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A criterion for void closure in the porous model during the forging of steel ingot and its application

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ABSTRACT

In this paper, on the basis of the new mathematical method formerly proposed, i.e., strain analysis method, (Chen et al., 2013), the criterion for multiple void closure was presented by mathematical derivation of the strain function. It indicates that the closure of each void is independent, but not accumulated in the porous model. Therefore, the criterion for single void closure formerly proposed can be completely applied on the porous model. Also, the criterion for two-dimensional void closure was derived from the elastic theory in the present paper. On this basis, the criterion for three-dimensional void closure applied on the practical process was discussed. It is shown that the deviation between them is less than 18%. Finally, this criterion for three-dimensional void closure was validated by numerical simulations for a typical steel ingot. It illuminates that with the criterion for void closure in the porous model, not only comparatively accurate results but also simplified model with voids are obtained in terms of prediction for void closure. It provides a new method with extensive application prospect for the optimization of the forging process.

1. Introduction

Steel ingot often contains void defects such as cavities and porosity, which will greatly deteriorate the mechanical properties of the large forgings [1]. Therefore, elimination of void defects in steel ingot is one of the important tasks of hot forging. It is very important to develop the criterion for void defects in terms of process design and rational utilization of scrap forgings [2].

With the development of computer technology and numerical method, numerical simulation based on finite element method (FEM) has already been the popular tools to research on the plastic deformation [3]. A number of studies have been conducted on using FE simulations to analyze the void closing in typical operation of the forging process, which contributes to investigate the pattern and influence factors of void closure [4–11]. However, it is difficult to disclose the mechanism of void closing because FE simulations can only focus on each specific operation of the forging process [12]. Therefore, starting with mechanics theory of materials is needed to obtain the quantitative rules of void defects closure.

With the deepening of research, it has been recognized that there should be some rules to describe the closure of internal void defects, which would provide the theoretical basis for process design. From the end of last century, research on the deformation behavior and the closure process of void has been done in view of mechanics theory and method, the purpose of which is devoted to establish the criterion for void closure expressed by stress and strain [13–20]. However, it is very inconvenient to implement the established criterion in practical applications because of the complex of the issue. From Ref. [21], it is shown that hydrostatic stress is a less important parameter in void closure as compared to effective strain. Also, the criterion for void closure has been presented on the basis of comparisons between the numerical and experimental results, i.e., a critical amount of local strain needed for effective void closure should be more than 0.6. However, this criterion is only the summary of experience, which lacks quantitative derivation and scientific explanation. Therefore, it would be difficult to acknowledge the application fields of the criterion.

A new mathematical analysis method has been formerly proposed to deal with the void closure inside the steel ingot, i.e., strain analysis method [22]. For this method, firstly, it gives numerical solution for the distributions of compressive strain obtained by FE simulations, then the analytic function of strain distribution is obtained by mathematical fitting, and finally the specific criterion for single void closure is determined by derivation and calculation

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of this function. In this study, research on the closure process and law of internal void during forging has been done in view of the mechanism of void closing, which is different from Ref. [21]. The aim in the present study is to extend the criterion for single void closure formerly derived to the porous model by further demonstration, i.e., based on the derivation and calculation, it is proposed to establish the criterion for multiple void closure with strong operability and solid theory, which provides a new methodology in terms of elimination of void defects. So, the study is the further extension of theoretical basis and application of Ref. [22].

The following discussion consists of four sections. The derivation of the criterion for single void closure is briefly presented in Section 1. The criterion for multiple void closure is proposed by further derivation and demonstration in Section 2, which aims to extend the criterion for single void closure to the porous model. The criterion for void closure in the porous model is validated and its concrete application is introduced in Section 4.

Based on elastic theory dealing with the stress–strain analysis of two-dimensional void, the criterion for two-dimensional void closure is determined by derivation and calculation of analytical solution for elastic plane problem in Section 3. The main concern is to present the derivation and demonstration of void closure in view of the elastic theory, in order to provide theoretical basis and support for the present study. On this basis, the criterion for three-dimensional void closure applied on the practical process is discussed.

2. Derivation of the critical condition for single void closure

The strain distribution has some pattern due to plastic deformation. In addition, the effects of small size defects on the global strain distribution within billet can be ignored regarding the Saint–Venant's Principle [23]. One of the innovation work in this paper is to present the criterion for multiple void closure by mathematical derivation of the strain function. However, it is based on the wok described in Ref. [22], i.e., the derivation of the critical condition for single void closure, and it is the continuation of previous paper. Therefore, to ensure the consistency and coherence of the entire derivation, a brief review of previous work is introduced in this section on the basis of Ref. [22], namely, the distributions pattern of the strain and the effects of single void defects on the distributions pattern are presented in this section.

2.1. The analytic function of strain distribution for the models without and with void

According to Refs. [22,24], the strain distribution in the pressing direction (z) within billet can be described by Gaussian function approximately. Concretely speaking, for the models without and with void, the distribution of compressive strain can be approximately expressed by Gaussian function and discontinuous Gaussian function, respectively. A cutoff vertical line is introduced to express on positions $z = z_1 \pm l'$, where sudden change in the curve of strain distribution occurs. The values of l' is determined by equal-area method, in order to assure total deformation remained constant pre and post approximation. The vertical line shown in Fig. 1b is cutoff bound of that discontinuous function.

For the models without and with void, it is expressed as follows, respectively:

$$\varepsilon_{z_0} = \beta e^{-\alpha z^2} \quad |z| \leqslant H/2\,, \tag{1a}$$

$$\varepsilon_z = \begin{cases} \varepsilon_{z_0} & z < z_1 - l', \\ 0 & z_1 - l' \leqslant z \leqslant z_1 + l', \\ \varepsilon_{z_0} & z > z_1 + l', \end{cases} \tag{1b}$$

where z_1 is the axial distance between symmetrical center of the void and the models with void; β denotes the maximum value of compressive strain distribution function for the models without void; α is a parameter related to width distribution of strain; l' represents cutoff bound of the strain distribution function for the models with void, which is obtained by equal-area method, and $l' = kd$,

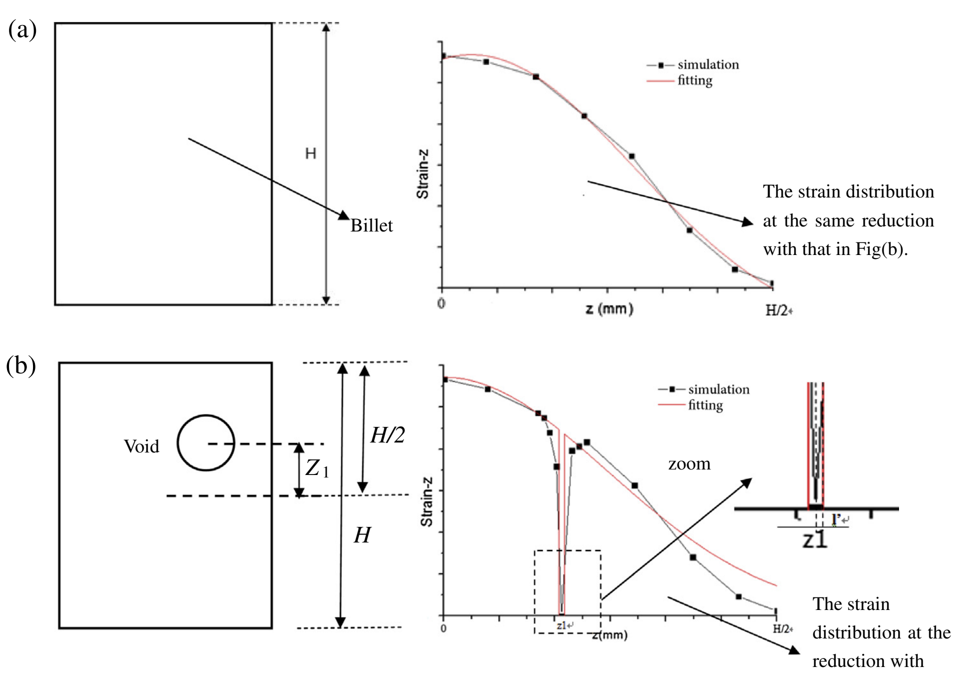

Fig. 1. The distributions curve of compressive strain ε_z with void closure in the pressing direction (z) for the models without and with void (a) models without void and (b) models with void.