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Multi-scale Analysis of Void Closure for Heavy Ingot Hot Forging

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Abstract

A multi-scale model towards simulating the void closure during hot forging was introduced in the present study and the derived void evolution model was programmed into commercial code DEFORM to simulate the void closure behavior in heavy ingot during the upsetting and blocking processes. From the simulation results, it can be concluded that: (1) the cymbal-shaped die is good at closing voids not only near the die but also around the axis of the ingot when the reduction is 36% in the upsetting process, (2) the effectiveness of V-shaped die is the best for consolidating voids around the axis and near the die when the reduction is 24% in a single blocking process, however, at about 22% reduction after 90° rotate, the void-closed regions become quite large around the axis both for flat dies and FML dies and the loads are much lower than those of V-shaped dies. Upon that, void closure in multi-stroke and multi-pass forging was also discussed. The multi-scale model and simulation results provide valuable sources of reference for design and optimization of die shapes and pass schedules for heavy ingots during hot working processes.

Keywords: multi-scale, modeling and simulation, void closure, heavy ingot, hot forging

1. Introduction

Internal defects such as shrinkage cavities and porosity are usually generated in heavy ingots during solidification in steel casting. These tiny voids must be closed up in the subsequent hot forging process to ensure high quality of the product (Dudra & Im, 1990). Because of its importance, void closure has been studied for more than 30 years. Various methods, such as physical simulation and experimental study (Chaaban & Alexander, 1976), upper bound analysis (Ståhlberg, 1986), finite element (FE) method (Tanaka et al., 1986; Park & Yang, 1997; Jiang et al., 2005; Lee et al., 2011) are used to develop predictive measures for void closure in heavy ingot during hot forging. However, since a large number of small voids usually exist in heavy ingot and the volume of the void is extremely small compared with the heavy ingot, modeling void closure in heavy ingot during hot forging is a multi-scale problem, and it is very difficult to find predictive measures based only on macro-mechanics.

In this study, a meso-mechanics approach is employed to deal with the multi-scale problem. A cell model is adopted to study the deformation rate of the void and a theoretical model towards simulating the void closure during hot forging is introduced. The derived void evolution equation is programmed into commercial software DEFORM to simulate the behavior of void closure in heavy ingot during the upsetting and blocking processes. The relative void volume, which is defined as the ratio of current void volume to initial void volume, is calculated during the deformation of heavy ingots in the hot working processes. Relative void volume and its distribution are used to evaluate the effectiveness of different die shapes and the processes for consolidating internal voids. Both upsetting and blocking processes for heavy ingots are studied. Upon that, void closure in multi-stroke and multi-pass forging is also discussed.

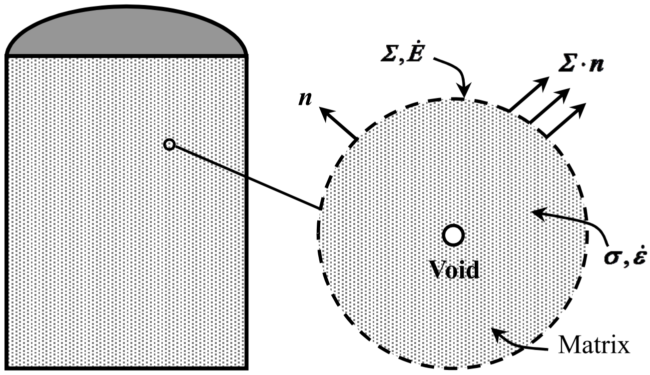
2. A Multi-scale Model for Void Closure

2.1 Cell Model and Void Evolution

A cell model is adopted to deal with the multi-scale problem of void closure and to analyze the evolution of void. The cell model which includes matrix and void is shown in Figure 1 with volume V_c and outer surface S_c, and subjected to remote (macroscopic) uniform stress $\boldsymbol{\Sigma}$. The matrix material is assumed to be isotropic and incompressible. The constitutive relation of the matrix during hot forging can be given as (Cocks, 1989; Duva & Hutchinson, 1984)

$$\dot{\boldsymbol{\varepsilon}} = \frac{3}{2}\frac{\dot{\varepsilon}_0}{\sigma_0}\left(\frac{\sigma_{\mathrm{e}}}{\sigma_0}\right)^{n-1}\boldsymbol{\sigma}' \tag{1}$$

where $\dot{\varepsilon}_0$ and σ_0 are reference strain-rate and stress respectively, n ($1 \le n < +\infty$) is the Norton exponent, $\boldsymbol{\sigma}'$ is the stress deviator and $\sigma_{\mathrm{e}} = \left(\frac{3}{2}\boldsymbol{\sigma}':\boldsymbol{\sigma}'\right)^{1/2}$ is the effective stress. An initially spherical void is contained in the cell. The volume of the void is V and the void surface is S. The void volume fraction is assumed small and void interaction is ignored. The aim is to obtain the velocity field in the matrix of the cell, and then the evolution of the void can be determined by this velocity field.



(a) (b)

Figure 1. (a) Heavy ingot: comprised of a matrix and a dilute dispersion of traction-free voids and (b) Cell model: volume V_{c}, outer surface S_{c}, uniform tractions $\boldsymbol{\Sigma}\cdot\boldsymbol{n}$ over S_{c}

To obtain an evolution equation of the void, a Rayleigh-Ritz procedure based on Hill's minimum principle (Hill, 1956) for the velocities is developed. The trial local velocity and strain-rate within the matrix are expressed as

$$\boldsymbol{v} = \boldsymbol{v}^0 + \tilde{\boldsymbol{v}}\,,\quad \dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{E}}^0 + \dot{\tilde{\boldsymbol{\varepsilon}}} \tag{2}$$

where $\boldsymbol{v}^0$ and $\dot{\boldsymbol{E}}^0$ are the uniform velocity and strain-rate due to $\boldsymbol{\Sigma}$ in the absence of the void. Then, among all additional velocity fields $\tilde{\mathbf{v}}$, the actual velocity field minimizes the functional (Duva & Hutchinson, 1984)

$$F(\tilde{\boldsymbol{v}}) = \int_{V_{\mathrm{m}}}[w(\dot{\boldsymbol{\varepsilon}}) - w(\dot{\boldsymbol{E}}^0) - \boldsymbol{\Sigma}:\dot{\tilde{\boldsymbol{\varepsilon}}}]dV - \int_S \tilde{\boldsymbol{v}}\cdot\boldsymbol{\Sigma}\cdot\boldsymbol{n}dS \tag{3}$$

where V_{m} is the volume of the matrix material in the cell, S is the surface of the void, $\boldsymbol{n}$ is the unit normal to the surface of the void pointing into the matrix, and

$$w(\dot{\boldsymbol{\varepsilon}}) = \frac{n}{n+1}\dot{\varepsilon}_0\sigma_0\left(\frac{\dot{\varepsilon}_{\mathrm{e}}}{\dot{\varepsilon}_0}\right)^{(n+1)/n} \tag{4}$$

in which $\dot{\varepsilon}_{\mathrm{e}} = (\frac{2}{3}\dot{\boldsymbol{\varepsilon}}:\dot{\boldsymbol{\varepsilon}})^{1/2}$ is the local effective strain-rate. Note that $\lim_{\rho\to 0}\dot{\boldsymbol{E}} = \dot{\boldsymbol{E}}^0$, where $\rho = V/V_{\mathrm{c}}$ is the void volume fraction and V is the volume of the void. Since the cell model considered for heavy ingots is infinite compared with the void, $\dot{\boldsymbol{E}} = \dot{\boldsymbol{E}}^0$ will be used throughout and

$$\dot{\boldsymbol{E}} = \dot{\boldsymbol{E}}^0 = \frac{3}{2}\frac{\dot{\varepsilon}_0}{\sigma_0}\left(\frac{\Sigma_{\mathrm{e}}}{\sigma_0}\right)^{n-1}\boldsymbol{\Sigma}' \tag{5}$$

As the matrix material is incompressible, the stream function can be introduced to characterize the additional velocity field $\tilde{\boldsymbol{v}}$ and the unknown variables in the stream function can be determined by minimizing $F(\tilde{\boldsymbol{v}})$ in Eq.(3) (Budiansky et al., 1982; Lee & Mear, 1994). Once the velocity field $\boldsymbol{v}$ has been computed from the Rayleigh-Ritz procedure, the change-rate of void volume is given by

$$\frac{\dot{V}}{V} = \frac{1}{V}\int_S \boldsymbol{v}\cdot\boldsymbol{n}dS \tag{6}$$

2.2 The Multi-scale Model for Void Closure

Based on the calculations of the Ritz procedure mentioned above, the numerical solutions were obtained in a previous study by Zhang et al. (2009). These numerical results can be used to formulate an explicit expression of the multi-scale model for void closure, which is suggested as

$$\begin{cases} \dfrac{V}{V_0} = \exp\left\{\mathrm{sign}(\Sigma_{\mathrm{m}})E_{\mathrm{e}}\left[\dfrac{3}{2}\left(\dfrac{3}{2n}\left|\dfrac{\Sigma_{\mathrm{m}}}{\Sigma_{\mathrm{e}}}\right| + \dfrac{(n-1)(5n+2)}{5n^2}\right)^n + q_1\left|\dfrac{\Sigma_{\mathrm{m}}}{\Sigma_{\mathrm{e}}}\right| + q_2E_{\mathrm{e}}^2 + q_3E_{\mathrm{e}}^4 + q_4\right]\right\} & \text{for } \Sigma_{\mathrm{e}} \neq 0 \\ \dfrac{V}{V_0} = \exp\left[\mathrm{sign}(\Sigma_{\mathrm{m}})\dfrac{3\dot{\varepsilon}_0 t}{2}\left(\dfrac{3}{2n\sigma_0}\left|\Sigma_{\mathrm{m}}\right|\right)^n\right] & \text{for } \Sigma_{\mathrm{e}} = 0 \end{cases} \tag{7}$$

where $\Sigma_{\mathrm{m}} \equiv \frac{1}{3}\mathrm{tr}(\boldsymbol{\Sigma})$ and $\Sigma_{\mathrm{e}} \equiv \left(\frac{3}{2}\boldsymbol{\Sigma}':\boldsymbol{\Sigma}'\right)^{1/2}$ are the remote mean stress and the remote effective stress, respectively, and $\dot{E}_{\mathrm{e}} = \left(\frac{2}{3}\dot{\boldsymbol{E}}:\dot{\boldsymbol{E}}\right)^{1/2}$ is the remote effective strain-rate, $\Sigma_{\mathrm{m}}/\Sigma_{\mathrm{e}}$ is the measure of stress triaxiality, q_1, q_2, q_3 and q_4 are four parameters and E_{e} is the macroscopic effective strain. In the present study, FE computations based on a cubic cell model are carried out to determine the values of q_1, q_2, q_3 and q_4 and the values of q_1, q_2, q_3 and q_4 are suggested and given in Table 1.

Table 1. The values of q_1, q_2, q_3 and q_4 in Eq. (7)

n	1	2	3	5	10	100
q_1	0.5048	0.4911	0.6016	1.1481	2.9132	6.5456
q_2	6.4675	0.8002	-0.6981	-4.2026	-11.6464	-15.3775
q_3	14.2610	53.8018	72.6397	108.2114	185.5622	324.4417
q_4	-0.3379	-0.2314	-0.1243	-0.2480	-0.6511	-1.9575

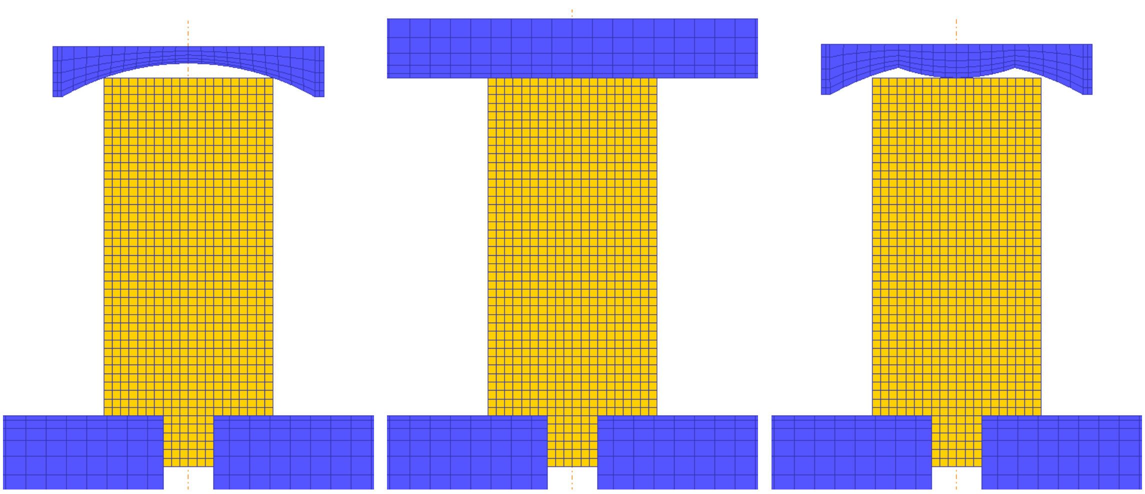
3. Multi-scale Simulation of Void Closure

Upsetting and blocking are two typical operations in the process of manufacturing heavy forgings. Upsetting is a process which increases the cross-section of the billet by compressing its length, while blocking is a process which reduces the cross-section of the billet and increases its length by repetitive side pressing and alternate ingot rotations. Both upsetting and blocking processes are often used to eliminate internal voids in heavy ingots. New die geometries which lower the press loads have also been investigated since the press load capacity of the forging machine is a limitation when forging heavy ingots.

In this section, the derived void evolution equation is programmed into commercial software DEFORM to simulate the behavior of void closure in heavy ingot during the upsetting and blocking processes. The relative void volume R_V, which is defined as the ratio of current void volume V to initial void volume V_0, is calculated during the deformation of heavy ingots in the hot working processes. Relative void volume and its distribution are used to evaluate the effectiveness of different die shapes and the processes for consolidating internal voids.

3.1 Void Closures in Upsetting

Upsetting of a cylindrical ingot with concave sphere die, flat die, M-shaped die, convex sphere die and cymbal-shaped die are simulated in this subsection to reveal the effect of die shapes on void closure. The FE models for upsetting with different die types are shown in Figure 2 and the diameter of the cylindrical ingot is D =1000 mm and the height is H = 2000 mm. The results of R_V by applying the multi-scale method (MSM) in simulation are shown in Figure 3 at 36% reduction. Note that $R_V \to 0$ means void closure, whereas $R_V \to 1$ indicates void has not closed. From Figure 3, it is clear that: (1) There is a void-unclosed region near the die during upsetting with concave sphere die and flat die (Figure 3(a) (b)). The void-unclosed region produced by concave sphere die is the biggest and R_V approaches 1 in that region. The void-unclosed region produced by flat die is smaller than that by concave sphere die, but it is still a disadvantage to obtain high quality forgings. It indicates that, from a point of view of eliminating voids in heavy ingots, concave sphere die and flat die are not suitable for upsetting. (2) The void-unclosed regions produced by convex surface die are much smaller than those by concave surface die and flat die (Figure 3(c) (d) (e)). Comparing M-shaped die, convex sphere die and cymbal-shaped die with each other, it can be seen that there is a relatively big void-unclosed region produced by M-shaped die near the intersection of the convex and concave surface, and R_V around the axis is also not uniform. Convex sphere die and cymbal-shaped die, however, can consolidate the void near the die during upsetting. Moreover, cymbal-shaped die upsetting provides an ideal result for void closure not only near the die but also around the axis of the ingot (Figure 3(e)). (3) Since the void-unclosed region always exists near the die during upsetting with concave sphere die, flat die and M-shaped die (Figure 3(a) (b) (c)), it is very difficult to achieve the goal of eliminating void in heavy ingots even by multiple upsetting along the axis. However, the voids near the die and those around the axis of the ingot can be eliminated with convex sphere die and cymbal-shaped die (Figure 3(d) (e)), so that the goal of eliminating voids can be achieved by multiple upsetting along the axis with convex sphere die and cymbal-shaped die. (4) Since the metallurgy defects in heavy ingots scatter mainly along the axis, the cavity defects would be eliminated completely only when all of the voids around the axis are closed. Since cymbal-shaped die is good at closing voids not only near the die but also around the axis of the ingot, and the loads for cymbal-shaped die are also relatively small, the cymbal-shaped die is suggested to use in upsetting.



(a) (b) (c)

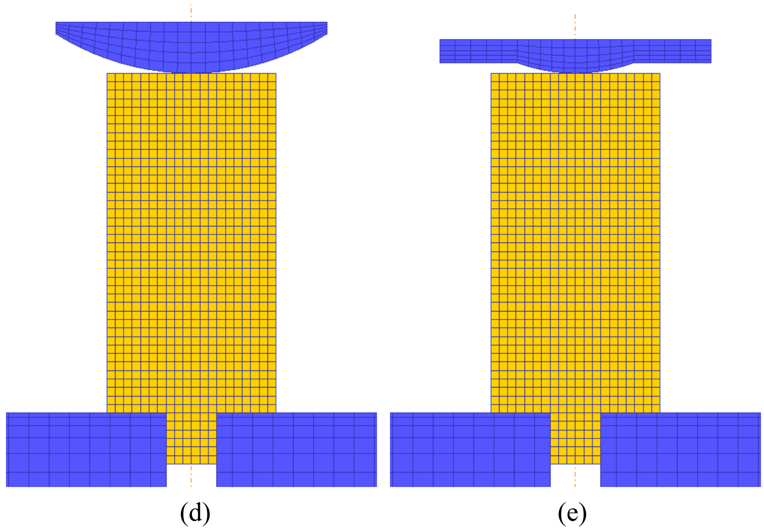


Figure 2. Finite element models for upsetting with different die types: (a) concave sphere die, (b) flat die, (c) M-shaped die, (d) convex sphere die and (e) cymbal-shaped die

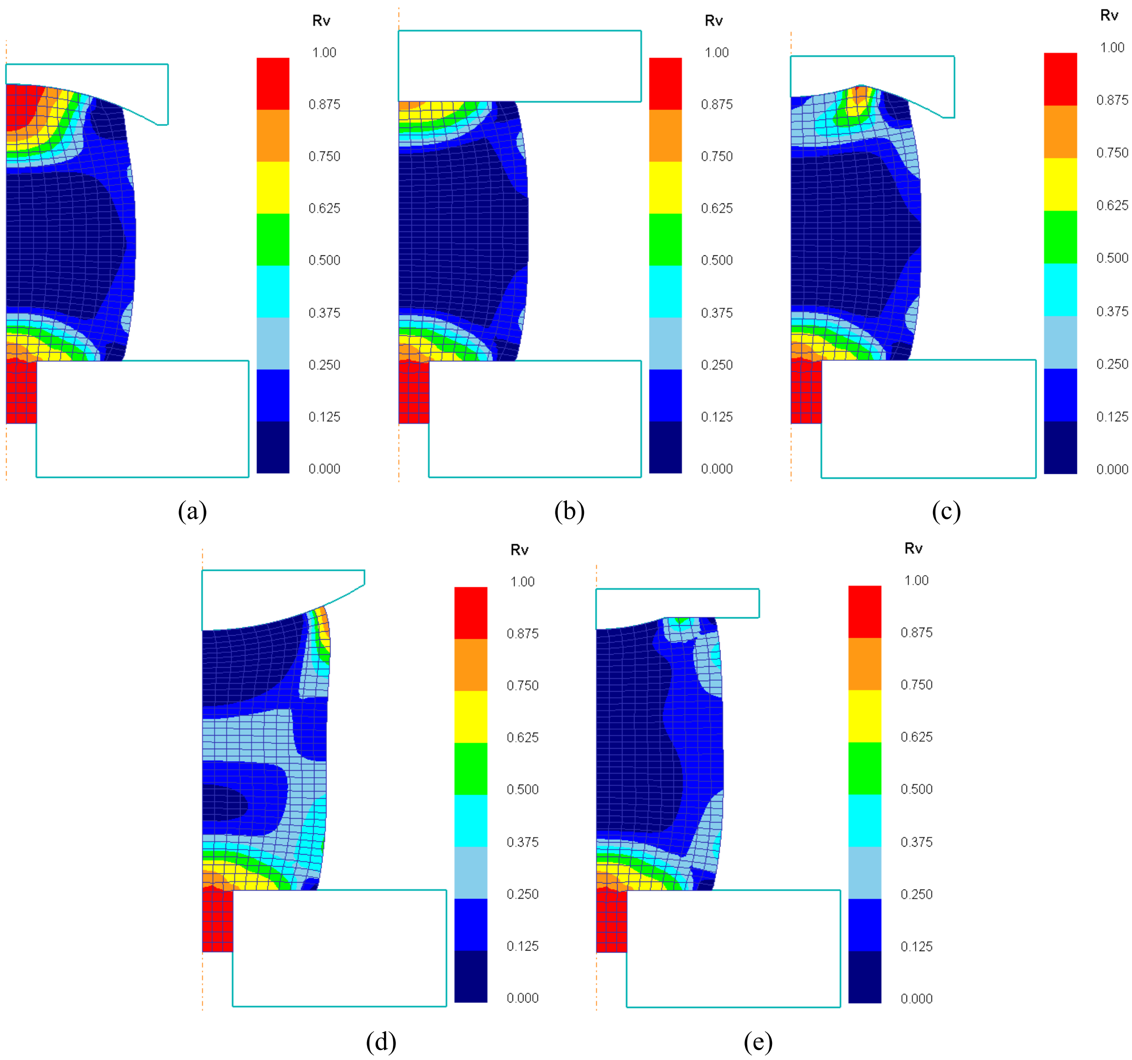
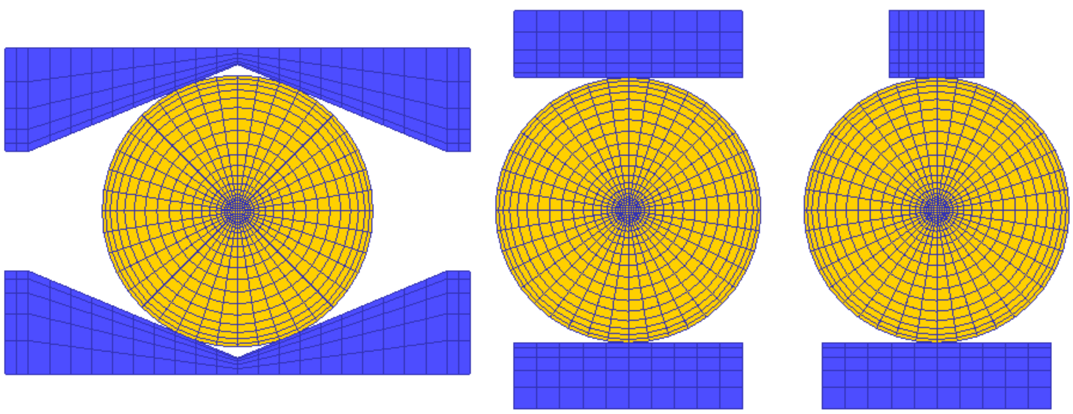


Figure 3. Relative void volume for upsetting with different dies at 36% reduction: (a) concave sphere die, (b) flat die, (c) M-shaped die, (d) convex sphere die, (e) cymbal-shaped die

3.2 Void Closures in Blocking

Blocking of a cylindrical ingot with V-shaped die, flat die and FML dies are simulated in this subsection to evaluate the effectiveness of these dies for consolidating internal porosity. The FE models for blocking with different dies are shown in Figure 4 and the diameter of the cylindrical ingot is 1400 mm. The results of R_V at 24% reduction are shown in Figure 5, Figure 6(a) and Figure 7(a). Press loads required for different dies are shown in Figure 8. From Figures 4~8, it is found that: (1) The distribution of void-closed region is significantly influenced by die shapes. Void-closed region produced by V-shaped die is the largest and effectiveness of V-shaped die is the best for consolidating voids around the axis and near the die (Figure 5). Void-closed region produced by flat die is mainly distributed around the axis (Figure 6(a)) and void-closed region produced by FML dies is mainly centered on a small area around the axis (Figure 7(a)). (2) The loads for V-shaped die increase rapidly from the beginning of loading and keep a high growth rate, whereas the loads for flat die and FML dies are relatively much smaller (see Figure 8). The loads for flat die and FML dies are almost the same when the reduction is less than 13% (the reduction time is 6 s). The loads for flat die are higher than those for FML dies when the reduction is greater than 13%. It indicates that, from a point of view of eliminating voids in heavy ingots, the effectiveness of V-shaped die is the best but the loads required are also the highest. The effectiveness of flat die takes second place with lower loads. The FML dies are less effective in each stroke than other dies for consolidating void in heavy ingot, but the loads required for FML dies are also the smallest. If the press load of the forging machine is enough, then the pair of V-shaped dies would be a good choice for blocking. These results are in good agreement with the experimental and theoretical results in literatures. (3) One of the characteristics of blocking is that the billet can be pressed repetitively with alternate ingot rotations. The distributions of R_V at 24% reduction and those at 22% reduction after 90° rotate are displayed in Figure 6 and Figure 7 with flat dies and FML dies, respectively. At the first 24% reduction, the void-closed regions produced by flat die and FML dies are very small (see Figure 6(a) and Figure 7(a)). At about 22% reduction after 90° rotate, however, the void-closed regions become quite large around the axis both for flat dies and FML dies (see Figure 6(b) and Figure 7(b)), and the loads are much lower than those of V-shaped dies (Figure 8). The void-closed region near the die during blocking with FML dies is larger than that with flat dies. If press load of the forging machine is a constraint, then the FML dies would be a better choice. It also implies that the voids in heavy ingots would be closed by multi-stroke and multi-pass blocking with flat dies and FML dies.



(a) (b) (c)

Figure 4. Finite element models for blocking with different die types: (a) 135°V dies, (b) flat dies, (c) FML dies

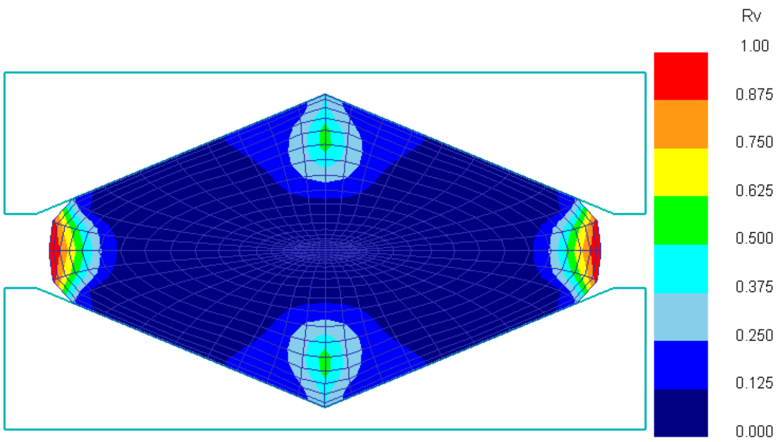
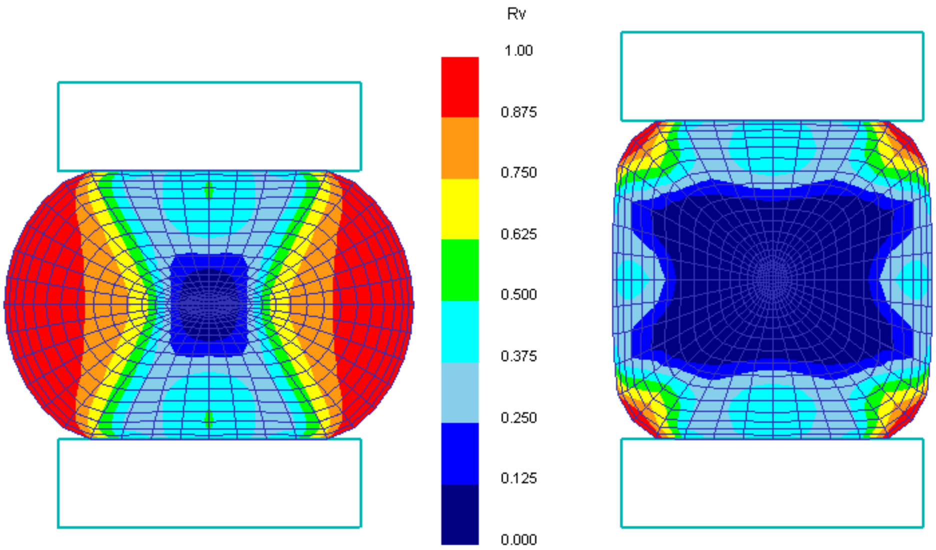
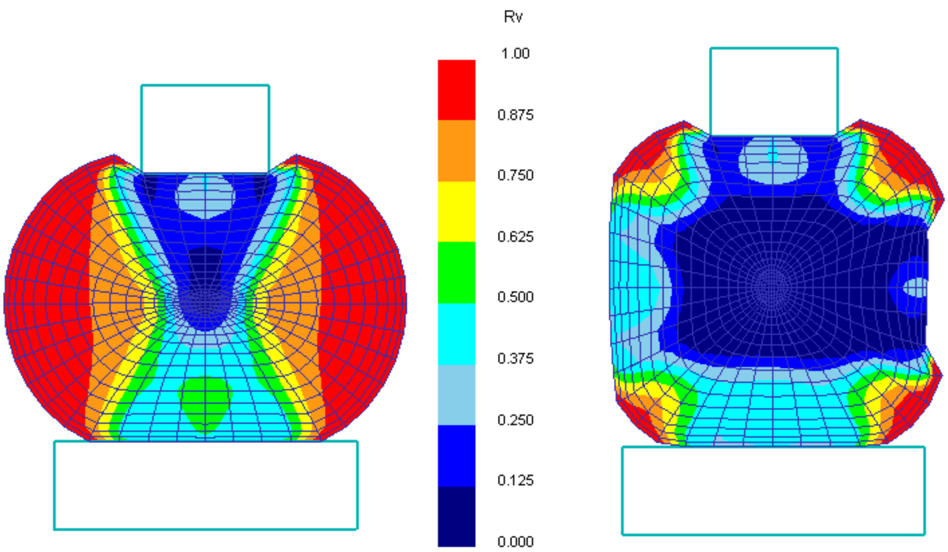


Figure 5. Relative void volume for 135° V dies blocking at 24% reduction



(a) (b)

Figure 6. Relative void volume for flat dies blocking: (a) 24% reduction, (b) 22.2% reduction after 90° rotates



(a) (b)

Figure 7. Relative void volume for FML dies blocking: (a) 24% reduction, (b) 22.6% reduction after 90° rotates

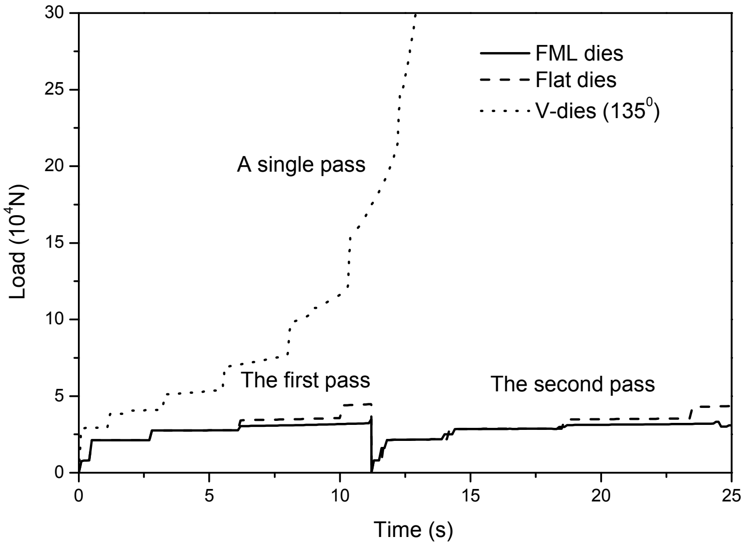


Figure 8. Loads for blocking with different dies

3.3 Multi-stroke and Multi-pass Forging

The forging process of heavy ingots usually needs a lot of strokes and many passes, therefore study on void closure in multi-stroke and multi-pass is very important. Only in this way, the course of forging can be evaluated in an all-round way and the process can be optimized as a whole.

Void closure in a square billet during multi-stroke blocking with a pair of flat dies is investigated in this subsection. The FE model of the square billet is shown in Figure 9 and its width is W =1000 mm, height is H = 1200 mm and length is L =3000 mm. The results of R_V after four strokes in the first pass are shown in Figure 10(a) and the reduction for each stroke is 25%. Figure 10(b) is a sliced plane view. After the first pass, the ingot is rotated 90° and five strokes are performed in the second pass. Figure 10(c) displays the results of R_V in the second pass. From Figure 9 and Figure 10, it can be seen that: (1) Looking from side, there are “X” shaped areas whose internal cavities are closed fairly well after four strokes in the first pass (see Figure 10(a)(b)). (2) The sliced plane view indicates that the voids in some local regions of the ingot has been closed after four strokes, nevertheless, continuous void-closed regions along the centerline of the ingot still have not appeared after one pass forging. (3) Since void-unclosed region always exists near the flat dies during every stroke, and void-unclosed region appears between strokes, the multi-pass blockings are needed to eliminate the internal voids in the ingot. Void-closed regions will be continuously produced by alternate press and rotate in multi-pass blocking (see Figure 10(c)). The goal of eliminating void would be achieved when these local void-closed regions are united as a whole in the ingot. (4) Application of the criterion for void closure in the CAE analysis makes it very convenient to evaluate and optimize various traditional forging processes, and provides a novel way for new process design in terms of elimination of voids in heavy ingots.

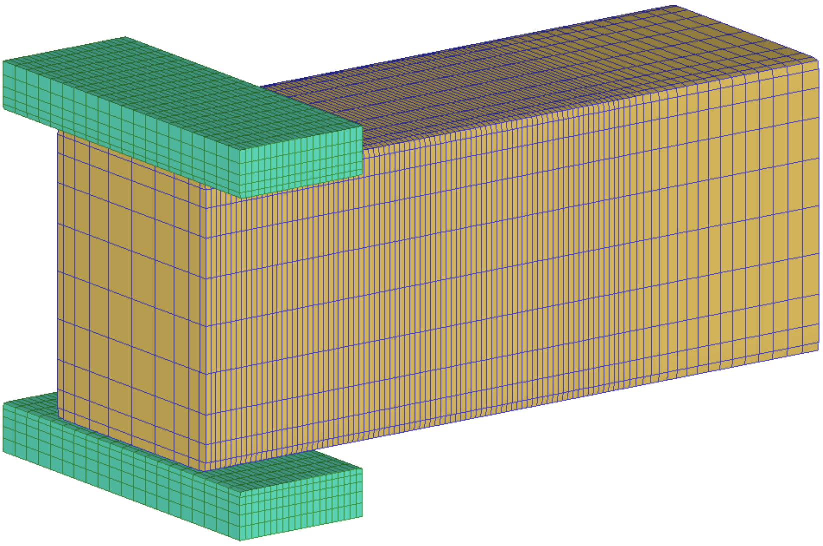
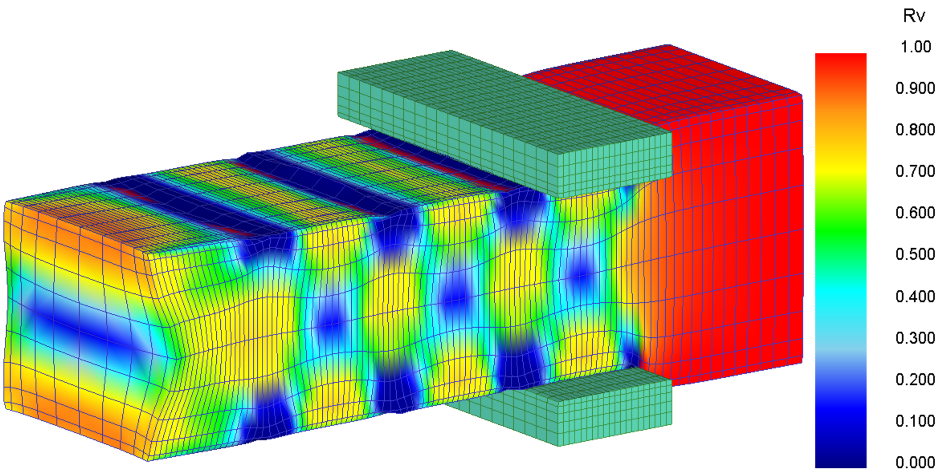
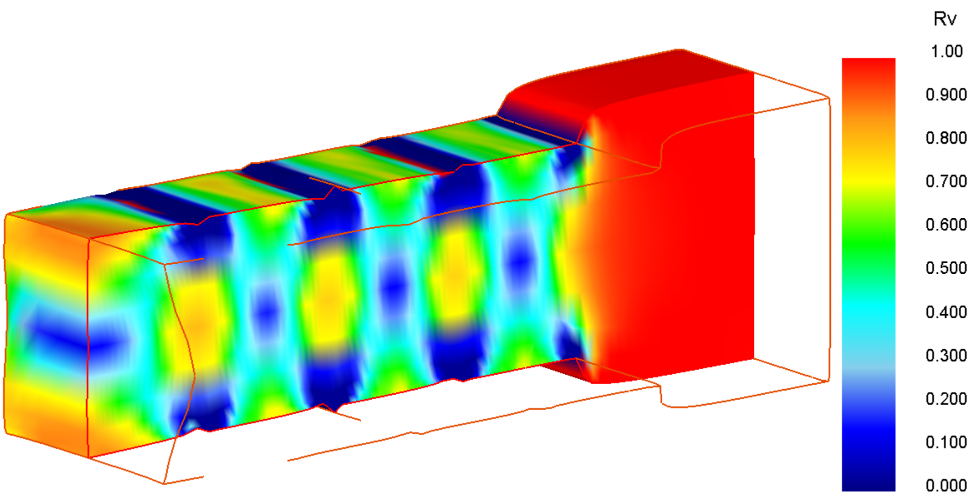


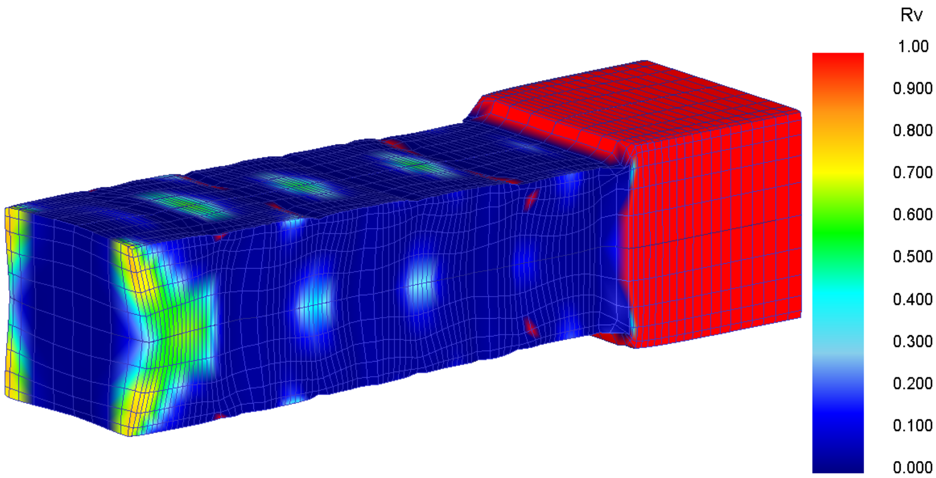
Figure 9. Finite element models for multi-stroke and multi-pass forging



(a)



(b)



(c)

Figure 10. Void closure in multi-stroke and multi-pass forging: (a) after four strokes in the first pass, (b) section plane view after four strokes in the first pass, and (c) after five strokes in the second pass

4. Conclusions

A multi-scale model towards simulating the void closure during hot forging is introduced in this study. A cell model, which includes a void-free matrix and a void, is adopted, and Rayleigh-Ritz procedure is used to study the deformation rate of the void. The derived void evolution model is programmed into commercial code DEFORM to simulate the void closure behavior in heavy ingot during the upsetting and blocking processes. It can be concluded that: (1) From a point of view of eliminating voids in heavy ingots, concave sphere die and flat die are not suitable for upsetting since a large void-unclosed region exists near the die. Since the cymbal-shaped die is good at closing voids not only near the die but also around the axis of the ingot, and the loads for cymbal-shaped die are also relatively small, the cymbal-shaped die is suggested to use in upsetting. (2) From a point of view of eliminating voids in heavy ingots, the effectiveness of V-shaped die is the best for blocking but the load required is also the highest. The effectiveness of flat die takes second place with lower loads. The FML dies are less effective in each stroke than other dies, but the loads required for FML dies are also the smallest. If the press load of the forging machine is enough, then the pair of V-shaped dies would be a good choice for blocking. If press load of the machine is a constraint, then the FML dies would be a better choice. (3) Since void-unclosed region exists near the flat die during every stroke, and void-unclosed region appears between strokes, the multi-pass blockings are needed to eliminate the internal voids in heavy ingots. Void-closed regions will be continuously produced by alternate press and rotate in multi-pass blocking. When the local void-closed regions are united as a whole in the ingot, the goal of eliminating void will be achieved. (4) By applying the multi-scale model for void closure in the CAE analysis, the optimal forging process, in terms of elimination of voids in heavy ingot, can be carried out and the schedule for multi-stroke and multi-pass can be arranged economically, and then high product quality would be obtained.

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