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A geometry-dependent model for void closure in hot metal forming

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ABSTRACT

During production of large metal workpieces, an internal presence of voids is usually observed. Such internal defects are generally closed up using hot metal forming processes, such as hot forging or hot rolling. Prediction models for void closure, associated with process simulation, are extremely powerful tools and might significantly support process design. However, there is at present a lack of accurate models being able to predict void closure according to industrial conditions, particularly in terms of void geometries. In this paper, an original model for void closure is presented, accounting for the void's geometry and orientation, as well as the mechanical state during deformation. The model is build and calibrated based on a wide campaign of finite element simulations at the scale of a representative volume element. Various void geometries are defined and several mechanical states are prescribed on a range that is representative of industrial loadings. The model's accuracy is verified using industrial data and was compared to several models from literature. Great advantages are obtained for non-spherical voids in terms of void volume evolution.

1. Introduction

Industrial needs for large metal components used in aerospace, transport or energy applications constantly increase. During the first steps of elaboration of ingots or preforms, defects, such as voids and internal cavities, may occur. An elimination of these internal defects is required to avoid catastrophic failure during process, or during service of final components. Void elimination is usually performed by means of hot metal forming processes, inducing large deformation in the material at high temperature, and leading to closure of internal voids. Optimization and control of such forming processes in terms of costs and final material soundness remains of prime importance.

The phenomenon of void closure is generally described using two stages: the *mechanical closure* of void, bringing internal surfaces into contact, and the *final bonding* of the internal surfaces providing complete healing and thus a sound material [11]. The present work focuses on the mechanical closure phenomenon.

Although main studies regarding void closure were published over the last two decades, some qualitative improvements in terms of process conditions were already pointed out using experimental observations in Tomlison et al. [20] for hot forging, and in Wallerö [21] for hot rolling. Tomlison et al. [20] studied the effect of hot forging process parameters on void closure and found out that concave dies are favourable for void closure. These results were confirmed by Dudra and Im [3] using FML[1] dies, by Banaszek and Stefanik [1] using bowl-shape dies and by Chen et al. [2] using V-shape dies. For hot rolling processes, Wallerö [21] pointed out that large roll diameters and large spread passes are recommended for better void closure. From such results, it was concluded that compressive states have tendency to improve the closure efficiency [16].

Ståhlberg and Keife [17] stated that initial cooling of workpieces can be favourable for void closure in the case of hot forging. It is explained by the fact that the temperature gradient induces more compressive stress states in the bulk of workpieces. Pietrzyk et al. [12] confirmed the favourable effect of pre-cooling workpieces in hot rolling. Överstam and Jarl [10] also pointed out a coupled effect between friction and temperature regarding their effect on void closure. In fact, all these studies deal with stress states in the workpiece and confirm the favourable effect of compressive states for void closure.

Ståhlberg et al. [18] studied the deformation of round and square voids in a rigid-perfectly plastic material. They proposed an upper bound for void closure based on the plane-strain condition, considering two different deformation modes around the voids.

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0168-874X/

Tanaka et al. [19] pointed out that a good indicator for void closure is the integral of stress triaxiality ratio over the cumulated strain. Nakasaki et al. [9] discussed the use of this variable in the case of hot rolling and proposed a modified model to fit experimental data. Kakimoto et al. [7] also used the same indicator to establish a criterion for void closure. Based on a series of finite element simulations, the authors concluded that voids are systematically closed when the integral of stress triaxiality reaches a threshold value.

Based on a similar approach, a stress triaxiality based (STB) model for void closure was proposed in the commercial software FORGE® as a post-processing mean-field model [14]. This model is able to provide maps of void volume prediction, according to the integral of stress triaxiality ratio over cumulated strain at any position in the workpiece. Calibration of this model can be performed using compression cases of a billet containing a given void (usually spherical), and is therefore limited to the chosen configuration.

Based on the analytical evolution of a sphere found by Duva and Hutchinson [4] and the analytical evolution of a crack-like shape found by He and Hutchinson [6], Zhang and Cui [22] proposed a model for predicting the volume evolution of an initially spherical void, by analytically taking into account the change of shape during deformation. A semi-empirical model was also proposed by the same authors [23], by adding correction terms to the solutions obtained by Duva and Hutchinson [4], in order to empirically take into account the change of shape during deformation. Although many improvements can be obtained using such models, both works of Zhang and co-workers were restricted to the case of initial spherical voids. Initial non-spherical void shapes may however have a non-negligible impact on void closure rate, such as observed by Lee and Mear [8] using ellipsoidal voids. In particular, the elongation and orientation of the void with respect to the main compression axis may significantly affect the void closure rate.

This paper presents a new prediction model for void closure, based on a large campaign of numerical simulations at the micro-scale, using a representative volume element (RVE) containing ellipsoidal voids. A description of the RVE simulations is given in the first section. Then a parametric sensitivity study to void geometry (orientation and aspect ratios) and to several material parameters is presented. The parameters that exhibit a first-order influence on void closure are then quantitatively assessed and the prediction model is defined and discussed in the fourth section. The benefits of this new model are demonstrated by regarding the dependence of void closure to initial geometry (initial dimensions and orientation). The effect of initial void geometry is significant on its volume evolution. To the authors' knowledge, existing models are unable to take into account this effect and their predictions may thus lead to large discrepancies. The fifth section, where the proposed model is validated and compared to other models, is dedicated to this question.

2. Description of the meso-scale approach

2.1. Representative volume element

The mechanisms of void closure are studied using finite element analysis in a tridimensional RVE. This methodology enables the closure mechanisms to be studied at the meso-scale and was presented in previous work [15]. In the present work, the dimensions of the RVE are $D_x = D_y = D_z = 10$ mm and mesh size is set to the value 0.1 mm around the void in order to ensure validity of the RVE simulations. An ellipsoidal void, with initial dimensions r_1, r_2, r_3 (see Fig. 1) is placed at the central position in the RVE. The

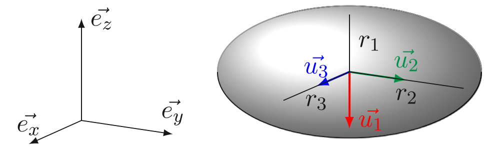

Fig. 1. Definition of the void's dimensions and orientation in the canonical basis $(\vec{e_x}, \vec{e_y}, \vec{e_z})$.

initial void volume fraction is $f_0 = 10^{-3}$. The initial aspect ratios are defined as the ratios $\frac{r_3}{r_1}$ and $\frac{r_2}{r_1}$.

Tridimensional unstructured volume meshing is used, with tetrahedral elements as shown in Fig. 2. The FE simulations are performed using the software FORGE2011®, using a mixed velocity–pressure $P1^+/P1$ formulation.

A visco-plastic behaviour law (Eq. (1)) is used. This law is known as the Hansel–Spittel law and is widely used for modelling the behaviour of metals at high temperature. The flow stress σ_0 is expressed as

$$\sigma_0 = A(\overline{\varepsilon}+\varepsilon_0)^n \dot{\overline{\varepsilon}}^m e^{m_4/(\overline{\varepsilon}+\varepsilon_0)}, \tag{1}$$

where A is the material consistency at the given temperature (isothermal conditions are assumed here), m the strain-rate sensitivity, (n, m_4) the strain hardening and softening coefficients, and ε_0 a regularization term that enables initial rigidity of the material.

2.2. Boundary conditions

In the large majority of models (e.g. micro-analytical solutions in Duva and Hutchinson [4], or empirical criteria in Kakimoto et al. [7]), equivalent strain and stress triaxiality ratio rise as key parameters regarding mechanical influence. Equivalent strain expresses as $\overline{\varepsilon} = \sqrt{\frac{2}{3}\varepsilon : \varepsilon}$ and stress triaxiality ratio $T_X = \frac{\sigma_m}{\sigma_e}$, where $\sigma_m = \frac{1}{3}\mathrm{tr}(\sigma)$ is the mean stress and $\sigma_e = \sqrt{\frac{3}{2}\sigma : \sigma}$ is the von Mises equivalent stress. Void volume evolution is generally presented as a function of equivalent strain $\overline{\varepsilon}$. It was also observed that strain-rate has no influence on void volume evolution [15]. Consequently, an arbitrary constant strain-rate is applied with the value $\dot{\overline{\varepsilon}} = 1\ \mathrm{s}^{-1}$. The constant strain-rate is prescribed using a normal velocity $V_z(t) = -D_z(t)$ on the upper surface of the RVE, i.e. along the z-axis (see Fig. 3).

In this work, it is chosen to prescribe a constant stress triaxiality ratio in order to quantitatively study its influence on void closure. Normal stresses are applied along the x and y-axes using axisymmetric conditions $\sigma_{xx} = \sigma_{yy}$. The matrix material is isotropic and the void volume fraction is very low. By neglecting the effect that might have the void on the global deformation of the RVE, it comes $\varepsilon_{xx} \approx \varepsilon_{yy}$. Equivalent strain therefore reduces to

$$\overline{\varepsilon} \approx |\varepsilon_{zz}| = \left| \ln\left(\frac{D_z^0 - D_z}{D_z^0}\right) \right|, \tag{2}$$

where D_z and D_z^0 are the current height and the initial height of the RVE, respectively. From the definition of stress triaxiality ratio, the condition $\sigma_{xx} = \sigma_{yy}$ leads to

$$T_X = \frac{\sigma_m}{\sigma_e} = \frac{\sigma_{xx}+\sigma_{yy}+\sigma_{zz}}{3\sigma_e} = \frac{2\sigma_{xx}+\sigma_{zz}}{3\sigma_e}, \tag{3}$$

and equivalent von Mises stress reduces to

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{xx}-\sigma_{yy})^2 + (\sigma_{yy}-\sigma_{zz})^2 + (\sigma_{xx}-\sigma_{zz})^2} = |\sigma_{xx}-\sigma_{zz}|. \tag{4}$$

It comes

$$\sigma_{xx} = \left(T_X + \frac{1}{3}\right)\sigma_e \quad \forall \sigma_{zz} \le \sigma_{xx},$$