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Numerical simulation and experimental verification of void evolution inside large forgings during hot working

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ABSTRACT

Large forgings are the essential parts of some nuclear, electrical power generation, rolling mill equipments. Generally, they are directly obtained by forging the large ingots containing some void defects. In this study, the evolution mechanisms for the spherical or spheroidal voids during hot working are investigated by the numerical simulations and experiments. The effects of the initial void size, aspect ratio and positions on the void evolution were discussed. The results show that the closure process of voids can be divided into two stages. i.e., when the deformation degree is relatively small, the void retains spheroidal. However, the void will not be spheroidal when the deformation degree is relatively large. The changes of void aspect ratio are slightly affected by the void size, but greatly by the initial aspect ratio and position of voids. It also suggests that the strain and stress fields around voids are the key factors influencing the evolution of void aspect ratio. The increase of effective strain contributes to the changes of void aspect ratio. Considering the effects of stress and strain fields on the void evolution, a void aspect ratio evaluation index, which is defined as a function of the stress deviator, effective strain and effective stress, is proposed to describe the changes of void aspect ratio. Based on the results from finite element simulation, a theoretical model is established to predict the changes of void aspect ratio in large forgings during hot working. A good agreement between experimental and simulated results indicates that the proposed void aspect ratio evaluation index and theoretical model can give an accurate description of the void evolution.

1. Introduction

Large forgings are the essential parts of nuclear, electrical power generation, rolling mill equipments. Generally, they are directly obtained by forging the large ingots containing some void defects. The void defects inside large forgings will greatly deteriorate their mechanical properties. So, to eliminate the voids inside large ingots is one of the important tasks of hot forging. Often, eliminating voids inside large ingots includes two stages: void closure and welding of the closed void surfaces (Park and Yang, 1997). The void closure process is to contact the void internal surfaces, which is one of most important issues to be investigated (Zhang et al., 2009).

A considerable amount of research on the void closure has been done in the recent decades. Ståhlberg et al. (1980) investigated the closure of artificial voids during the plastic deformation, and pointed out that the rate of void closure increases with the increase of deformation degree. Tanaka et al. (1987) studied the upsetting process of a cylinder with a void by finite

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element method. Their results showed that the effective strain and hydrostatic stress around the void are the main factors for the void closure. Sun and Guo (1987) investigated the closing and consolidation of internal cavities in heavy rotor forgings by finite element method, and introduced a parameter called shrinkage energy as a criterion to evaluate the void closure. Dudra and Im (1990) carried out the simulations of a solid cylinder pressed with flat dies, V-shaped dies and FML dies. They found that the V-shaped dies are the most effective to close the internal void. Wang and Ren (1993) investigated the relationship between the strain and the closure of voids. The effect of the cooling of steel ingot surfaces on the closure of the internal voids were also investigated by Ono et al. (1994) and Park and Yang (1997). The results showed that the pre-cooling can increase the hydrostatic stress at the central zone of the ingot and contribute to the void closure. Pietrzyk et al. (1995) developed a finite element model to simulate the closure of a single void in a matrix during the plastic deformation, and investigated the influence of stress state on the void closure. Banaszek and Stefanik (2006) studied the influence of the anvil shape and the main forging process parameters on the elimination of metallurgical defects. Nakasaki et al. (2006) chose the integration of the hydrostatic stress, G_m, as a parameter to describe the closure of center voids, and found that the cross-sectional area of the void is in proportion with G_m in single-pass rolling. Li et al. (2008) simulated the closure of the void in the cylindrical forging during the upsetting process, and the critical deformation degree for the void closure was obtained. Zhang et al. (2009) proposed a criterion for the void closure in large ingots during hot forging by a cell model. Kakimoto et al. (2010) calculated the closing evaluation value of internal voids, and quantified its limit value for completely closing void. Chen et al. (2010) studied the evolution of different void defects during forging, and found that the closure of tetrahedral void is most difficult. Kim et al. (2011) carried out a numerical analysis of the upsetting and cogging processes, and proposed an efficient forging process to eliminate void defects. Chen et al. (2011) developed a comprehensive procedure to predict the void closure degree by finite element analysis and neural network.

The void growth has been also a very hot topic for decades because the void nucleation, growth and coalescence often characterize damage process in ductile metals (Lubarda, 2011; Voyiadjis et al.,2011; Khan and Liu, 2012a,b). McClintock (1968) and Rice and Tracey (1969) investigated the growth rates of a cylindrical and a spherical void in an infinite plastically deformed material with no strain hardening, respectively. Budiansky et al. (1982) studied the growth rate of an isolated spherical void in power-law matrix under the axisymmetric deformation, and established the famous BHS model. Following this work, Duva and Hutchinson (1984) derived a constitutive relation for an incompressible, isotropic power-law material containing a concentration of spherical void. Fleck and Hutchinson (1986) developed the analogous constitutive potentials for the solids containing a dilute concentration of circular-cylindrical void. Then, the growth rates of a dispersion of randomly oriented elliptical voids in incompressible power-law material were investigated by Mear and his co-workers (Lee and Mear, 1999; Yee and Mear, 1996). For porous ductile materials, Gurson (1977) developed an approximate yield criteria (Gurson model) and flow rule. Simplified physical models for porous ductile materials were employed, with the matrix material idealized as ideally plastic solid. Wen et al. (2005) extended the Gurson model to account for the void size effect based on the Taylor dislocation model. It was shown that the yield surfaces for micron- and submicron-sized voids are significantly larger than that given by Gurson model. In order to consider the role of void shape on the overall response of porous ductile materials, some researchers assumed voids as spheroidicity or elliptic cylinder and improved Gurson model (Chen et al., 2005; Chew et al., 2006; Flandi and Leblond, 2005; Gao et al., 2011; Gologanu et al. 1993; Hsu et al. 2009; Leblond et al., 1995; Lecarme et al.,2011; Li and Huang, 2005; Pardoen and Hutchinson, 2000; Zaïri et al., 2011; Monchiet and Kondo, 2013). Additionally, finite element methods were widely employed to investigate the growth of voids in the elastic–plastic materials (Li et al., 2000), plasticity strain hardening gradient materials (Li et al., 2003), nonlocal elastic–plastic materials (Tvergaard and Niordson, 2004), anisotropic plastic materials (Keralavarma et al., 2011), dual phase steels (Kadkhodapour et al., 2011), and so on (Chung et al., 2011; Li et al., 2011; Segurado and Lorca, 2010).

As described above, a wide range of studies have been conducted, and many beneficial conclusions have been gained for guiding the design of forging process to eliminate voids inside large ingots. Generally, the ratio of current cross-sectional area (A) to initial cross-sectional area (A_0) of a void or the ratio of current volume (V) to initial volume (V_0) of a void was chosen as the measurement to quantify the closure degree of voids. However, the void shape was not considered in many void evolution models. In fact, it is an important factor for void evolution (Lee and Mear, 1999; Gao et al., 2005; Yee and Mear, 1996). The shortcomings will lead to an inaccurate prediction for the closure degree of voids after a multi-pass stretching process. Take the void evolution during two two-pass stretching cases as an example. For these two cases, the initial sizes of spherical voids and the forging processing parameters of the corresponding pass are the same. But, for case 1, the initial spherical void is compressed in different directions during passes 1 and 2. i.e., the billet is forged in the horizontal direction during pass 1, and forged in the vertical direction during pass 2. For case 2, the initial spherical void is compressed only in the same direction during passes 1 and 2. Due to the same forging processing parameters, the volume and shape of the initial spherical void after pass 1 are the same for two cases. However, because the billet is forged in the vertical direction during the pass 2 of case 1, the initial void aspect ratio for the pass 2 of case 1 becomes the reciprocal of that for the pass 2 of case 2. Therefore, the final volume and shape of the void in cases 1 and 2 are different, although the initial sizes of spherical voids and the forging processing parameters of two cases are the same (Lee and Mear, 1999). If the void shape is not considered in a void evolution model, the predicted void volume can be expressed as,

$$\left.\begin{array}{l}\text{For case 1},\ V_{1-1}/V_0 = f(P_1), \quad V_{1-2}/V_{1-1} = f(P_2) \Rightarrow V_{1-2} = f(P_1)\times f(P_2)\times V_0 \\ \text{For case 2},\ V_{2-1}/V_0 = f(P_1), \quad V_{2-2}/V_{2-1} = f(P_2) \Rightarrow V_{2-2} = f(P_1)\times f(P_2)\times V_0\end{array}\right\} \Rightarrow V_{1-2} = V_{2-2} \tag{1}$$