Journal of Materials Processing Technology 237 (2016) 371–385

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Investigation on the void closure efficiency in cogging processes of the large ingot by using a 3-D void evolution model

Chao Feng, Zhenshan Cui*, Mingxiang Liu, Xiaoqing Shang, Dashan Sui, Juan Liu

Institute of Forming Technology and Equipment, Shanghai Jiao Tong University, 1954 Huashan Road, Shanghai 200030, China

ARTICLE INFO

Article history:
Received 6 February 2016
Received in revised form 9 June 2016
Accepted 19 June 2016
Available online 21 June 2016

Keywords:
Void
Closure efficiency
Large ingot
Cogging process

ABSTRACT

The internal void defects often exist in the large ingot inevitably due to the non-uniform solidification of the materials. To guarantee the mechanical performance of the products, these voids should be closed and eliminated in the subsequent forging process. The main purpose of this study is to investigate the void closure efficiency in different cogging processes of large ingot by using a 3-D void evolution model. In order to obtain a more reasonable description of the actual engineering condition, the voids were considered as prolate ellipsoidal, and the influences of the instantaneous void shape changing, stress state and deformation history were taken into account for the void evolution. According to the results, alternate compression in different directions makes the changing of the void shape counteracted and decreases the void closure efficiency. The initial void shape impacts the void closure significantly, as the non-spherical void shape causes the anisotropy of the void closing behavior. It can be found that the compression perpendicular to the longer principal axis of the prolate void provides the higher void closure efficiency than the compression aligned with this direction. Therefore, using the extend-forging as the first step in cogging process is more efficient to close the voids, considering the morphology of the real voids in the ingot. Moreover, appropriate processing parameters were determined to enhance the void closure efficiency in extend-forging. Besides, the surface bonding experiments show that the high pressure and temperature, as well as the long holding time, are favorable to eliminate the void defects after the void closure. It implies that the processing sequence, which can make the void closed completely at high pressure and high temperature and keep the sufficient interval time between forming stages, should be emphasized in the process planning.

1. Introduction

In the heavy industry, an increasing number of large forgings are applied as the key components of the equipment to satisfy the higher demands of production efficiency and security. For instance, the rotor of the ultra-supercritical steam turbine in the power plant is manufactured from a large ingot (more than 300 tons) by hot forging process. However, the internal void defects often exist in the ingot inevitably, because the large size of the ingot brings about the non-uniform solidification of the materials during casting. These defects should be eliminated in the cogging process, or else they may deteriorate the mechanical performance of the large forging products severely.

Void closure and surface bonding are the essential stages to eliminate the void defects. In the literature, finite element (FE) simulations and deformation experiments with embedded voids in the billet were the main methods to study the void closure, and conclusions were summarized for some specific forming conditions. In the open-die forging process, Tanaka et al. (1987) chose the integration of hydrostatic stress and effective strain as the main factors to evaluate the void evolution. Park and Yang (1997) found that with the pre-cooled ingot surface, the hydrostatic pressure at the central zone of the ingot was increased during forging so that the void closure became easier. Kakimoto et al. (2010) chose the hydrostatic integration as the index, and suggested that the cylindrical void closed in extend-forging when the index reached 0.21. Lee et al. (2011) found that the local effective stain should be at least 0.6 to close the void during the forging process. Banaszek and Stefanik (2006) carried out the FE simulations of the forging processes to investigate the influence of different parameters on the internal void evolution and proposed the proper forging parameters for the specific cases. Kim et al. (2011) found that the height to diameter ratio of 1.29 for the ingot and the maximum pressing depth in each stroke were more effective for the void closure. Chen

* Corresponding author.
E-mail address: cuizs@sjtu.edu.cn (Z. Cui).

http://dx.doi.org/10.1016/j.jmatprotec.2016.06.030
0924-0136/

et al. (2012) proposed a fitted function to express the strain distribution in the billet and established a relationship between the void closure and the compressive strain in the upsetting process. Park (2013) investigated the cylindrical void evolution under plane-strain compression, and found that uniaxial forging is superior to biaxial forging for void closure. Chen and Lin (2013) pointed out that the change of loading directions during multi-stage forging was crucial to the void evolution, and they established an index considering the influence of deviatoric stress to predict the changes of the void aspect ratio. Besides, the void evolution in the rolling process was also investigated in the literature. Wang et al. (1996) pointed that high temperature and large deformation were effective for the void closure during hot rolling. Nakasaki et al. (2006) found the void cross-sectional area was in proportion to the hydrostatic integration in single-pass forming process, but this relationship should be modified in multi-pass rolling. Chen (2006) simulated the rolling process of the porous metal sheet containing internal void defects, and discussed the influence of the thickness reduction, friction factor and initial void shape on the void evolution. Using the neural network, Chen et al. (2011) developed a comprehensive procedure to predict the void closure during the rolling of aluminum sheet. Wang et al. (2015) performed the simulations and experiments of the hot rolling of medium plates, and investigated the evolution and closure of voids with different sizes in multi-stage rolling.

Based on the experiments and FE simulations with the embedded voids in billet, those studies provide valuable information on void closure. However, most of the conclusions are phenomenological and applied only for several specific conditions, because limited kinds of void shapes, positions and forming processes were considered. In fact, the void evolution is governed directly by the stress and strain in the local region around the void. Therefore, the representative volume element (RVE) method was adopted to investigate the relationship between the void evolution behavior and the stress-strain state. The RVE method was firstly used in the analytical investigation to study the constitutive theories for the porous materials with finite porosities. Gurson (1977) proposed a complete analytical constitutive model by analyzing the deformation of spherical void in the ideal rigid-plastic material under the axisymmetric loadings. In the literature, many studies were carried out to extend the application of Gurson's model. Gologanu et al. (1993) extended Gurson's analysis to the spheroidal volume containing a confocal prolate void, and then to the volume containing a confocal oblate void (Gologanu et al., 1994). Flandi and Leblond (2005a,b) proposed an improved constitutive model for the non-linear viscous porous material on the basis of Gurson's model with considering the effects of material viscosity and the spheroidal void shape. Gurson's model was further extended to the material containing the general (non-spheroidal) ellipsoidal void by Madou and Leblond (2012a,b). Besides, an approximate homogenization-based constitutive model was proposed by Danas and Castañeda (2009a,b) for estimating the effective response and associated void evolution in visco-plastic porous material. Afterward, Danas and Aravas (2012) proposed a new constitutive model for elasto-plastic (rate-independent) porous materials subjected to general three-dimensional finite deformations. As the accumulation of the void growth significantly influences the ductile fracture behavior, Cao et al. (2015) proposed a Gurson-like nonlinear model based on the homogenization method to predict the ductile fracture, with consideration of the effects of void shape change and rotation. Meanwhile, studies on the evolution of dilute voids were also carried out by using RVE in the literature. These researches are more valuable for describing the void evolution behavior in the metal forming process, especially for the hot compressive deformation, because the distribution of the void defects is generally dilute and the void volume is negligibly small in the metal ingot. Saby et al. (2013) established an RVE model containing a real void geometry obtained from the microtomography, and emphasized the influence of the load direction on the void closure. Zhang et al. (2009) obtained the void evolution behavior in the RVE by numerical calculation, and presented a void closure criterion using the stress triaxiality and effective strain as the main factors. Based on the similar calculation method, Chen et al. (2014) established an evolution model for elliptic-cylindrical and circular-cylindrical voids in power-law viscous solids. However, most of the criteria and models based on RVE are restricted to the axisymmetric or plane-strain problems, which are not quite close to the actual engineering condition in the hot forging process of the large ingot. Therefore, it is necessary to further research the evolution behavior of the void under complex stress and strain state. Using the RVE method, Feng and Cui (2015) established a 3-D model to describe the evolution behavior of the arbitrary ellipsoidal void, considering the influences of load condition and instantaneous void shape changing. Combining this model with stress and strain distributions obtained in FE simulation, the evolution of void shape and volume can be predicted in all the regions of the ingot, without the need of embedded void geometries in the billet.

Most of the voids in the ingot can be closed by drastic compression with a huge height reduction. However, using a reasonable cogging process can improve the forming efficiency and utilize the workability of the press machine more effectively. The main purpose of this study is to perform a comprehensive investigation of the void closure efficiency in different cogging processes of the large ingot, by adopting the 3-D void evolution model established by Feng and Cui (2015). The actual void defects in the large ingot are treated as the prolate ellipsoidal voids, and the influences of void shape, position and stress-strain state on void closure efficiency are analyzed. Reasonable processing parameters, including die width and height reduction, are obtained to improve the void closure efficiency. Besides, experiments are implemented to study the surface bonding after the void closure, which indicates that making the void closed completely at high temperature and keeping sufficient interval time between forming stages are favorable to eliminate the void defects.

2. The 3-D void evolution model

In the large ingot, the shapes of void defects are generally irregular and difficult to be obtained exactly. In many studies on void evolution, the initial shape of the void was simplified as spherical. However, this simplification is not quite appropriate, since the real void defects, as shown in Fig. 1(a), often have a longer principal axis aligned with the ingot axial direction due to the non-uniform solidification in the casting process. Actually, the material in the local region around the void generally contains a considerable extent of shrinkage porosity. According to Gurson's model, the volume fraction of void can greatly decrease the strength of the porous material (as shown in Fig. 1(b)). Therefore, in the forming process, this porous material region can be approximately treated as the void domain. As the enveloping shape of the poor-strength region (containing the void defect and the surrounding porous material) is approximately ellipsoidal, it is reasonable to use the evolution behavior of an assumed ellipsoidal void to describe the evolution of real void defects in the large ingot. Moreover, the critical closure condition of the assumed ellipsoidal void is generally more difficult than that of the real void defects, because the porous material existing in the assumed ellipsoidal void region will be compacted and fill the void domain gradually when the void is closing. Therefore, it indicates that the real void defect will be closed completely provided that the volume of the corresponding assumed ellipsoidal void reduces to zero. Besides, the void size is very small compared to the size of the large ingot, as shown in Fig. 1(a), the size ratio of