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Understanding and modeling of void closure mechanisms in hot metal forming processes: a multiscale approach

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Abstract

After casting, metal ingots may contain voids of different shapes and sizes which need to be eliminated in order to deliver a sound material. Hot metal forming processes are regularly used in the industry to reach this goal, but the calibration of these processes to get a complete closure of internal voids is still an issue. Existing models in the literature are either based on explicit full-field approaches or micro-analytical approaches. Both approaches have significant limitations regarding industrial issues. A new multiscale approach is thus proposed here. Based on realistic macroscopic loading conditions, extracted from the process scale, meso-scale simulations are conducted on a representative volume element containing an ellipsoidal void. The ellipsoidal void's shape factor and orientation with respect to the loading direction are considered in the void closure evolution law in addition to the classical mechanical parameters (equivalent plastic strain and stress triaxiality ratio). Several process and void morphological parameters are analyzed regarding void closure and the proposed mean field model is validated by comparison with explicit full field simulations of hot rolling.

Keywords: Hot metal forming; Void closure mechanism; Multiscale approach

1. Introduction

During production of large metal workpieces, an internal presence of voids is usually observed. Such internal defaults are generally closed up during the first stages of hot forming processes. Yet, there is at present a lack of knowledge regarding void closure mechanisms and there is no reliable model that can accurately predict void closure. The amount of non-deliverable products is consequently relatively high. The present work aims at

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understanding void closure mechanisms with respect to the involved materials, processes and voids' morphological parameters.

Existing models in the literature are either based on explicit full-field approaches or micro-analytical approaches. Both approaches have significant limitations regarding industrial issues. A detailed review of existing models can be found in (Saby et al., 2014a). In the present work, a new meso-scale approach is proposed in order to take advantage of both main approaches. The meso-scale approach enables the mechanisms of void closure to be accurately studied at the micro-scale, using full-field explicit simulations in a representative volume element, and using boundary conditions that are representative of the thermomechanical conditions during macroscopic processes.

Local mechanisms of void closure are studied using a large campaign of 3D finite element simulations at the representative volume element scale. The studied parameters are: the materials parameters, the void's morphology and the thermomechanical loading that a void might undergo during hot forming processes. The study shows that both the void's morphology and the stress state exhibit a first-order influence on void closure. Materials parameters exhibit a second-order influence on void closure. A new reliable prediction model is thus proposed with respect to the first-order parameters. The void's morphology is quantitatively studied in terms of equivalent dimensions (tridimensional aspect ratios), and orientation (with respect to principal deformation direction). The stress state is expressed using the stress triaxiality ratio.

The new prediction model for void closure is finally implemented in the finite element software for metal forming FORGE 2011 and compared to existing mean-field models from literature using real industrial process cases. A detailed description of the methodology and of the model calibration can be found in (Saby, 2013; Saby et al., 2013; Saby et al., 2014b).

In the present paper, this new mean-field model (called *CicaPoro* in the following) will be presented and compared to two other existing mean-field models existing in the literature: the stress triaxiality based (STB) model implemented in the finite element (FE) software FORGE by P. Lasne and detailed in (Saby, 2013)) and the semi-analytical model proposed by (Zhang et al., 2009).

The definition of these 3 models is given in the following section. The third section presents an evaluation of the *CicaPoro* model for a case of hot rolling. The new prediction model is compared to the two existing models from the literature (the STB model and the Zhang model) and to the explicit simulations at the workpiece scale containing voids of different morphologies and orientations.

2. Void closure models

2.1. Stress Triaxiality Based (STB) model

In FORGE 2011 software, the existing prediction model for void closure is based on the integral of the stress triaxiality ratio T_X over the cumulated equivalent strain $\Delta\bar{\epsilon}$. The ratio between the void volume variation ΔV and the initial void volume V_0 is given by:

$$\frac{\Delta V}{V_0} = K_C \cdot T_X \cdot \Delta\bar{\epsilon}, \quad \forall T_X < 0, \quad (1)$$

where the value of K_C is an initial parameter and can be user-defined. A default value $K_C = 5$ was proposed by Lasne (see Saby, 2013 for more information). This value was obtained by a calibration using simple compression cases of a billet containing an initially spherical void. In this model, void closure depends on the evolution of stress triaxiality, only. It will be called stress triaxiality-based (STB) model in the following.

2.2. Zhang model

The prediction model proposed by Zhang et al. (2009) was identified as the currently most accurate existing model in the literature. The model is based on micro-analytical solutions that were obtained by Duva and Hutchinson (1984) for the volume evolution of a sphere in a viscoplastic material (without considering the change

of shape of the void during deformation). Corrective terms were added by Zhang et al. (2009) using a polynomial function with four parameters $\{q_i, 1 \leq i \leq 4\}$ q_1, q_2, q_3 and q_4 in order to consider the change of shape of the sphere during deformation. The model assumes that the change of void shape during deformation depends on the cumulated equivalent strain, only. The parameters were calibrated using finite element simulations in an RVE containing an initially spherical void. The incremental volume change is expressed as:

$$\frac{\Delta V}{V} = -[f(m^*, T_X) - q_1 T_X + 3q_2 \bar{\epsilon}^2 + 5q_3 \bar{\epsilon}^4 + q_4] \Delta \bar{\epsilon}, \tag{2}$$

$$\text{with } f(m^*, T_X) = \frac{3}{2} \left[-\frac{3}{2n^*} T_X + \frac{(n^*-1)(5n^*+2)}{5(n^*)^2} \right]^{n^*} \text{ and } n^* = \frac{1}{m^*}, \tag{3}$$

where $\{q_i, 1 \leq i \leq 4\}$ are corrective terms and are tabulated for several values of m^* in Zhang et al. (2009). The model takes into account a dependence to a material parameter m^* . This material parameter corresponds to the strain-rate sensitivity coefficient in the case of a visco-plastic material without strain hardening. The effect of strain hardening was studied and is presented in Saby (2013) and Saby et al. (2014b). It was shown that an arbitrary value of m^* may reasonably be chosen in order to assess the capabilities of the Zhang model for the configuration with strain hardening presented in section 3. For more information about the choice of the m^* value ($m^*=3$ in the following), the reader can refer to Saby (2013).

2.3. CicaPoro model

As shown in Saby et al. (2014b), two of the most important parameters regarding void closure are void shape and void orientation with respect to loading direction. Based on numerous representative volume element simulations with different ellipsoidal void shapes, different void orientations and different stress triaxiality ratios, the *CicaPoro* model was built with the following differential form:

$$\frac{\Delta V}{V_0} = [B + 2C \bar{\epsilon}] \Delta \bar{\epsilon}, \text{ with } \begin{cases} B = \sum_{i=1}^3 \sum_{j=0}^2 \sum_{k=0}^1 b_{jk} (T_X)^k (\gamma_i)^j p_i \\ C = \sum_{i=1}^3 \sum_{j=0}^2 \sum_{k=0}^2 c_{jk} (T_X)^k (\gamma_i)^j p_i \end{cases}, \tag{4}$$

where γ_i are the geometry parameters and p_i the orientation parameters. The constant values b_{jk} and c_{jk} were identified based on multiple RVE simulations detailed in Saby et al. (2014b).

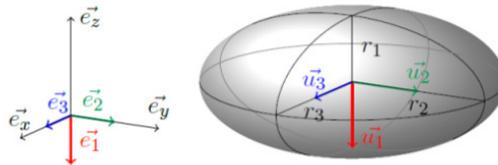


Fig. 1. Definition of geometry and orientation parameters.

- **Geometry parameters:** the geometry parameters γ_i are function of the three ellipsoidal dimensions r_1, r_2 and r_3 (see Fig. 1) and of the initial void volume V_0 :

$$\gamma_i = \sqrt[3]{V_0} / r_i, i = 1, 2, 3;$$
- **Orientation parameters:** the orientation parameters p_i are defined using the principal deformation direction, noted \vec{e}_1 in Fig. 1 and the three eigenvectors of the void inertia matrix \vec{u}_i such as:

$$p_i = (\vec{u}_i \cdot \vec{e}_1)^2, i = 1, 2, 3$$

This definition verifies $p_1 + p_2 + p_3 = 1$. When the mean-field prediction model is used, the orientation parameter is updated in time at each integration point according to the local current deformation state. The principal deformation direction \vec{e}_1 is also updated in time and space.

3. Applications to hot rolling

3.1. Hot rolling simulations

A hot rolling process simulation, provided by Ascometal, is studied here. The material behavior is viscoplastic with strain hardening. Two simulations were performed:

- An explicit simulation, containing 9 meshed ellipsoids located close to the centerline position as shown in Fig. 2.a.
- A void-free simulation where the three mean-field models described previously are used and compared. Regarding the CicaPoro model, geometry and orientation parameters were defined according to the exact voids geometry and orientation of the explicit configuration.

Fig. 2.b describes the evolution of equivalent plastic strain and stress triaxiality ratios for the 9 ellipsoids during the hot rolling process. Stress triaxiality is negative when material points are under the roll. It becomes positive after the roll, but no void opening occurs since it is associated to zero strain rate values (constant equivalent strain after the roll exit).

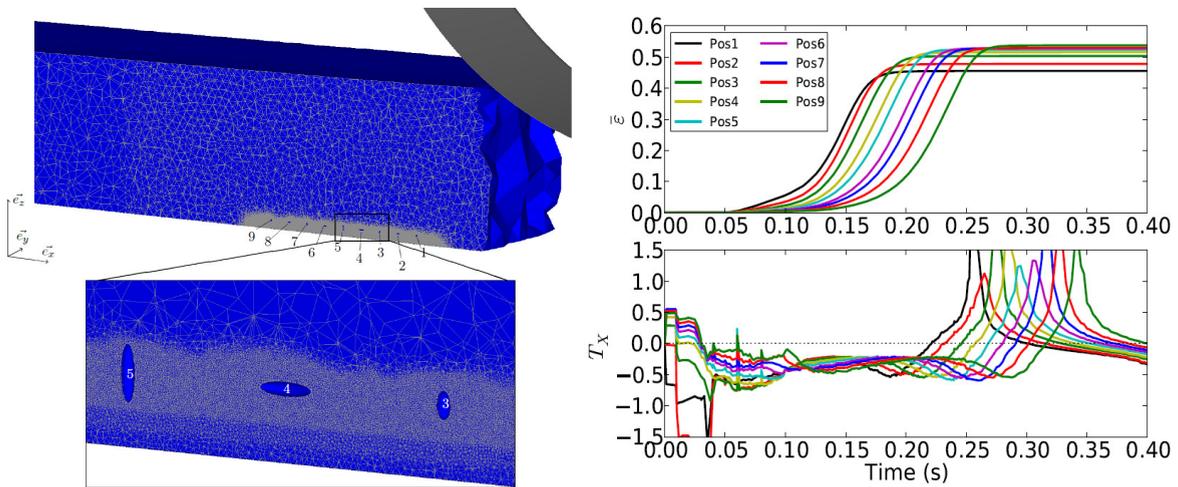


Fig. 2. a) mesh of the explicit simulation containing 9 ellipsoids and b) equivalent plastic strain and stress triaxiality ratios for the 9 ellipsoids during the rolling process.

Table 1 summarizes the number of elements and CPU time for both simulations. The void-free simulation is 60 times faster and run in 2 hours on 12 processors. Such a difference explains why mean-field approaches are preferred to full explicit simulations.

Table 1. Hot rolling simulations performed using 12 CPUs (3GHz, 24Go RAM)

Simulation	Voids	Nb elements	CPU time
Explicit	9	3 865 000	5 days 13 hours
Void-free	-	59 000	2 hours

3.2. Results and discussion

The three mean-field models are compared to the explicit simulations in term of void volume evolution for the 9 ellipsoids. Fig. 3.a shows an example of void volume evolution for a prolate ellipsoid $(r_1, r_2, r_3) = (2, 1, 1)$ elongated in the direction of principal strain. Dashed points correspond to the explicit simulation and are assumed to be the reference solution. It can be seen that the *CicaPoro* model gives the best results on this particular configuration, whereas STB and Zhang models tend to overestimate void closure.

The discrepancies that were obtained in terms of final void volume are synthetized in Fig. 3.b. The discrepancies are given for each prediction model, and for all presented void cases. Negative values indicate that a model overestimates void closure compared to the explicit simulation, as the predicted volume is lower than the explicit one. Positive values indicate that the model underestimates void closure.

The STB model significantly overestimates void closure for ellipsoids elongated along the principal strain direction (A2, B2, C2, E2), while it underestimates void closure for ellipsoids elongated perpendicular to the principal strain direction (A1, B1, C1, E1). The discrepancies are larger for larger aspect ratios. The lowest discrepancy is obtained for the spherical case.

The largest discrepancies were obtained for the Zhang model. From all presented cases, the Zhang model generally exhibits a stronger overestimation of void closure. The second orientation cases (A2, B2, C2, E2) lead to very high discrepancies, between 40% to 88% overestimation. On the other hand the first orientation cases (A1, B1, C1, E1) were predicted with rather good accuracy, as the discrepancy does not exceed 10%. It must be noted however that this model was developed initially for a viscoplastic behavior without strain hardening whereas the material studied here has a strain hardening.

Since the new model *CicaPoro* was built according to similar assumptions as the Zhang model, this general tendency is observed as well. The new model *CicaPoro* generally overestimates the final void volume. From all tested voids, the model did not exhibit any underestimation of void closure. Nevertheless, the largest discrepancy was obtained for the ellipsoid A in its first orientation case (A1), with about 19% difference with respect to the explicit simulation. In all other cases, the discrepancy remained lower than 7%. This remark demonstrates the ability of the new model *CicaPoro* to take into account the effect of initial geometry of the void.

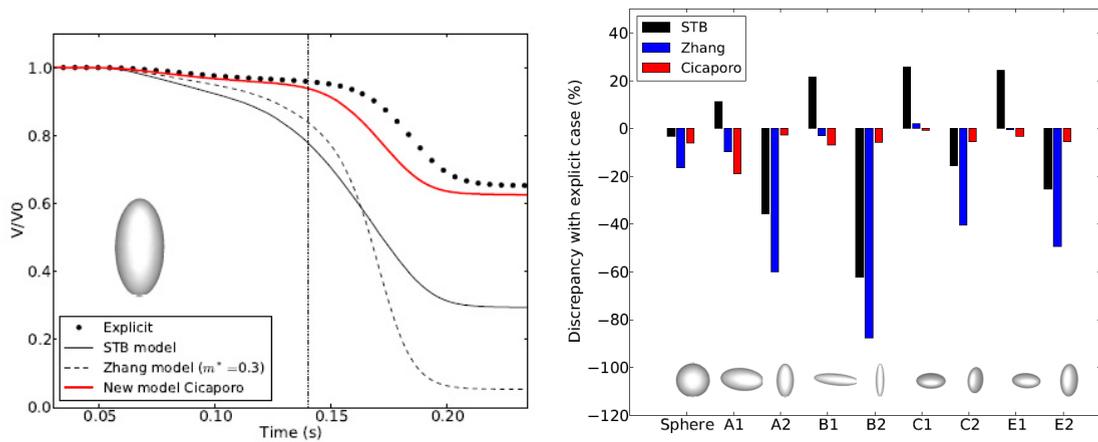


Fig. 3. a) void volume evolution for a prolate ellipsoid elongated in the main deformation direction b) Final discrepancies in terms of void volume obtained with the STB model, the Zhang model and the new model *CicaPoro* for the hot rolling case

The general overestimation that is observed in each model might be explained by the assumptions that are used at the meso-scale to calibrate these models:

- homogeneity of boundary conditions,
- axisymmetry of boundary conditions,
- uniformity of the deformation direction.

The observation of final void shapes in the explicit process simulations indicated that behavior of voids in the industrial process is rather different from the one observed at the RVE-scale. From the two first assumptions, the available information was insufficient to clearly determine whether it is the homogeneity, or the axisymmetry which leads to the largest discrepancy. The improvement of boundary conditions at the representative volume element scale according to both aspects constitutes a perspective to this work.

The third assumption regarding the uniformity of the main deformation direction results from the fact that the current orientation of the void is unknown when using the mean-field model. Using the presented approach, the current orientation parameters are obtained between the current deformation direction and the initial orientation of the void. In other words, it is assumed that the initial orientation of the void remains constant during deformation, in a first approximation. Predicting the evolution of the void orientation would be thus of great interest to enhance the model.

4. Conclusion

The new void closure model *CicaPoro* was implemented in the finite element software FORGE 2011 as a post-processing subroutine, and was compared to the existing STB model proposed by Lasne [2008], and to the model of Zhang et al. [2009]. The models were confronted to explicit simulations using a hot rolling process. Various ellipsoidal voids were used, using different dimensions and different orientations, and were submitted to different mechanical loading paths.

The benefits of the new model *CicaPoro* were demonstrated regarding the dependence to initial geometry (initial dimensions and orientation). The effect of initial geometry of a void is significant on its volume evolution. The STB model and the Zhang model are unable to take into account this effect and their predictions may lead to discrepancies up to 88% in some cases. The new void closure model *CicaPoro* is able to predict the effect of initial geometry with greater accuracy, as the maximum discrepancy obtained did never exceed 19% and was generally of the order of 7%.

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