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

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Abstract. The presence of voids after casting processes of large metal workpieces requires the use of adapted hot metal forming processes to deliver sound products. 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. A new model accounting for both stress triaxiality ratio and Lode angle is proposed. Based on an advanced multiscale approach, this model also accounts for voids shape and orientation with respect to loading direction.

1 Introduction

After casting of large metal workpieces, internal voids may remain and need to be eliminated. Hot forming processes such as hot rolling and hot forging are used, but the amount of compressive plastic strain that needs to be applied to close these voids remains an issue. The present work aims at understanding void closure modeling with respect to voids morphologies and orientations. In addition, the influence of the stress state is analyzed by accounting for stress triaxiality ratio and Lode angle.

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 [1]. One of these models, called *Cicaporo1*, accounting for void shape and orientation was presented in [2, 3].

In the present work, a new multiscale approach is proposed in order to build a mean field model that can be used at the macroscopic scale. The definition of this model relies on microscopic RVE (Representative Volume Elements) simulations that will be presented in the first part. The influence of stress state on void closure can be analyzed at this microscale. In addition to stress triaxiality ratio, it is proved here (section 2) that Lode angle also influences void closure. Finally, an optimization strategy allowing the definition of a new void closure model is presented in section 3.

2 RVE simulations

The aim of RVE simulations is to quantify the influence of void geometry, void orientation and stress state on void closure. It was shown in [2] that, in the considered range of thermomechanical conditions, material parameters are of the second order with respect to void closure.

2.1 Geometrical parameters

Voids are defined by ellipsoids (Figure 1.a) and are placed at the centre of a cubic RVE (Figure 1.b) with a given orientation with respect to the principal loading direction.

The geometry parameters γ_i are function of the three ellipsoidal dimensions r_1, r_2 and r_3 (see Figure 1.a) and of the initial void volume V_0:

$$\gamma_i = \sqrt[3]{V_0}/r_i, i = 1, 2, 3 \quad (1)$$

The orientation parameters (p_i) are defined by the cross product of the void principal directions (e_i) and the principal loading direction (e_L). More details can be found in [4].

2.2 Boundary conditions

Boundary conditions are defined on the RVE faces with one prescribed velocity, two prescribed stresses and three symmetry planes (see figure 1.b). All models in the literature rely on axisymmetric loading assumption for simplicity reasons. This means that lateral applied stresses (σ_1 and σ_2 in figure 1.b) are equal. In these models, the stress state is defined by the stress triaxiality ratio (T_x) which is the ratio between hydrostatic pressure (σ_h) and equivalent stress (σ_{eq}). However, as shown in [4], the stress state cannot be defined in a unique way by using only stress triaxiality. This is the reason why the

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Lode parameter (μ) is used as well. This parameter, detailed in [4, 5], is defined by:

$$\mu = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} \quad (2)$$

where σ_i are principal stresses with $\sigma_1 \geq \sigma_2 \geq \sigma_3$, and $\sigma_1 \neq \sigma_3$.

By playing on V_z, σ_1 and σ_2 it is possible to prescribe any equivalent strain rate and stress state T_x and μ. (See [4] for more details). Axisymmetric loading hypothesis leads to μ=1.

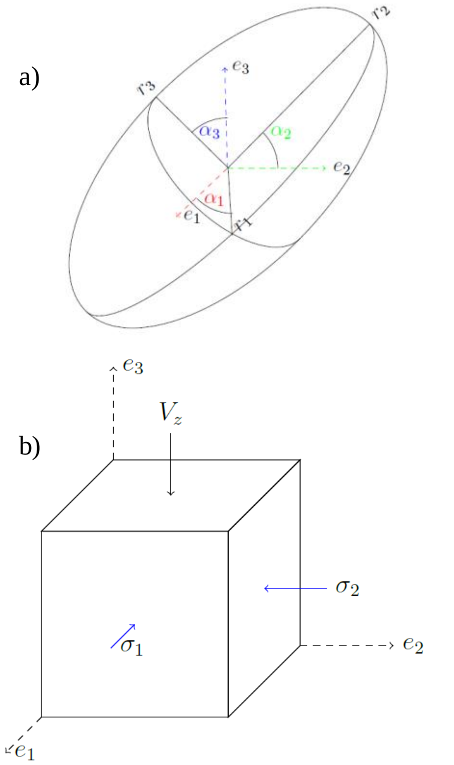

Figure 1. a) Geometrical definition of voids and b) RVE boundary conditions

3 Influence of Lode angle on void closure

As shown in many studies [3, 6], void closure (define here as the ratio between the current void volume V and its initial value V_0) is a function of equivalent plastic strain and stress triaxiality ratio. Lower triaxiality ratio values mean higher triaxial compression and consequently faster void closure.

Figure 2 shows void closure with respect to equivalent strain ($\bar{\epsilon}$) for two stress triaxiality ratio values and four Lode parameter values. It can be seen that Lode parameter also influences void closure. Its influence is decreasing when stress triaxiality decreases as well. It is interesting to point out that the axisymmetric loading hypothesis (μ=1) corresponds to the fastest void closure rate. This means that all models built under axisymmetric loading hypothesis tend to overestimate void closure rate.

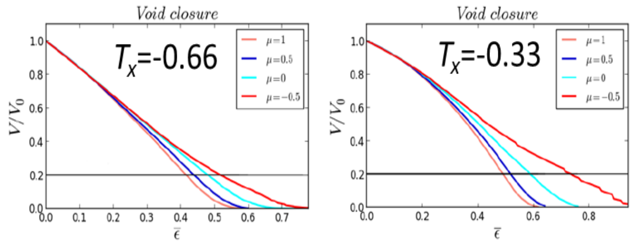

Figure 2. Influence of stress triaxiality ratio and Lode parameter on void closure

4 New void closure model

The void closure mean field model is built thanks to a database containing RVE simulation results parameterized by the values of the considered first order parameters which are: void geometry (γ_i), orientation (p_i), stress state (T_x and μ) and equivalent strain ($\bar{\epsilon}$). All these simulations are run once and stored in the database together with the V/V_0 resulting void volume evolution.

A polynomial analytical function is defined by the user. In the following, this function is given by:

$$\frac{V}{V_0} = 1 + (A_0 + A_1 T_x + A_2 \mu + A_3 S)\bar{\epsilon} + (A_4 + A_5 T_x^2 + A_6 \mu^2 + A_7 S_s)\bar{\epsilon}^2 \quad (3)$$

$$where\ S = \sum_{i=1}^{3} \gamma_i . p_i \ \ and\ S_s = \sum_{i=1}^{3} (\gamma_i . p_i)^2$$

A specific optimization methodology is developed so as to identify the model parameters (A_i, $i=0,\ 7$) by minimizing the L^2 norm of the error (Eq. 4) between the void volume predicted by the explicit RVE simulations (*num* subscript) and the void volume given by the mean field model defined in Eq. 3 (*mod* subscript).

$$E_r = \frac{1}{N} \sum_{i=1}^{N} \left| \left(\frac{V}{V_0}\right)_{num} - \left(\frac{V}{V_0}\right)_{mod} \right| \quad (4)$$

Compared to the model presented in [3] (with twelve parameters), the number of parameters has been reduced to eight by coupling void geometrical and orientation parameters. However, if this hypothesis occurs to be too strong, the analytical function can be easily enriched.

Due to the large number of model parameters and input variables, it was decided to split the optimization procedure in three steps as shown in figure 3. After an initialization stage on a single configuration, three subsets of RVE results are considered in which some variables are fixed (the red ones in figure 3) and others vary (the green ones). In this way, the first iteration deals with stress triaxiality, the second with the Lode parameter and the last one with geometrical and orientation parameters. For each iteration, some of the model parameters are kept constant and equal to the values identified in the previous steps. For example, when T_x is varied (simu subset 1), A_0, A_1, A_4 and A_5 are identified whereas A_2, A_3, A_6 and A_7 are taken constant and equal to the values identified in previous steps. The BFGS [7] minimization algorithm is used and convergence is achieved when the difference between two sets of identified parameters is lower than a user fixed threshold.

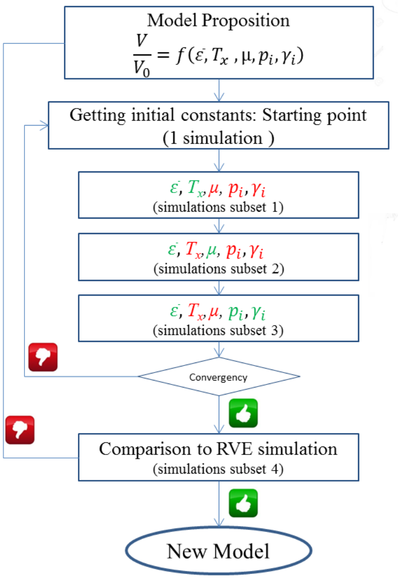

Figure 3. Calibration chart of the void closure parameters

4 Results and validation

The eight model parameters were identified based on a set of 46 RVE simulations (11 for T_x, 11 for μ and 24 for void geometry and orientation). The mean field model is then tested and compared to the results obtained with 99 other explicit RVE simulations. Figure 4 illustrates the good prediction of the mean field model for two particular cases.

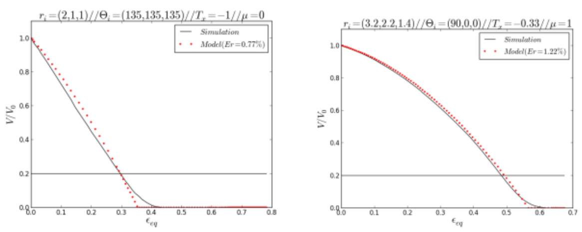

Figure 4. Comparisons between explicit RVE results and mean field model prediction

For the 99 tested configurations, the mean error (equation 4) is lower than 15%. Moreover, 88% of the tested configurations give an error lower than 6%. The main differences are observed for values of V/V_0 lower than 0.2 where a change of slope can be observed. Such a change of slope cannot be described accurately with the quadratic form of the tested model and would require enriching the analytical form of it.

For general stress states, the new model also gives better prediction than the initial *Cicaporo1* model. This was expected since this former model was defined based on axisymmetric loading hypothesis. But the new model is also more accurate for μ=1 despite the lower number of parameters.

5 Conclusion and discussion

A new void closure model was presented. This model accounts for void geometry and orientation with respect to the main loading direction. The axisymmetric assumption was not considered here and the influence of the Lode parameter on void closure was demonstrated. Lode parameter influence is higher for low negative values of stress triaxiality.

A new form of the void closure model was proposed with only eight parameters. These parameters were identified using a database of explicit RVE simulations results parameterized by the values of the considered first order parameters. The calibration stage, based on a three iterative minimization procedure, is very efficient.

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