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A MECHANICAL BEHAVIOR LAW FOR THE NUMERICAL SIMULATION OF THE MUSHY ZONE IN WELDING

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Abstract. The aim of this work is to propose a mechanical behavior law dedicated to the mushy zone located between the solid phase and the weld pool in welding. The objective is to take into account of the influence of the mushy zone in the simulation of welding in order to improve the computation of induced effects such as residual stresses.

1 INTRODUCTION

During welding, the material can be liquid in the weld pool or solid in the rest of the assembly. These two states can co-exist in the mushy zone located between the weld pool and the structure as shown in figure 1. This zone is caracterized by a temperature between the liquidis temperature and the solidus temperature.

From the simulation point of view, the mushy zone is not always considered for the computation of residual effects such as residual stresses. For example, Heuzé suggests to use two independent behavior laws without considering a mushy zone. His approach consists in coupling a Lagrange solid and a Euler fluid using a melting temperature criterion. This criterion defines the temperature at which, the base material is switched "sharply" between solid and liquid phases, as for an isothermal transformation. This technique has been implemented in the software SYSWELD® [4].

Unfortunately, the computation of residual stresses requires to take accurately into account the behavior of the solid state during all the cooling stage including the solidification in the mushy zone. The finite element simulation of such phenomenon is not always obvious. To take account of the mixture mechanical behavior in the mushy zone, Decultieux [1] and Vicente [3] propose a specific law depending on the solidification state. They consider a half fluid visco plastic behavior for a fluid fraction f_L between 50% and 100% and a half solid elasto visco plastic behavior for $0\% \prec f_L \prec 50\%$. Jaouen [2] has used this approach to model the solidification of alloys in casting. He has defined a reference temperature called coherence temperature corresponding to $f_L = 50\%$, at which the mixture behavior changes.

In this paper, we propose a new approach based on a continuous transition between the solid and the liquid phases through the mushy zone. It is a phenomenological and pragmatic approach to compute the mixture behavior in a solid context. An example of a spot weld is proposed to show the interest of such an approach.

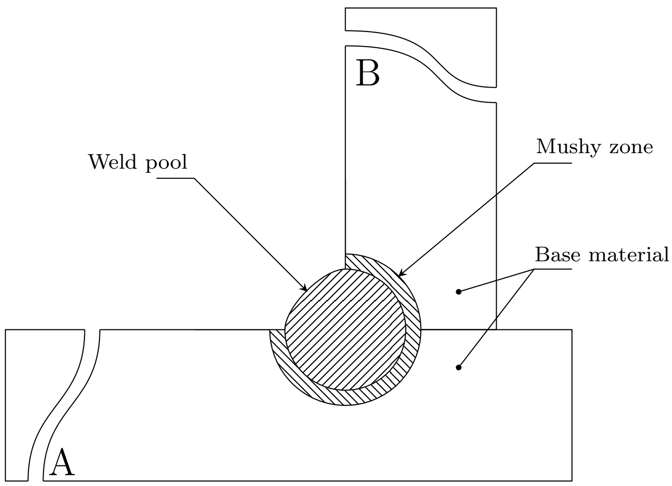


Figure 1: Schematic description of welding

2 Behaviour law

2.1 Formulation

The new behavior law proposed in this work is based on a combination of parallel and serie behaviors. The use of a pure parallel behaviour is unrealistic because the deformation is therefore the same in the solid and the liquid which do not behave in the same way. Indeed, the liquid is assumed to be incompressible unlike solid which is not. With such an approach, as soon as a fluid drop appears, the behavior of the mixture becomes incompressible. To overcome this difficulty, we propose a more complex combination of parallel and serie behaviors. The parallel behavior is modeling the deviatoric part of the stress tensor whereas the serie behavior is modeling the spherical part as shown in the figure 2.

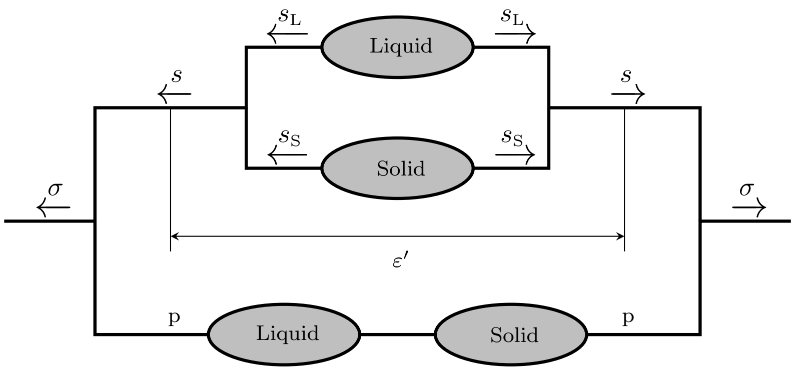


Figure 2: Rheological scheme of the combined model

The pressure and the deviatoric part of the deformation are supposed to be the same in the solid and the liquid. The stress tensor is obtained by:

$$\bar{\bar{s}} = f_L \, \bar{\bar{s}}_L + f_S \, \bar{\bar{s}}_S \tag{1}$$

$$p_S = p_L = p \tag{2}$$

$$\bar{\bar{\sigma}} = \bar{\bar{s}} + p \, \bar{\bar{I}} \tag{3}$$

Where T, p, $\bar{\bar{\sigma}}$, $\bar{\bar{s}}$ represent respectively the temperature, the pressure, the stress tensor and it's deviatoric part. The indexes L and S are related to the solid and the liquid phases. f_L and f_S denote the liquid and solid fraction depending on the temperature only with $f_S = 1 - f_L$. Using a linear mixture rule, we get

$$\begin{cases} f_L = 1 & si \quad T \succcurlyeq T_L \\ f_L = \frac{T - T_S}{T_L - T_S} & si \quad T_S \preccurlyeq T \preccurlyeq T_L \\ f_L = 0 & si \quad T \preccurlyeq T_S \end{cases} \tag{4}$$

where T_L and T_S denote the liquidis temperature and the solidus temperature.

2.2 Implementation

Considering that the pressure is identical in the solid and the liquid, it's computed by means of the compressibility coefficient of the solid phase. As shown above, the stresses state is an overlay of both the solid and the fluid behaviour for the deviatoric part. From the numerical point of view, the deviatoric part is computed in each phase separately. At first, $\overline{\overline{s}}_{\mathrm{S}}$ is calculated using the solid mechanical behavior as follows:

$$\overline{\overline{s}}_{\mathrm{S}}= 2\mu^{\mathrm{s}} \, \overline{\overline{\varepsilon}}'^{e} \tag{5}$$

where $\overline{\overline{\varepsilon}}'^{e}$ denotes the deviatoric part of the elastic strain rate tensor $\overline{\overline{\varepsilon}}^{e}$. μ^{s} is respectively one of the Lamé parameters. In the fluid part, $\overline{\overline{s}}_{\mathrm{L}}$ is then obtained as follows

$$\overline{\overline{s}}_{\mathrm{L}}= 2\mu^{\mathrm{f}} \, \overline{\overline{\dot{\varepsilon}}}' \tag{6}$$

where $\overline{\overline{\dot{\varepsilon}}}'$ denotes the deviatoric part of the strain rate tensor and μ^{f} is the viscosity of the liquid. The stress tensor of the mixture is therefore given by:

$$\overline{\overline{\sigma}}= 2\mu^{\mathrm{s}} \left(1 - f_{\mathrm{L}}\right) \overline{\overline{\varepsilon}}'^{e} + 2\mu^{\mathrm{f}} f_{\mathrm{L}} \, \overline{\overline{\dot{\varepsilon}}}' + p \, \overline{\overline{I}} \tag{7}$$

The interest of such a model remains in the fact that we can use any kind of solid behaviour law. For the computation of the solid mechanical behavior, the history of the material in terms of plastic strain needs to be known at each time step. Because this history is deleted during the liquefaction in heating, it is necessary to distinguish several cases during the solidification:

- the existing solid fraction which has all its history,
- the existing fluid fraction which has not any history,
- the new formed solid fraction which has a virgin state.

In this way, the plastic strain and the cumulative plastic strain [6] need to take into account of the new formed solid fraction. The new values are those of a new solid fraction and they are given by:

$$\langle X_i \rangle = \frac{f_S{}^{\star}}{f_S} \quad X_i^{\star} \quad + \quad \frac{1}{2} \quad \frac{f_S^{\star} + f_S}{f_S} \quad (X_i - X_i^{\star}) \tag{8}$$

where X_i denotes the hardening strain or the cumulative plastic deformation, $\langle X_i \rangle$ is the mean value of X_i. The exponent "star"denotes the value of the variable at the previous time step.

3 Application

3.1 Description of the problem

We are interested in the 3D simulation of a SPOT welding. We consider a square plate of 40 *mm* side and 3 *mm* thick. This plate admits two plane of symmetry. Thus, only the quarter of the plate is modeled.
The mesh is represented on the figure 3. It contains 3,389 node and 12,261 linear tetrahedron element.

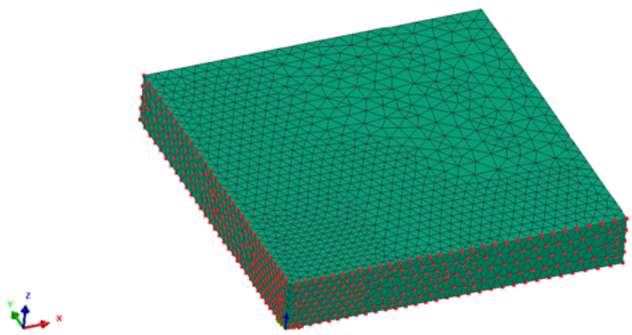


Figure 3: The mesh related to the quarter of the plate. The symmetry conditions are applied on the red nodes.

3.2 Boundary conditions

The thermal load is represented by an equivalent heat source applied on the top center of the plate. The heating is active during the first two seconds. A temperature of 293 K is imposed on the lateral side of the plate. The maximal temperature reached is 2368 K on the centre of the top side. After the first two heating seconds, the plate is cooled by conduction to reach the ambient temperature. The figure 4 shows the temperature of the center of the plate top side during the welding.

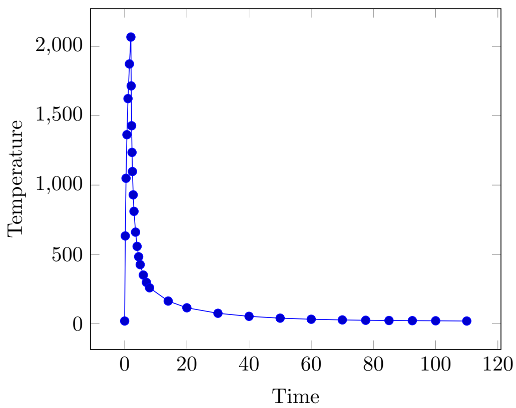
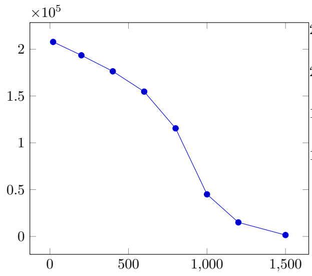
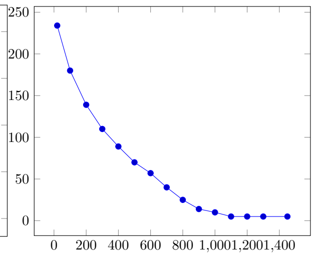


Figure 4: Temperature on the center of the plate top side

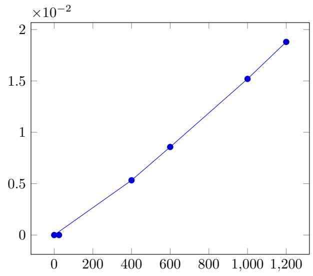
We consider an elasto-plastic solid behaviour with an isotropic hardening strain. The Young modulus, the yield stress, the thermal strain and the hardening strain depend on the temperature. They are represented on the figure 5. The Poisson's ratio is equal to $0,3$. The solidification and liquefaction temperature range is situated between $T_{\mathrm{S}} = 1673[K]$ and $T_{\mathrm{L}} = 1773[K]$.



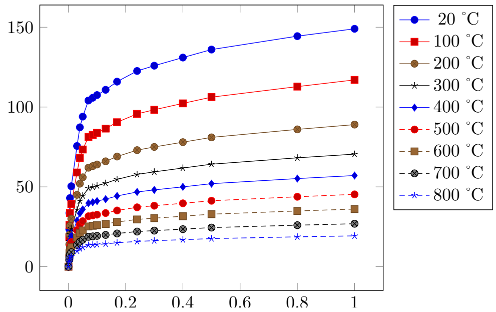
(a) Young modulus [MPa]



(b) Yield stress [MPa]



(c) Thermal strain

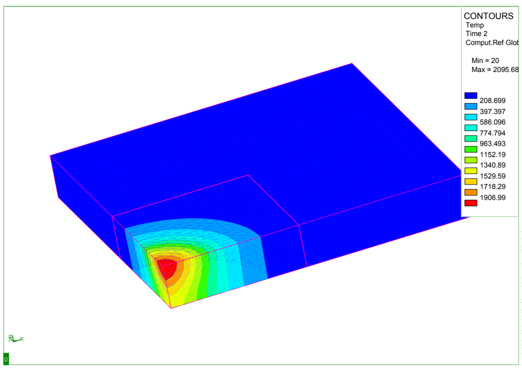


(d) Hardening strain [MPa]

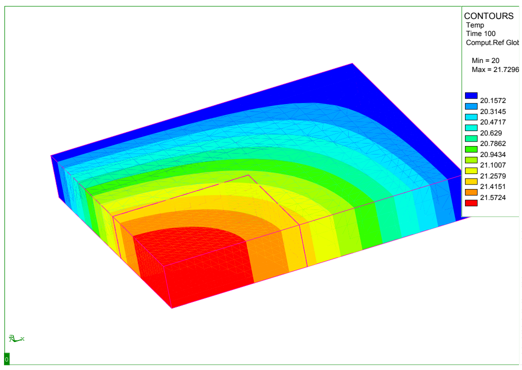
Figure 5: Material data

3.3 Numerical results

The temperature fields obtained at different times are presented on the figure 6. Concerning the pressure or the spherical part of the stress tensor, the figure 7 shows that



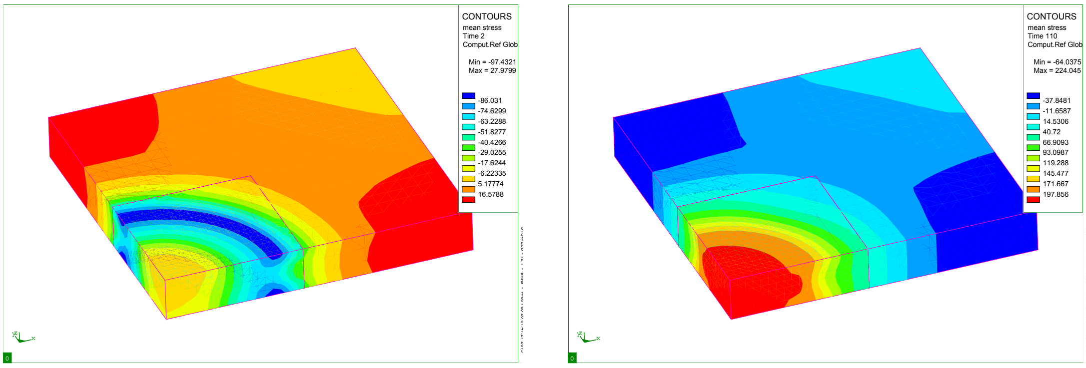
(a) 2 sec



(b) 110 sec

Figure 6: The temperature fields

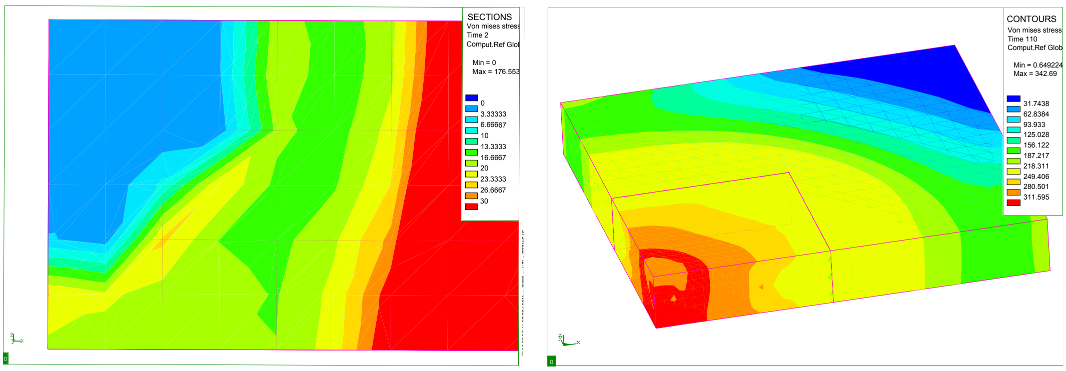
the pressure is uniform in the fluid and the mushy zone. We also mention that the new solid formed is under a tension state. Finally, the interest of the numerical simulation of



(a) 2 sec (b) 110 sec

Figure 7: The pressure fields

welding remain in the calculation of the residual stresses. The figure 8(a) shows that the stresses become weak in the mushy zone and approach zero in the molten pool. However, the figure 8(b) shows that, on the ambient temperature, we obtained a large Von mises stresses.



(a) Von mises at the time 2 sec (b) Von mises at the ambient temperature

Figure 8: Von mises stresses field

3.4 Conclusion

In this paper, we propose a new approach of a behaviour law able to simulate the mushy zone during the material transition in the welding process. This pragmatic approach is already implemented in the finite element software SYSWELD. The first results converges properly and leads to a satisfactory results.

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