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A 3-D model for void evolution in viscous materials under large compressive deformation

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ABSTRACT

The paper presents a study on the evolution of dilute ellipsoidal voids in power-law viscous materials under triaxial loading condition. Firstly, referring to the work of Eshelby (1957), a semi-analytical expression is deduced to evaluate the deformation of ellipsoidal void in linear viscous material. Then, for the non-linear viscous materials, the concept of mesoscopic representative volume element (RVE) is applied to study the voids deformation under different stress states, and a rigid visco-plastic finite element (FE) procedure is applied to solve the RVE model. For the condition of stress triaxiality ranging from -1 to $+1$, it is found that the voids deformation behaves similarly in both linear and non-linear viscous materials. Due to this fact, the framework of the expression of void deformation in linear viscous material is inferred to describe the void evolution in non-linear viscous materials, while the parameters of the expression are re-evaluated for the specific materials. The results show that the void shapes and loading conditions take important roles in the void evolution. Therefore, for an ellipsoidal void, the void radius strain rate is expressed as a function of the void shape index, the macroscopic stress and strain-rate. Meanwhile, the void volume strain rate is obtained as a function of the void radius strain rate. This void evolution model is integrated into FE code and applied to study the void closure problem in the metal forming process. The FE simulation provides the evolution of macroscopic stress, strain and strain-rate, and then the model is used to calculate the changes of void shape and volume in each step of the deformation history. It can be found that the results predicted by this model agree well with the analytical solution, experiment measurements and numerical simulations with embedded void shapes, which demonstrates that this method can be appropriately used to predict the void evolution during the large compressive deformation process.

1. Introduction

The evolution of internal void greatly influences the mechanical property of materials. In the large metal ingot, the void defects (such as shrinkage cavities and porosities) will severely deteriorate the strength of the products. In manufacturing, it is essential to eliminate these internal voids by appropriate forming process. Generally, the void closure behavior, which brings about the contact of the void internal surface, is a necessary step to eliminate the void defects. Therefore, the evolution of the void shape and volume during the forming process becomes a crucial issue that needs to be investigated.

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Many researches were implemented to study the effects of some notable factors on the void evolution. In the fields of metal forming, finite element (FE) simulation with embedded voids in the mesh was used as a popular way to study the void deformation behavior. According to the simulations, some phenomenological conclusions for closing the voids were summarized for the specific conditions. Tanaka et al. (1987), Nakasaki et al. (2006), Kakimoto et al. (2010) and Lee et al. (2011) took the integration of hydrostatic stress and/or effective strain as the main factors to describe the closure of internal voids. Park and Yang (1997) investigated the void closure behavior during different forging processes. They found that with the precooled ingot surface, the hydrostatic stress at the central zone of the ingot was increased during forging so that the void closure became easier. Chen et al. (2010) simulated the evolution of the spherical, cylindrical and tetrahedral voids during upsetting process, and found that the closure of tetrahedral void was most difficult. Besides, Dudra and Im (1990), Banaszek and Stefanik (2006) and Kim et al. (2011) also carried out the FE simulations of the forging processes to investigate the influence of different parameters (such as the die shape, forming temperature, void shape, height reduction, etc.) on the internal void evolution and proposed the proper forging parameters for the specific cases. By applying the FE simulation results, Chen et al. (2012b) proposed a fitted function to express the strain distribution in the billet and established a relationship between the void closure and the forming parameters in the upsetting process. Chen and Lin (2013) pointed out that the change of loading directions during multi-stage forging was crucial to the void evolution, but unfortunately this effect was not included in most prediction models for void evolution. For this reason, they established a void evolution index with considering the influence of deviatoric stress to predict the changes of the void aspect ratio in cogging process. Besides, the void evolution during different kinds of metal forming processes was also focused in the literature. Chen (2006) simulated the rolling process of the porous metal sheet containing internal void defects, and discussed the influences of the thickness reduction, friction factor and initial void shape on the void evolution. Combining the neural network with the FE simulation results, Chen et al. (2011) developed a comprehensive procedure to predict the void closure during the cold rolling process. Chen et al. (2012a) studied the void evolution in the hot radial forging process and proposed a global–local combined method to enhance the accuracy of the FE simulation.

However, the FE simulation with embedded voids in models can only demonstrate the void evolution in specific positions where the voids are embedded. Actually the size of the voids is tiny while the number of the voids is many, and the voids are distributed irregularly in the materials. It is impossible to establish the FE model with the actual voids distributions. To deal with this issue, the representative volume element (RVE) method in the mesoscopic level was adopted to study the relationship between the void evolving and the loadings. Segurado et al. (2002) applied RVE model to study the effects of pores shape and size to the densification of porous molybdenum during uniaxial compression, and found that the initial spherical pores became lens-shaped when strain exceeded critical value. Saby et al. (2013) established an RVE model containing a real void geometry obtained from the X-ray computed micro-tomography, and simulated the void closure in the material under non-uniform compressions. Significant influence of the loading directions on the void evolution was observed and emphasized.

The RVE model is also adopted extensively in the analytical investigation of the void evolution in the past decades. To establish the relationship between the void evolution and loading condition, numerous constitutive theories and models have been proposed. For the porous materials with finite porosities, the well-known Gurson (1977) model was the first complete and analytical model which was based on a micromechanical analysis of a spherical void in matrix. Afterward, Tvergaard (1981, 1982), Tvergaard and Needleman (1984), Needleman and Tvergaard (1984) developed Gurson's work with the description of void nucleation, growth and coalescence, and established the GTN (Gurson–Tvergaard–Needleman) model. To extend the application of Gurson's model, Gologanu et al. (1993, 1994), Flandi and Leblond (2005a, 2005b), Monchiet et al. (2007) and Monchiet and Bonnet (2013) proposed the improved yielding surfaces for porous materials. Furthermore, Gurson's model and the associated studies were widely employed to deal with some important engineering issues (such as fracture) for numerous materials. Following the concept of “linear comparison variational homogenization method”, Castañeda and Zaidman (1994) established a visco-plastic constitutive model for porous solids. The model took into account of the microstructure evolution under general triaxial loading conditions. This model is available for the materials with finite porosities or dilute voids. Although good accuracy was achieved for deviatoric loadings, this model provided an overestimation of the yield limit under hydrostatic loading. Based on Castañeda (2002a, 2002b)'s “second-order homogenization method”, this demerit was remedied in the studies by Danas and Castañeda (2009a, 2009b). Besides, Castañeda and Zaidman (1994)'s yield surface was also improved by Agoras and Castañeda (2013) with the “iterated linear comparison variational approach”. In addition, the variational homogenization method has been extended to include the elasto-plastic behavior of the matrix material by Aravas and Castañeda (2004) and Danas and Aravas (2012).

Many contributions for the evolution of dilute voids can also be found in the literature. Those researches are valuable for describing the void evolution behavior in the metal forming process because the distribution of the void defects is generally dilute and the void volume is negligibly small in the metal ingot. McClintock (1968) and Rice and Tracey (1969) investigated the growth rate of a cylindrical/spherical void in an infinite plastic matrix subjected to an axisymmetric loading at remote boundary. Budiansky et al. (1982) studied the growth of the isolated cylindrical/spherical void in the power-law matrix under axisymmetric loading and established the BHS (Budiansky–Hutchinson–Slutsky) model for computing the void volume change under high stress triaxiality conditions. Then, Duva and Hutchinson (1984) derived a constitutive relationship for an incompressible, isotropic power-law material containing a dilute concentration of spherical voids. Fleck and Hutchinson (1986) developed analogous constitutive potentials for the solids containing a dilute concentration of circular-cylindrical voids. The macroscopic response of an incompressible power-law matrix containing a dispersion of aligned spheroidal

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