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Influence of Lode angle on modelling of void closure in hot metal forming processes

A. Chbihi*, P.-O. Bouchard, M. Bernacki, D. Pino Muñoz

Mines ParisTech, CEMEF – Centre de Misee Forme des Matériaux, CNRS UMR 7635 CS 10207, 1 rue Claude Daunesse, 06904 Sophia Antipolis cedex, France

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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. The main aim of this work is to develop a highly accurate mean field model able to predict the evolution of the voids volume after each forming stage. This proposed model is accounting for both stress triaxiality ratio T_x and Lode angle θ in order to override the hypothesis of axisymmetric loading, which is generally considered in the existing models handling void closure in the literature. Based on an advanced multiscale approach, this model also accounts for voids shape and orientation. An optimization method, using a database of explicit RVE simulations, is developed in order to calibrate the new proposed model. Several void morphological parameters and an industrial range of mechanical loading parameters are analyzed regarding void closure. The proposed mean field model is validated by comparison with explicit full field simulations and with a recent pre-existing mean field model, named Cicaporo1 model hereafter (Saby et al., 2015 [19]). In comparison with Cicaporo1, the new model, named Cicaporo2 hereafter, uses less constants and is more accurate.

1. Introduction

Microvoids are frequently detected during large ingots production, which decrease the material quality thereafter. In the industry, hot forming processes are generally used to close these voids and end up with sound products. To insure that the total closure is achieved, the use of 3D X-ray analyses is not possible on such large ingots. Ultrasonic analysis is an alternative solution to detect defects on final products, but its accuracy is quite low and it does not help in finding solutions to close them. Therefore, mathematical models are useful to predict void volume evolution and provide an estimation of void closure for given applied plastic strain under given stress states.

To deal with this industrial issue, numerous models were defined in the literature using two principal approaches: macroscopical approach and micro-analytical approach. The first approach considers a full-field explicit description of an entire workpiece containing explicit voids. Using adequate numerical features, the description may be accurate for studying void closure in real processes according to a given case study. In micro-analytical analyses, a single void in an infinite incompressible matrix is considered. The matrix is usually considered viscoplastic and is defined by a power law type. The evolution of the initial void is studied with respect to various mechanical parameters for different types of material. A large number of studies consider this approach [26,17,4]. Voids are typically assumed to be spherical or cylindrical. Most studies do not consider any change of shape during strain and the resulting equations are often inappropriate for large deformation [1,8,26].

However, both approaches have significant limitations in industrial applications. For instance, macroscopic approaches undermine difficulties to take into account, in the same simulations, void-scale characteristics and process-scale parameters. This can lead to the use of heavy meshes, case-dependent description/results and high numerical cost. Regarding micro-analytical approaches, assumptions made for void geometries, loading conditions and material laws are usually too strong for real industrial processes modelling.

It is worth mentioning that the elimination of internal voids is achieved in two principal stages: *closure* of void volume until the contact between faces is reached and the subsequent *bonding* of the contact surfaces under sufficiently high temperature and compressive stresses [14]. The present work concerns only the void closure stage.

Ståhlberg et al. [20] presented a micro-analytical criterion for void closure. They considered square and circular voids in a rigid perfectly plastic material. The proposed model defines the necessary reduction R_c to completely close the void to be proportional to the square root of

* Corresponding author.
E-mail address: abdelouahed.chbihi@gmail.com (A. Chbihi).

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its initial volume V_0. Experiments were carried out in order to validate the theoretical model and an agreement was found. Tanaka et al. [21] suggested that the integral Q of stress triaxiality ratio T_x over equivalent strain $\bar{\epsilon}$($Q = \int T_x d\bar{\epsilon}$) was a better way to predict void closure. They developed an empirical void closure parameter based on Q and using linear regression to get model constants. Based on the work of Lasne, Saby [15] introduced the stress triaxiality based (STB) model which is implemented in the finite element software FORGE®. The STB model states that the void volume prediction could be computed by the integration of the stress triaxiality T_x multiplied by a proportionality coefficient, identified by simulations of compression on a spherical void, over the equivalent strain. Budiansky et al. [1] proposed an analytical solution which takes into account the influence of the stress triaxiality T_x and introduces a material parameter m and considered voids as spherical during the whole strain. Based on this solution Zhang et al. [26] proposed a semi-empirical solution to predict void closure adding the influence of the void shape evolution. Lee and Mear [8] stated that the non-spherical form of void in the beginning of deformation can significantly influence the evolution of void closure. In fact, real voids exhibit complex forms with significant tortuosity, which makes a sphere far from real voids shape. Therefore, by using ellipsoidal voids, which are closer to reality, the orientation and elongation of voids could also be studied. Recently, Feng and Cui [4] studied the evolution of dilute ellipsoidal void in power law viscous material under triaxial loading conditions. A semi-analytical expression was defined to predict void closure for large compressive strain. The model accounts for the void's shape to characterize the pores and assumes that the void's orientation is parallel to the principle stress. It considers that main void directions are parallel to the compression directions, which is not in agreement with experimental observations. Saby et al. [19] used a mesoscale method to develop a model based on a large campaign of simulations on representative volume elements (RVE). This is the only model, to the authors' knowledge, that accounts for the geometry of voids (orientation and form) in addition to mechanical loading parameters (stress triaxiality ratio T_x and equivalent strain $\bar{\epsilon}$). Several configurations of voids were tested in a large range of mechanical loading conditions corresponding to industrial applications. This model (Cicaporo1) presented a great accuracy compared to explicit simulations of real industrial processes [17]. Nevertheless, one of its limitations lies on the assumption of axisymmetric loading. Indeed, all void closure prediction models existing in the literature consider this hypothesis, for which loading conditions are defined using only stress triaxiality. However, this parameter does not allow us to define a unique stress state. A detailed review of existing models can be found in Saby et al. [18].

Therefore, the aim of the present work is to propose an enhanced model based on an improved and more accurate description of the stress state in the material. This is achieved by involving the three stress invariants.

Within the context of material damage and failure analysis, many authors have introduced the *Lode angle* θ, which is a function of the third invariant of deviatoric stress tensor. Danas and Castañeda [3] modelled the damage of porous elastoplastic materials by two approaches according to the state of the stress triaxiality. They proved that for triaxial tensile cases, the Lode angle appears to have no effect on the developed model. However, it seems to be an influencing factor for triaxial compressive cases. Cao et al. [2] studied the calibration of ductile damage models for high strength steels using microtomography. They confirmed that the use of the Lode angle is a good way to represent the stress state for low or negative stress triaxiality conditions. Other works realized by Keshavarz et al. [7], Xue and Wierzbicki [25] and Mirone and Corallo [12] confirmed that the combination of the stress triaxiality ratio T_x and Lode angle θ was necessary to define the stress state accurately.

In this paper, a new void closure model is proposed to improve the prediction accuracy by eliminating the axisymmetric loading hypothesis. The calibration of this model is achieved by using a database of explicit RVE simulations. In the following section, the mesoscale method used to perform explicit simulations is presented. Several configurations of voids and mechanical loading conditions are considered in order to study their influence on void closure. The way of defining boundary conditions on the RVE for given stress triaxiality and Lode angle is detailed. The third section concerns the influence of specific parameters on void closure: void orientation and form as geometry parameters and applied stress triaxiality and Lode angle as mechanical loading parameters. The fourth section is dedicated to the development of the calibration methodology. This methodology is based on an optimization algorithm that enables the identification of the void closure model parameters according to a large number of RVE explicit simulations. This optimization approach also enables us to change the void closure analytical function and to proceed to a new calibration in a reduced time. In the fifth section, results of the new model are presented and compared to RVE explicit simulations and Cicaporo1 model predictions. Last section is dedicated to conclusions and perspectives.

2. Mesoscale approach and boundary conditions

In this section, a short description of the mesoscale approach used to perform explicit simulations is presented. For more details, the reader can refer to Saby et al. [16]. Boundary conditions are also detailed in order to take into account the effect of Lode angle θ in addition to stress triaxiality ratio T_x.

2.1. Representative volume element (RVE)

In this work, a mesoscale method is used to perform full-field simulations. In fact, void dimensions are assumed very small with respect to the workpiece dimensions. Several works considered a small void/billet ratio: 0.01–0.06 in Kakimoto et al. [6], 0.05 in Wallerö [22] and 0.06 in Wang et al. [23]. From this condition, two main assumptions can be made: (a) the presence of voids has no effect on macroscopic deformation and (b) the thermo-mechanical fields that are obtained from the macroscopic scale are considered as locally homogeneous and can be used as remote boundary conditions at RVE scale [15,16]. The objective is then to perform multiple explicit simulations with stress states representative of industrial conditions (stress triaxiality ratio T_x and Lode angle θ). The finite element (FE) simulations were performed using the software FORGE® NxT1.0. The void was represented by an ellipsoid of main dimensions (r_1, r_2, r_3) located at the center of the RVE. A convergence study has been carried out in order to determine the dimensions of the RVE and the optimal mesh size. The RVE dimensions (d_1, d_2, d_3) are set as four times the ellipsoid initial radii. The maximum mesh size in the RVE is 0.5 mm while r_1, r_2, r_3 vary between 1 mm and 4 mm. A mixed velocity–pressure formulation with P_1^+/P_1 tetrahedral elements and local refinement are used for an accurate description of void closure.

The viscoplastic material is defined by a Hansel–Spittel law. The equivalent stress is then expressed as:

$$\bar{\sigma} = A(\bar{\epsilon}, T) * \dot{\bar{\epsilon}}^m, \quad (1)$$

with

$$A(\bar{\epsilon}, T) = K_0 T^{m_1} (\bar{\epsilon} + \epsilon_0)^n e^{m_4/(\bar{\epsilon}+\epsilon_0)}, \quad (2)$$

where $\bar{\epsilon}$ is the equivalent strain, T is the temperature, m is the strain rate sensitivity, K_0 is the material consistency, m_1 the temperature sensitivity, (n, m_4) the hardening and softening coefficients, respectively, and ϵ_0 is a regularization term.