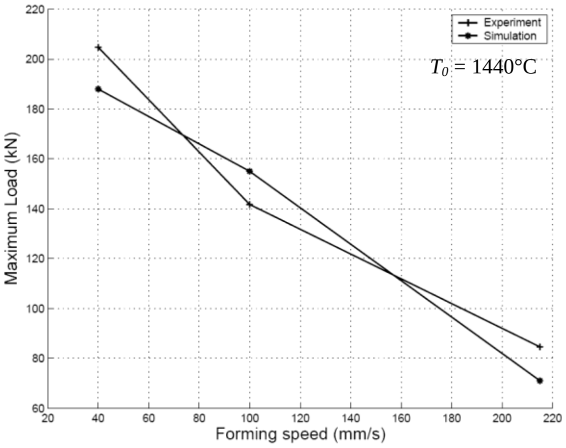

Fig.4 Load variation with forming speed, comparison between experiments

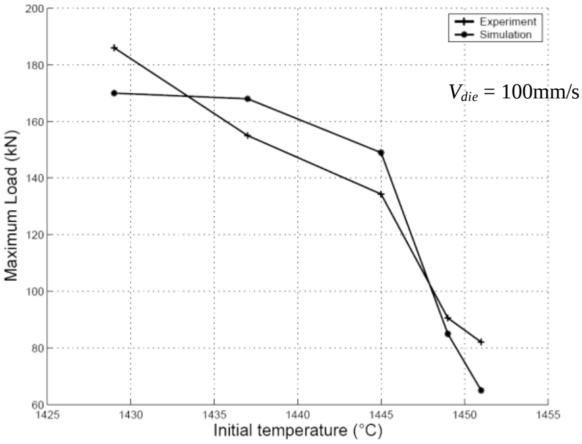

Fig.5 Load variation with initial temperature, comparison between experiments and simulations

The experiments showed that the forming load decreases if the forming speed increases. The same effect can be seen with the initial temperature in the billet. These facts are well reproduced by the simulations, as we can see in Fig. 4 and 5.

This shows that semi-solid thixotropic behavior is very sensitive to process parameters and that it is important to choose the right set of parameters. Indeed, even if both reductions of the forming speed or of the initial temperature will decrease the load, it will not give the same results in terms of final product, as illustrated in Fig.6. Numerical simulations can be of great help in this task.

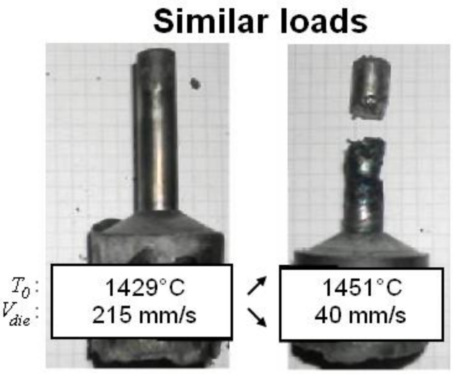

Fig.6 Illustration of the need for a right set of process parameters

4 Double-cup extrusion test

Another test that has been studied is the double-cup extrusion test with steel alloy 100Cr6, for which parameters are described in Table 2.

Table 2 Material parameters for steel alloy 100Cr6

Young modulus: $E = 210 - 0.1T$ (GPa)	Shear modulus: $G = \frac{E}{2.6}$	
Equilibrium partition ratio: $r = 1.5$	Solidus: $T_s = 1297$ ($^\circ$C)	Liquidus: $T_l = 1451$ ($^\circ$C)
Cohesion degree: $a = 0.035$ (1/s); $b = 0.15$; $c = 1.5$ (s); $d = 0.001$; $\lambda_{initial} = 1$; $f_c = 0.6$		
Viscosity: $k_1 = 0.45$ (Pa); $k_2 = 0.1$; $k_3 = 12.173$; - *Original model*: $m_1 = 1$; $m_2 = 0.1$; $m_3 = m_4 = 0$		
Hardening: $h_1 = 6.87$ (MPa) ; $h_2 = 2.5$; $\sigma_y^0 = 63.32$ (MPa)		

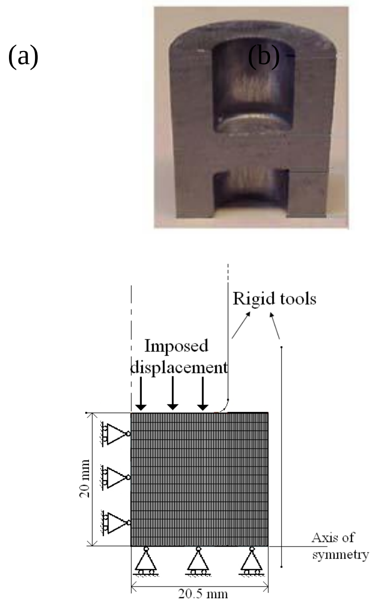

Fig.7 Description of the double-cup extrusion experiment (a) and simulation (b)

The test is illustrated in Fig. 7. It can again be considered as axisymmetric, moreover, we assume here an horizontal orthogonal symmetry. The billet is 40mm high and has a radius of 20.5mm. One section is discretized using a 60 by 15 mesh. The die velocity is 50mm/s. The friction coefficient is 0.1 and the initial temperature is 1410°C.

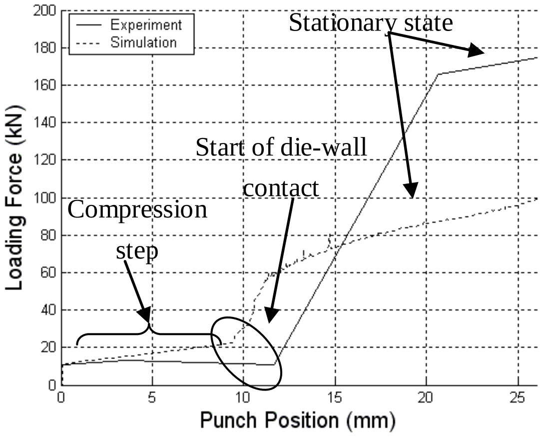

Fig.8 Loading force evolution during the double cup extrusion, comparison between experiments

It can be seen in Fig. 8 that, in terms of the loading force evolution, the simulations are in good qualitative agreement with the experiments [3]. The loading curve can be divided in three steps in both experimental and numerical results, the curves presenting three different slopes. During the first step, the slug is under a simple compression with constant load and there is no contact with the external wall yet. Then, during the second step, the extrusion starts, which leads to a raise of the loading force. Finally, the extrusion reaches a stationary state and the loading-position curve slope decreases. The slopes of each parts of the loading curve are the same in both cases. The differences come from the duration of each step that are underestimated by the model.

The numerical simulation results are illustrated in Fig. 9.

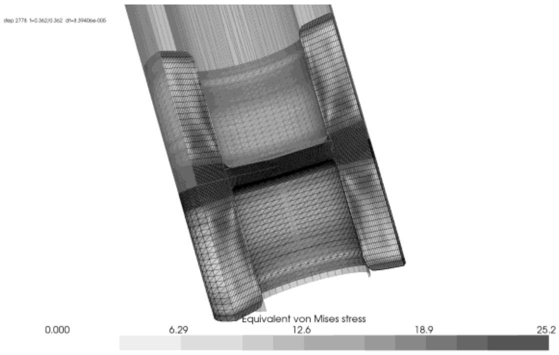

Fig.9 Numerical simulation of the double cup extrusion

5 Conclusions

In summary, this paper refers to the development of a constitutive model for semi-solid thixoforming. An original constitutive model for thixoforming has been presented. It is integrated in a home-made FE code in ALE, applicable to different materials, and able to reproduce the main particularities of thixoforming processes.

Also the phase change effects on thermal conduction have been studied and can be taken into account in the numerical simulations.

The model is tested with the simulation of extrusion tests. The results are in good agreement with the experiments. So far, some material parameters used in the model are chosen to best fit the experiments. Thus, the next steps of the research are the accurate experimental identification of the material parameters.

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