INTEGRATION OF A RECRYSTALLISATION MODEL COUPLED WITH AN ELASTO-VISCO-PLASTIC LAW. EXPERIMENTAL TESTS AND CALIBRATION OF THIS MODEL.

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Abstract: The recrystallisation model is based on the model developed by Kopp [1,2]. This model is implemented in our finite element code "lagamine" and is coupled with a thermo-mechanical elasto-visco-plastic law. It assumes that each integration point in the mesh is represented by a number of sub-structures with a different volumic recrystallised fraction.
In order to be able to calibrate such a model, we need to perform a lot of experimental tests. Hot compression tests on small cylinder at different temperatures and strain rates are made till strain level from 0.1 up to 0.7. The compressed cylinders are quenched after the tests.
A metallographic study of the quenched cylinders gives the recrystallised fraction function of the strain, the strain rate and the temperature.
So experimental, numerical and metallographic studies of hot compression tests aim the definition of an accurate predictive thermo-mechanic metallurgical model able to simulate forging processes.

Keywords : Recrystallisation, Coupling, Numerical model

1 Introduction

Nowadays, more and more hot metal forming industries need to know the mechanic behaviour at high temperatures of their materials. These such defined characteristics allow to simulate various forging schemes with the aim to improve the physical phenomena understanding and to enable the process optimization at a relative low cost.
During these various forging schemes, the number of dislocations increases and the recrystallisation process allows to immediately anneal a lot of these dislocations.
This model is based on the concept published by Sellars [3] and has been implemented in our non linear finite element code called LAGAMINE [4] which is an updated lagrangian code.

2 The elasto-visco-plastic law

In solid elements, the stresses are computed by an elasto-visco-plastic constitutive Norton-Hoff type [5] law with thermal effects. Its formulation is :

$$\bar{\sigma} = K_0 \bar{\varepsilon}^{p4} . \exp(-p_1 \bar{\varepsilon}) p_2 . \sqrt{3} (\sqrt{3} . \dot{\bar{\varepsilon}})^{p3} \qquad (1)$$

where $\bar{\sigma}$ and $\bar{\varepsilon}$ are respectively the equivalent Cauchy stress and strain, $\dot{\bar{\varepsilon}}$ the equivalent strain rate and K_0, p_1, p_2, p_3, p_4 are material parameters. The deviatoric visco-plastic strain rate $\hat{\dot{\varepsilon}}^{vp}_{ij}$ gives the tensorial form of this law.

$$\hat{\dot{\varepsilon}}^{vp}_{ij} = \frac{(J_2)^{\frac{1-p_3}{2p_3}} . \bar{\varepsilon}^{\frac{-p_4}{p_3}} . \exp(\frac{p_1}{p_3} \bar{\varepsilon}) . \hat{\sigma}_{ij}}{2.(K_0 p_2)^{1/p_3}} \qquad (2)$$

where $\hat{\sigma}$ is the deviatoric stress tensor and $J_2 = \frac{1}{2} \hat{\sigma}_{ij} \hat{\sigma}_{ij}$ the second stress invariant. Such description allows the modelization of a behaviour which includes hardening and softening.

The thermal dependence of the parameters p_1 to p_4 is defined by :

$$p_4 = \text{cons tan t} \qquad p_3 = \text{cons tan t}$$
$$p_1 = -\left(\frac{T}{C_1}\right)^{C_2} + C_3 \qquad p_2 = \left(\frac{C_4}{T}\right)^2 + \frac{C_5}{T} + C_6 \tag{3}$$

where T is the temperature and C_1, C_2, C_3, C_4, C_5, C_6 are material constants.

The integration is computed by an implicit method :

$$\hat{\dot{\sigma}}_{ij} = 2G\left(\hat{\dot{\varepsilon}}_{ij}^{total} - \hat{\dot{\varepsilon}}_{ij}^{vp}\right) + \frac{1}{G}\frac{\partial G}{\partial T}\hat{\sigma}_{ij}\,\dot{T} \tag{4}$$

or

$$\hat{\underline{\dot{\sigma}}}(t) = h(\hat{\underline{\sigma}}, \bar{\varepsilon}, T) + g(t, T) \tag{5}$$

where t is the time and the second order tensors are either expressed by their indicial notation or underlined.
If we suppose that we known $\hat{\underline{\sigma}}_k$ at $t = t_o$, the difficulty is to compute $\hat{\underline{\sigma}}_{k+1}$ at time $t = t_o+\Delta t$. Developing the equation (5) in a Taylor series of first order, we found the expression giving the variation of the deviatoric stress tensor:

$$\left[\underline{\underline{I}} - \left.\frac{\partial h}{\partial \hat{\underline{\sigma}}}\right|_{t_o} .\theta.\Delta t\right]\Delta\hat{\underline{\sigma}} = \Delta t.\left[h\left[\hat{\underline{\sigma}}_k, \bar{\varepsilon}_k, T(t_o)\right] + \underline{g}(t_o + \theta\Delta t, T(t_o))\right] + \theta.\Delta t\left[\left.\frac{\partial h}{\partial \underline{\underline{\varepsilon}}}\right|_{t_o} \Delta\bar{\varepsilon} + \left.\frac{\partial h}{\partial T}\right|_{t_o} \Delta T + \left.\frac{\partial g}{\partial T}\right|_{t_o} \Delta T\right] \tag{6}$$

with $0<\theta<1$. Generally we use $\theta = 2/3$.

3 The recrystallisation model

When the dynamic recrystallisation appears, sub-structures are present at the same time and lead to material properties that are different from the initial material properties. These sub-structures are defined by their volumic fraction and hardening degree.
The individual σ-ε curve of each sub-structure is a function of the forming condition (strain rate, temperature). The stress formulation is defined by the equation (2). The end of this curve represented by [1] on the next figure is defined by a hypothetical stationary stress.

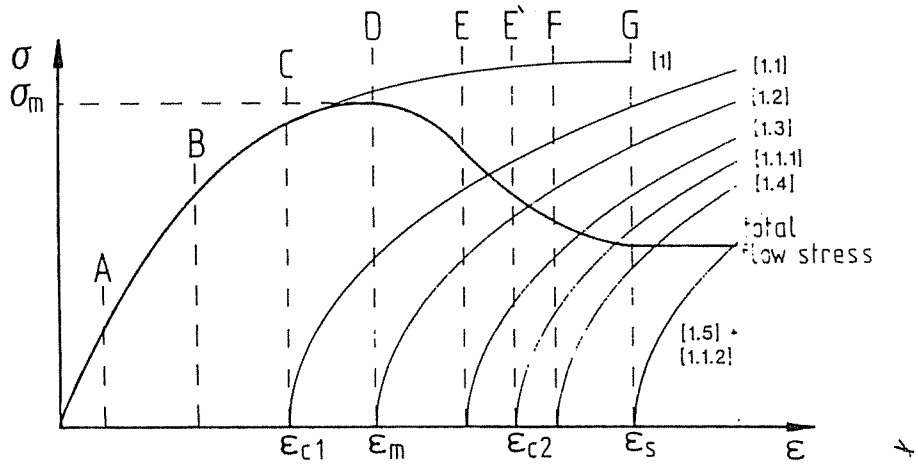


Figure 1. Sub-structure and total σ-ε curves.

A new sub-structure appears when the old one has reached the critical value of the recrystallisation strain ε_c. The stresses and the strain of this new sub-structure is thus equal to zero.
The calculation of the sub-structure volume A_{ij} is defined by the additivity law. The subscribe j characterizes the sub-structure and the subscribe i the time or strain increment.

The recrystallisation kinetic is described by an Avrami law:

$$X_{dyn} = 1 - \exp\left(p_8 \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_s - \varepsilon_c}\right)^{p_9}\right) \quad (7)$$

with X_{dyn} = recrystallised volume fraction

ε_c = equation defining the strain value at the beginning of the recrystallisation = $p_5 Z^{p_6}$ (8)

ε_s = equation defining the strain value when the stationary stress is reached = $p_7 Z^{p_{10}}$ (9)

p_5, p_6, p_7, p_8, p_9, p_{10} = parameters.

Z = Zener Hollomon parameter

When the recrystallisation begins or goes on, we have a new sub-structure because of the new forming conditions:

$$X_{i,j+1} = X_{dyn\,i,j} - X_{i-1,j} \quad (10)$$

The volume of this new sub-structure depends on the volume of the sub-structure that is recrystallised.

$$A_{i,j+1} = A_{i-1,j} X_{i,j+1} \quad (11)$$

$$A_{i,j} = A_{i-1,j} - A_{i,j+1} \quad (12)$$

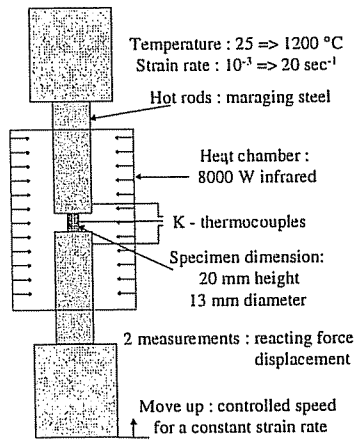
This approach is completely based on the additivity rule that supposes the recrystallisation kinetic only depends on the recrystallised volume and the forming conditions (strain rate, temperature).

The stress-strain curve of this composite structure is the sum of the stress-strain curve of each sub-structure factored by their volumic fraction:

$$\sigma_i = \sum_j A_{i,j}\sigma_{i,j} \quad (13)$$

4 Experimental tests

Hot compression tests on small cylinders at different temperatures and strain rates are made till strain level from 0.1 up to 0.7. The temperature is regulated by using type K thermocouples and the heating is performed by using a quad elliptic chamber with four infrared lamps. The temperature and the strain rate $\dot{\varepsilon}$ are kept constant during the compression test thanks to regulation. The compressed cylinders are quenched after the tests.
A metallographic study of the quenched cylinders gives the recrystallised fraction function of the strain, the strain rate and the temperature.
This model has been developed to modelize the forging of steel .At this time, we are not able to show the metallographic study results because this study is still in progress. But we have tested our model with parameters available for a zinc alloy. The results of these simulations are shown in next paragraph.



5 Numerical simulation

The simulation represents a compression test. Only the upper half part of the cylinder has been discretized and the simulation is axisymetric.
We have compared the results obtained with the recrystallisation model coupled with the thermo-mechanical law and with the same uncoupled models.
The reacting force decreases when we take the coupling between the recrystallisation and the mechanics into account (fig 2). But this reacting force is given by the experimental tests and should be the same in both cases. So we need to improve the calibration of our model to be more accurate. The volumic recrystallised fraction is the same in both simulations (see fig. 3).

We can also see, on figures 4 and 5, that the distribution of the equivalent stresses for the coupled model (fig. 4) is more constant along the cross section than for the uncoupled one (fig 5).

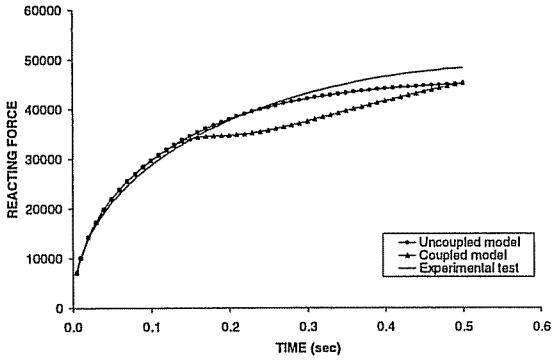


Figure 2 : Comparison of the reacting forces

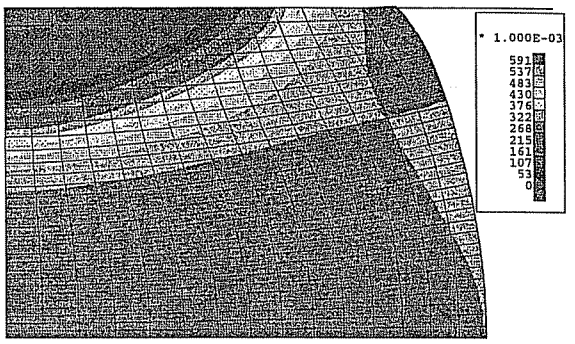


Figure 3 : Volumic recrystallised fraction map

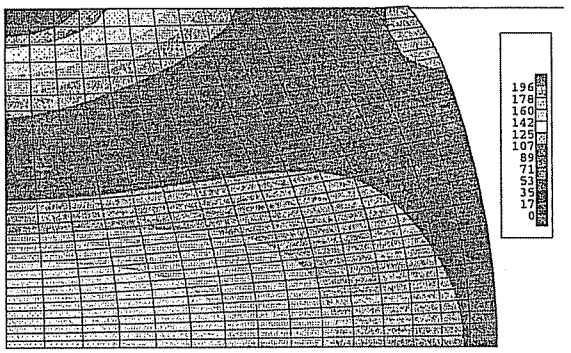


Figure 4 : Equivalent stresses map : no coupling (Mpa)

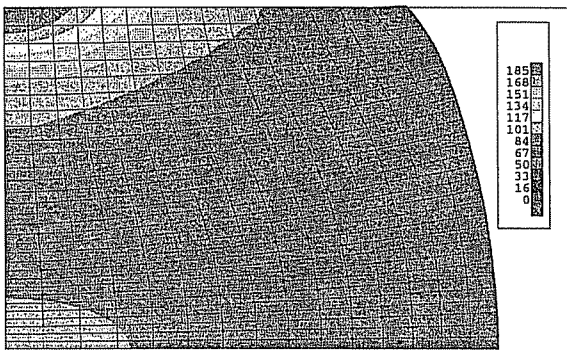


Figure 5 : Equivalent stresses map : coupling (Mpa)

6 Conclusion

Our model has been roughly calibrated with the program Excel assuming a full homogeneity of stresses, strain and strain rate across the section at half height of the tested samples. In fact, the experimental tests give the total flow stress as shown on figure 1 and we need to calibrate the flow stress of each sub-structure represented by [1] on the same figure. But this flow stress cannot be deduced from the experimental tests. So we strongly need to develop an inverse method to make our results more accurate. This will be done in the near future and will be used to calibrate the model for the forging steel we are now studying.

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