Finite-Element Analysis of Cylindrical-Void Closure by Flat-Die Forging

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Voids in a bloom produced by continuous casting are cylindrical in shape and located along the longitudinal direction. In the present study, the closure phenomenon of these voids by flat-die forging was investigated by the rigid-plastic finite-element analysis and experiments using plasticine specimens. The void closure was found to progress through contraction followed by collapse, and to be completed as the effective strain at the location of the void reached a certain value. The value was found to be dependent on the aspect ratio of the cross section of a void, but not on the size of the void. The relationship between the effective strain and the aspect ratio was established by which the closure of such a void with any aspect ratio can be predicted in terms of the effective strain in uniaxial forging. Compared to biaxial forging, uniaxial forging was found to be far more effective for the void closure in a bloom.

KEY WORDS: void; steel; forging; plasticine; finite-element analysis.

1. Introduction

Voids in a bloom produced by continuous casting are often evolved by the decreased gas solubility as well as the contraction of volume during cooling and solidification processes. Since the voids adversely affect tensile and fatigue properties of the material, they are required to be closed by subsequent forging or rolling processes.

Many studies have been carried out to understand the closure phenomenon of a void during forging or rolling. Stahlberg et al.1) analyzed the closure of a void in a continuously cast billet through plane strain forging with parallel dies by the upper bound method, and found that it is disadvantageous to turn the billet too early since the rate of void closure increased with reduction in height. Fukui et al.2) investigated closing of internal cavities in free forging of large products, and suggested that the heated ingot should be pushed down by a wide tool to a high reduction at the early stage of forging. Tsuda et al.3) studied adequate rolling conditions for closing of internal voids in a bloom, and found that the width to height ratio of the cross section of the specimen between 1 and 1.5 was most adequate for closing. Wallero4) studied the closure of longitudinal voids, and found that the rate of closure increased with increasing reduction in height and increasing hydrostatic stress. Wang et al.5) investigated the closure and welding phenomena of cylindrical and round voids during hot rolling. They found that heavy reductions with large rolls were effective for the void closure and that large magnitudes of hydrostatic stress for a sufficient time were effective for welding closed voids.

Hamzah and Stahlberg6,7) investigated the void closure in forging of heavy rings, and found that voids were easily closed by closed-die forging due to large strains with large magnitudes of hydrostatic stress. Banaszek and Stefanik8) investigated the effect of anvil shape on the void closure, and found that asymmetric anvils are favorable in the initial stage while flat anvils are favorable in the final stage. Nakasaki et al.9) introduced a hydrostatic integration parameter to indicate the reduction of a central void in a billet during forging or rolling. Zhang et al.10) investigated the void closure by a multi-scale approach in which the constitutive relations of a void-free matrix in macro-scale and a cell model in micro-scale were integrated. They derived an equation of the volumetric strain of a void under the assumption that the void remained spherical during deformation. Ji et al.11) investigated the void closure in a heavy slab by rolling and found that the void closure at the middle layer was the most difficult, since the effective strain and the hydrostatic stress at the layer were the least in magnitude. Kim et al.12) studied forging of a large ingot, and found that the height to diameter ratio of 1.29 and the maximum pressing depth per stroke were most effective for the void closure.

As described above, results of these studies were mostly rather qualitative. It was probably due to the fact that the closure phenomenon occurring in the material was difficult to be observed and analyzed quantitatively. In the present study, the longitudinal voids were assumed to be cylindrical with circular or elliptical cross-sections, and to be located along the length of a bloom. The void closure during flat-die forging was investigated by experiments using plasticine...
and by the rigid-plastic finite-element method using a commercial code DEFORM. The dies were so long that the bloom was regarded to be under plane-strain compression. The progress in the void closure, obtained from a finite-element model containing a void, was related to the effective strain and the hydrostatic stress at the location of the void, obtained from a finite-element model containing no void.

2. Finite-element Analysis

A bloom of AISI-1015, which is usually used for producing structural components, was selected for investigation in the present study. The liquidus and solidus temperatures of this material were 1400°C and 1370°C, respectively. In continuous casting, the melt of the material was heated to 1500°C and solidified to a bloom as the heat was extracted by the mold and the water spray. The cross section of the bloom was a rectangle with dimensions of 300 mm × 500 mm.

The cooling pattern on the cross section of the bloom greatly depends on the IHTC (Interface Heat Transfer Coefficient) at the interface between the melt and the mold, as Alvarez et al. demonstrated. Figure 1 shows two different cooling patterns on the cross section of the bloom, which was cooled by the mold, the water spray, and the air sequentially and then homogenized in an adiabatic furnace. A void is usually evolved at a location that is solidified the most lately. When the IHTC was uniform throughout the interface, the void was found to evolve at the center of the cross section, as shown in Fig. 1(a). On the other hand, when the IHTC at the upper and lower interfaces was smaller than that of the side interfaces, the voids evolved at the middle regions between the center and the upper and lower interfaces, as shown in Fig. 1(b). In fact, the void can evolve at any location on the cross section depending on the circumstances provided. The average temperature on the cross section was about 1100°C in both cases.

Flat-die forging of a bloom is illustrated in Fig. 2, where the bloom is forged by two dies reciprocating symmetrically in y direction while it moves in z direction. Accordingly, the width of the bloom decreases from \( w_0 \) to \( w_f \) while the thickness increases from \( t_0 \) to \( t_f \). The dies are so long that deformation of the bloom in z direction is quite restricted; it is thus regarded as a plane-strain compression. Closure of a longitudinal void in the bloom, by the flat-die forging at 1100°C isothermally, was analyzed by the rigid-plastic finite-element method. The flow stress of the material at this temperature was given by \( \sigma = 132 E^{0.144} \sigma_0^{0.163} \) MPa.

2.1. Circular Cross-section

The void closure was expected to differ by locations as deformation of the bloom through the flat-die forging was inhomogeneous. A finite-element model of the cross section containing a void of 10 mm in diameter located at the center is presented in Fig. 3, where four other locations of the void are designated with numbers. Fine elements were distributed around the void where severe deformation was expected or detailed geometric descriptions were required. The finite-element analysis was performed separately for each of these locations of the void, and as a result the void closures at these locations were obtained as shown in Fig. 4. The void closure was noted to progress through contraction followed by collapse; it was completed in the order of locations 1, 4, 2, 5, and 3 at 16%, 21%, 22%, 27%, and 42% reductions in height, respectively. The voids at locations 4 and 5 were tilted counterclockwise due to shear strain. The elements were repeatedly redistributed as they were severely distorted during the analysis.

Relations between the effective strain and the cross-sectional area are presented in Fig. 5. Here the effective strain at the location of the void was obtained from a finite-element model containing no void. The curve of location 3 was the lowest, while the hydrostatic stress at this location was the largest in magnitude. Values of the effective strain

![Fig. 1. Temperature contours on the cross section of the bloom: (a) uniform IHTC at the mold interface and (b) nonuniform IHTC at the mold interface.](image1)

![Fig. 2. Schematic drawing of flat-die forging of a bloom produced by continuous casting.](image2)

![Fig. 3. Finite-element model with a void at the center; other locations are designated by numbers.](image3)
for increase in the aspect ratio at the locations are given in Table 1. Here, the aspect ratio $\alpha$ was defined by the horizontal axis divided by the vertical axis of the cross section. As the effective strain in average increased to 0.145, 0.195, 0.235, and 0.268, the aspect ratio of the cross increased to 2, 3, 4, and 5, respectively. However, the void at each location was found to be closed as the effective strain at the location reached 0.32 in average. For a given aspect ratio, the cross-sectional areas differed by location due to different values of hydrostatic stress. The hydrostatic stress was noted to influence the size of the cross section, but not the shape. For reference, the hydrostatic stress at 18% reduction in height was $-53.2$ MPa, $-62.7$ MPa, $-66.2$ MPa, $-51.3$ MPa, and $-48.3$ MPa at locations 1, 2, 3, 4, and 5, respectively.

### 2.2. Horizontally Elliptical Cross-section

The phenomenon of the void closure was also investigated for a horizontally elliptical cross-section with the aspect ratio of 3. While keeping the cross-sectional area to be the same as that of the circular one, the horizontal and vertical axes of the cross section were calculated to be 17.3 mm and 5.8 mm, respectively. Three locations of the void were selected as 1, 2, and 3 in Fig. 3. The finite-element analysis was performed for each of these locations, and the progresses in the void closure were obtained as shown in Fig. 6. The void closure occurred in the order of locations 1, 2, and 3 at 9%, 10%, and 15% reductions in height, respectively. All voids were located at the centerline and none became tilted. Compared to the circular cross-section, these cross sections closed at smaller reductions in height due to a shortened duration of contraction.

The relations between the effective strain and the cross-sectional area are presented in Fig. 7. Values of the effective strain for increase in the aspect ratio at the locations are given in Table 2. As the effective strain in average increased to 0.028 and 0.046, the aspect ratio of the cross increased to 4 and 5, respectively. The voids were found to be closed as

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>location 1</td>
<td>0.151</td>
<td>0.198</td>
<td>0.245</td>
<td>0.271</td>
<td>0.320</td>
</tr>
<tr>
<td>location 2</td>
<td>0.144</td>
<td>0.199</td>
<td>0.235</td>
<td>0.273</td>
<td>0.320</td>
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<tr>
<td>location 3</td>
<td>0.143</td>
<td>0.189</td>
<td>0.225</td>
<td>0.259</td>
<td>0.310</td>
</tr>
<tr>
<td>location 4</td>
<td>0.143</td>
<td>0.195</td>
<td>0.237</td>
<td>0.273</td>
<td>0.320</td>
</tr>
<tr>
<td>location 5</td>
<td>0.144</td>
<td>0.194</td>
<td>0.233</td>
<td>0.264</td>
<td>0.320</td>
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<tr>
<td>average</td>
<td>0.145</td>
<td>0.195</td>
<td>0.235</td>
<td>0.268</td>
<td>0.318</td>
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</tbody>
</table>

Fig. 4. Progresses in void closure at different locations ($\alpha_o = 1$).

Fig. 5. Relations between the effective strain and the cross-sectional area ($\alpha_o= 1$).

Fig. 6. Progresses in void closure at different locations ($\alpha_o = 3$).
the effective strains at the locations reached 0.13 in average.
For a given aspect ratio, the cross-sectional areas are different for the locations due to different hydrostatic stress. For reference, the hydrostatic stress at 4.4% reduction in height was –34.4 MPa, –40.2 MPa, and –46.1 MPa at locations 1, 2, and 3, respectively.

2.3. Vertically Elliptical Cross-section

The void closure was also investigated for a vertically elliptical cross-section with the aspect ratio of 0.5. Maintaining the cross-sectional area to be the same as the previous ones, the horizontal and vertical axes of the cross section were 7.07 mm and 14.14 mm, respectively. Three locations of the void were selected as 1, 2, and 3 in Fig. 3. The finite-element analysis was performed for each of these locations, and as a result the progresses in the void closure were obtained as shown in Fig. 8. The void closure occurred in the order of locations 1, 2, and 3 at 23%, 35%, and 58% reductions in height, respectively. Compared to the previous ones, these cross sections closed at larger reductions in height due to an extended duration of contraction.

The relations between the effective strain and the cross-sectional area are presented in Fig. 9. Values of the effective strain for increase in the aspect ratio at different locations are given in Table 3. As the effective strain in average increased to 0.195, 0.31, 0.40, 0.45, and 0.48, the aspect ratio increased to 1, 2, 3, 4, and 5, respectively. The voids were closed as the effective strains at the locations reached 0.54 in average.

Table 2. Values of the effective strain for increase in the aspect ratio at different locations ($\alpha_o = 3$).

<table>
<thead>
<tr>
<th>location</th>
<th>$\alpha = 4$</th>
<th>$\alpha = 5$</th>
<th>closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>location 1</td>
<td>0.029</td>
<td>0.048</td>
<td>0.140</td>
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<tr>
<td>location 2</td>
<td>0.028</td>
<td>0.045</td>
<td>0.135</td>
</tr>
<tr>
<td>location 3</td>
<td>0.028</td>
<td>0.046</td>
<td>0.125</td>
</tr>
<tr>
<td>average</td>
<td>0.028</td>
<td>0.046</td>
<td>0.133</td>
</tr>
</tbody>
</table>

Table 3. Values of the effective strain for increase in the aspect ratio at different locations ($\alpha_o = 0.5$).

<table>
<thead>
<tr>
<th>location</th>
<th>$\alpha = 1$</th>
<th>$\alpha = 2$</th>
<th>$\alpha = 3$</th>
<th>$\alpha = 4$</th>
<th>$\alpha = 5$</th>
<th>closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>location 1</td>
<td>0.189</td>
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<td>0.409</td>
<td>0.471</td>
<td>0.499</td>
<td>0.545</td>
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<tr>
<td>location 2</td>
<td>0.212</td>
<td>0.337</td>
<td>0.437</td>
<td>0.471</td>
<td>0.499</td>
<td>0.524</td>
</tr>
<tr>
<td>location 3</td>
<td>0.184</td>
<td>0.282</td>
<td>0.354</td>
<td>0.408</td>
<td>0.443</td>
<td>0.550</td>
</tr>
<tr>
<td>average</td>
<td>0.195</td>
<td>0.310</td>
<td>0.400</td>
<td>0.450</td>
<td>0.480</td>
<td>0.540</td>
</tr>
</tbody>
</table>

3. The Curve of the Effective Strain vs. the Aspect Ratio of the Cross Section

The relations between the effective strain and the aspect ratio of the cross section obtained from the three different initial cross-sections were combined in Fig. 10. In this figure, the curve used to fit the case of $\alpha_o = 1.0$ was possibly applied to fit the other cases with less than 5% error. In result, one curve can represent the others by adjustments along the axis of the effective strain in accordance with the initial aspect ratio of the cross section. For example, the curve of $\alpha_o = 0.5$ can be lowered by 0.22 and 0.41 along the...
axis of the effective strain to represent those of $\alpha = 1.0$ and $\alpha = 3.0$, respectively. Further the curve of $\alpha = 1.0$ can be lowered by 0.19 along the axis of the effective strain to represent that of $\alpha = 3.0$. These are called the curves of the effective strain vs. the aspect ratio of the cross section.

The curve was utilized to predict the progress of the void closure during biaxial forging. The initial cross section of the void was a circle of 10 mm in diameter. The friction factor at the interface between the bloom and the dies was assumed zero in order to solely evaluate the influence of the directionality of forging on the void closure. The biaxial-forging process was arranged by two identical cycles, in each of which the bloom was forged in y direction by 11.5% reduction in height followed by forging in x direction by 18.3% reduction in height, expecting the aspect ratio to increase to 2 and decrease to 1 according to the curve. The effective strain in the curve was converted to reduction in height in arranging the process. A series of the finite-element analyses were performed to confirm the expectations, and as a result the progress in the void closure was obtained as shown in Fig. 11. In the first cycle, the aspect ratio was found to change as expected. However, in the second cycle, the reduction in height was reduced to 9.7% in y direction and 15% in x direction to attain the expectations of the aspect ratio. This discrepancy was mainly due to inhomogeneous hardening developed in the local region around the cross section, especially at the vertices of the cross section. Consequently, the cross section became out of a round shape in the second cycle. The effective strain accumulated to as large as 0.68, but the cross section was not closed yet. In uniaxial forging, the effective strain required for void closure is reminded to be only 0.32.

The effective strain was found to be an excellent parameter to indicate the void closure, as it is a rational and comprehensive measure of plastic deformation. However, it worked only for uniaxial forging due to the intrinsic nature of the void closure.

4. Verification by Experiment

Plasticine has been used to investigate various aspects of plastic deformation of steel at high temperatures. In the present study, a series of experiments with plasticine specimens were performed to verify the progress in the void closure predicted by the finite-element analysis. Each specimen was 20 mm in thickness, 60 mm in width, and 100 mm in height. A cylindrical void with a circular cross-section was drilled at the center of the specimen. Two voids with diameters of 2.7 mm and 6.2 mm were prepared for comparison. Schematics of the experiment are presented in Fig. 12. The specimen that stood on its smallest plane was located between the front and back plates made of transparent acrylic, which were separated by 20 mm; the specimen became in tight contact with the plates. Machine oil was applied to the interface between the specimen and the plates to keep the friction as low as possible. In consequence, the specimen was able to be compressed under the condition of plane-strain deformation. Other plates such as the upper moving die and the lower die were not lubricated so that high friction conditions were expected at those interfaces.

The progress in the void closure was observed through the transparent acrylic plates and photographed at several reductions in height. As shown in Fig. 13, the cross section became flattened and elliptic, folded at the ends of the major axis of the cross section, and completely closed at about 16% reduction in height; this observation was valid for both cross sections with different diameters. A series of finite-element analyses were performed to obtain variations of the
effective strain at the center of the cross section with reduction in height under various friction conditions. Figure 14 presents effects of the friction condition on the barreling profile and the effective-strain variation at the center of the specimen. As the friction factor increased, the barreling became more pronounced. The case of \( m = 0.7 \) was found to fit the experiment using the plasticine specimen; this value in fact has been often used for the analysis of hot forging of steel with cold dies. As the friction factor increased, the reduction in height required for a certain value of the effective strain decreased. Based on the comparison of the barreling profile, the case of \( m = 0.7 \) was utilized to analyze the experimental result.

Variations in length of the major and minor axes in this case were compared with those from the experiment in Fig. 15; they were in good agreement. The curves for the two different cross sections were almost identical, confirming the fact that the progress in the void closure was independent of the size of the cross section; this statement is valid as far as the void is extremely small compared to the bloom. As aforementioned, the void closure was found to proceed through contraction followed by collapse; the major axis increased in the former and decreased in the latter while the minor axis decreased continuously. Therefore, the rate of closure became high in the collapse stage.

The variations in the major and minor axes were simplified as a triangle as shown in Fig. 16(a), and the variation in the aspect ratio for the effective strain was depicted as shown in Fig. 16(b). The angles of \( \alpha \), \( \beta_1 \) and \( \beta_2 \) were evaluated assuming the same linear scale on both coordinated axes. The contraction stage between A and B corresponded to the path between a and b where the aspect ratio increased monotonically with decreasing rate. The collapse stage between B and C corresponded to the path between b and c where the aspect ratio was constant. The location of b could be varied depending on the process conditions, and the aspect ratio would vary along the path of a-b'c'. However, the effective strain required for complete closure of a void with the initial aspect ratio of one was approximately 0.32 regardless of the variation of the aspect ratio.
5. Conclusions

Closure of a longitudinal void with a circular or elliptical cross section in a bloom by flat-die forging was investigated by the rigid-plastic finite-element analysis and experiments using plasticine specimens. The void was found to be closed as the effective strain at the location of the void reached a certain value; this value was dependent on the aspect ratio of the cross section but not on the size. The curve of the effective strain vs. the aspect ratio of the cross section was established and as a result, the closure of a void with a round cross section of any aspect ratio could be predicted in terms of the effective strain. The effective strain distribution in the workpiece can be easily obtained by a finite-element model containing no void.

Other findings are summarized as follows:

(1) The void closure progressed through contraction followed by collapse. The major axis increased in the former and decreased in the latter while the minor axis decreased continuously.

(2) The rate of void closure was high during collapse where folding proceeded from vertices of the major axis. Shear strain can be introduced to shorten the period of contraction for the purpose of expediting void closure.

(3) The effective strain was an excellent parameter to indicate the void closure, although it was effective only for uniaxial loading due to the intrinsic nature of the void closure.

(4) Hydrostatic stress influenced the size of a void but not the aspect ratio. Therefore, its role in void closure was limited.

(5) Uniaxial forging is superior to biaxial forging for void closure. In the latter, the void was difficult to collapse since the aspect ratio fluctuated although the void was continuously reduced in size.

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