Internal void closure during the forging of large cast ingots using a simulation approach

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\textbf{ABSTRACT}

Large cast ingots often contain defects or undesirable microstructural features, such as voids and zones related to casting. Some of these features can remain after hot open die forging, which is an important process for converting large cast ingots into wrought components. During the initial cogging and deformation steps prior to the detailed open-die-forging operations, any internal voids should be eliminated. The present work focuses on the closure of internal voids during open die forging so as to produce a sound component. Hot compression tests were conducted to obtain the flow strength of the cast microstructure at different temperatures and strain rates. The measured flow strength data together with other appropriate material properties were used to simulate the forging steps for a large cast ingot. The numerical simulations for the forging deformation and for the internal void behavior were performed using DEFORM-3DTM. Actual defects were measured in commercial ingots with an X-ray scanner. The simulation results for the void deformation behavior are compared with voids measured before and after forging. Through the comparison of experimental results and numerical simulation, a criterion for void closure is proposed. The criterion is that a local effective strain value of 0.6 or greater must be achieved for void closure during forging. Such a criterion can be used in conjunction with simulations to insure that a sound component is produced during the hot open die forging of large cast ingots.

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1. Introduction

Recently, there is an increasing need to produce large forged components for aerospace, naval, energy, and other applications. Open die forging of large cast ingots is the primary process used to produce high quality large wrought components. Cogging or side-pressing processes are used in the primary stages during most open-die forgings. In this study we will use the industrial term “upsetting” for what is sometimes called side pressing in the literature. Upsetting in the present study is not the compression of a cylinder along its axis, but rather the compression of a cylinder perpendicular to the axis of symmetry. During the preliminary deformation processes, any internal voids from the initial cast ingot need to be eliminated. If these voids are not closed during the initial deformation stages, they may nucleate a crack or be a source for a defect during the subsequent open die hot forging steps. Fig. 1 shows an example of an internal void and the surface crack that can result if the void was not closed during the initial cogging or upsetting operations.

1.1. Background

A number of studies have been conducted on using finite element analysis to help with the operation and control of open die forging processes. Kiefer and Shah (1990) used three-dimensional FEM to examine the effects of die width and reduction on the internal stresses and strains in an open die forging of rectangular shaped workpieces. Lee et al. (2008a,b) examined the effects of temperature and strain rate on high temperature deformation behaviors to draw deformation processing map. Dudra and Im (1990a) used two-dimensional FEM to study the axial compression of a cylinder and the plane-strain side pressing (i.e. upsetting) of a circular cross-sectioned workpiece by open die forging. The side-pressing study used dies of different configurations to investigate press loads and internal strains. Cho et al. (1998) also used three-dimensional FEM to study the effect of die configuration, die width and reduction on the open die forging of rectangular billets. They evaluated their results by comparing the calculations to small sized laboratory...
experiments using plasticine model materials at a scale of 1–40. Tamura and Tajima (2001) used three-dimensional FEM to study the formation of a surface deformation pattern that they called “concave defect”. They verified their results by laboratory experiments using lead as a model material. From their analysis they also provided a recommendation for a small die modification to avoid the surface defect. Tamura and Tajima (2003) and Tamura and Tajima (2004) extended their work to develop a pass schedule for open die forgings, which provides a more homogeneous strain distribution within the workpiece. Tamura et al. (2005) further extended their studies of open die forging to determine a die shape that would minimize overlap defects during multiple pass side pressing of an octagonal workpiece into a circular cross-sectioned shape. Dyja et al. (2004) used three-dimensional FEM to investigate the effect of some complex die shapes on the deformation patterns in open die forging. They validated their calculations with laboratory scale experiments using steel as the workpiece. Choi et al. (2006) used three-dimensional FEM to optimize the open die forging process for conversion of a rectangular/square cross-sectioned workpiece into one with a circular cross section. They focused on feed rate and rotation angle in the study. It is evident from these studies that FEM simulations can be very helpful in understanding and controlling open die forging processes. Furthermore, the deformation behavior has also been analyzed by FEM in conjunction with constitutive model. Yoon et al. (2010) predicted plastic flow behavior by considering an operating deformation mechanism and strain hardening model.

One of the main benefits of open die forging is the ability to close internal voids that come for cast ingots. There have been a number of previous studies examining how to open the die forging process to best close these internal voids. Dudra and Im (1990b) extended their two-dimensional FEM analysis to study the closure of centerline pores during side pressing of circular shaped billets using dies with various shapes. From their analysis they indicated that effective strain appears to be a better indication of void closure than hydrostatic stress. Park and Yang (1996) proposed a bonding mechanism based on hot pressing that could help in studying the closure of voids during open die forging. Park and Yang (1997a) used three-dimensional FEM together with a Taguchi set of experiments to study void closure during open die forging of large ingots. It appears that they assumed centerline voids in the analysis. They found that the die width ratio and proper die shape are beneficial in closing voids whereas cooling of the ingot surface does not appear to be helpful for void closure. They also provide some insight on the bonding efficiency as the void surfaces came together. Park and Yang (1997b) extended their bonding efficiency study with FEM modeling and experiments. They also investigated the bonding as a function of void position in the ingot. They found that die shape in conjunction with reduction in height controls the bonding process. Kim et al. (2002) developed a neural network algorithm for the closure of voids in open die forging of rectangular cross-sectioned workpieces. They studied a large number of process parameters and used the algorithm to recommend a forging pass schedule that would close voids effectively and efficiently. Overstam and Jarl (2004) used three-dimensional FEM to examine the closure of centerline voids in rectangular cross-sectioned workpieces. They found that the bite ratio was a critical factor in getting the pores to close. Banaszek et al. (2005) and Banaszek and Stefanik (2006) used two-dimensional FEM to study the effect of die shape and other process parameters on void closure in open die forgings. They examined voids at various locations in the ingot and provided verification with experimental tests using a highly alloyed steel. They found that die shape had a major effect on void closure and advocated the use of shaped dies during the initial stages and flat dies during the final forging stages to achieve best results. Chun et al. (2006) examined the closure of centerline voids in rectangular cross-sectioned workpieces using three-dimensional FEM. They studied the effect of die width ratio, die feed rate, die shape, and number of passes on the closure of voids. Skubisz et al. (2008) studied the closure of centerline voids during open die forging both numerically and experimentally. They found that a critical amount of effective strain was needed to close these voids. Lee et al. (2008a,b) used three-dimensional FEM to examine centerline void closure during the axial compression of cylindrical workpieces. They found that a critical amount of effective strain was needed to close the voids. Zhang and Cui (2009a) developed an analytical model for the closing of a spherical void during axial compression of a cylinder. They verified their model using two-dimensional FEM. Zhang et al. (2009b) indicated that void closure in forgings is a multi-scaled problem and they developed a mesomechanics approach to the issue. They indicated that during the early stages void closure increases with the level of stress triaxiality increases. Their criterion for void closure depends on the hydrostatic stress, the effective stress, the effective strain, the Norton exponent (essentially the inverse of the strain hardening model).
rate sensitivity exponent) and four numerical values that were determined as a function of the Norton exponent via FEM analysis and regression. Kakimotoa et al. (2010) used both two-dimensional and three-dimensional FEM to study the closure of centerline voids during axial compression and side pressing of circular and rectangular crossed-sectioned forgings. They calculated a void closing index, Q-value, which must achieve a value of 0.21 to insure void closure. They indicate that the Q-value uses Oyane’s equation and was initially proposed by Ono et al. (1993).

Void closure has also been studied in other large shapes produced by deformation. Hamzah and Ståhlberg (1998) studied pore closure in manufacturing of heavy rings using two-dimensional FEM. They found that piercing of the initial hole in a closed container produced a pore free ring whereas open die piercing of the hole did could produce a final ring with pores. They attributed the successful manufacturing route to the large strains created during the piercing in a closed die. Hamzah and Ståhlberg (2001) extended their ideas in proposing a new route for producing pore free rings, which primarily depended on high strains during piercing and subsequent forming. They also found that the hydrostatic pressure was a less critical parameter for pore closure.

<table>
<thead>
<tr>
<th>No.</th>
<th>( \Delta ) (mm)</th>
<th>Volume of void ((\text{mm}^3))</th>
<th>Volume percentage of void relative to the total specimen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>82</td>
<td>353</td>
<td>0.028</td>
</tr>
<tr>
<td>P2</td>
<td>102</td>
<td>276</td>
<td>0.022</td>
</tr>
<tr>
<td>P3</td>
<td>185</td>
<td>256</td>
<td>0.020</td>
</tr>
<tr>
<td>P4</td>
<td>189</td>
<td>268</td>
<td>0.021</td>
</tr>
<tr>
<td>P5</td>
<td>189</td>
<td>325</td>
<td>0.026</td>
</tr>
<tr>
<td>P6</td>
<td>189</td>
<td>22,280</td>
<td>1.752</td>
</tr>
</tbody>
</table>
1.2. Objective of study

It is evident from these previous investigations that effective strain is an important parameter in determining whether or not a void will close. Although stating that effective strain is important, many studies do not give the specific amount needed for effective void closure. It is also interesting to note that several of the studies have found that hydrostatic stress is a less important parameter in void closure as compared to effective strain. Although Kakimoto et al. (2010) have proposed a very specific criterion for void closure during open die forging, their criterion is fairly complex and requires knowledge not only of the effective strain, but also the effective stress, the hydrostatic stress as well as some flow properties of the material. Although a good theoretical study, it would be difficult to implement their criterion in a production environment.
The present study is concerned with the elimination of the internal voids in large ingots so as to obtain a sound final product. Most of the previous studies have only investigated voids in the center of the workpiece rather than throughout. In the present study voids at various locations in the workpiece are investigated and a specific criterion for the amount of effective strain needed for void closure is proposed based on the analysis of the results generated. The criterion for eliminating internal voids provides important information for the design and operation of an open die forging process that results in a good quality, sound product.

In this study, hot compression tests were conducted to obtain the flow strength of cast ingot material at different temperatures and strain rates. FEM simulations were performed to investigate the deformation behavior of cast ingots during the various forging stages. The measured flow strength data as well as appropriate thermal property data were used to simulate the upsetting process of cast ingot. DEFORM-3D™ was used to perform the numerical analysis of void closure. The calculated results for void deformation behavior are compared to experimentally measured results before and after upsetting of actual ingots/forgings, which were determined by X-ray scans. From the comparison of the numerical simulations and experimental results, the criterion for the amount of deformation needed for void closure was developed. Fig. 2 shows the flow chart for this investigation into void closure of cast ingot during the initial upsetting stages of open die forging.

### Table 2

<table>
<thead>
<tr>
<th>Case no.</th>
<th>First upset</th>
<th>Second upset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Void closed</td>
<td>Remained as closed void</td>
</tr>
<tr>
<td>Case 2</td>
<td>Void closed</td>
<td>Opened again</td>
</tr>
<tr>
<td>Case 3</td>
<td>Void not closed</td>
<td>Remained as open void</td>
</tr>
</tbody>
</table>

2. Experiments

#### 2.1. Flow strength of cast ingot material

The material used in this study was AISI4140 (SCM440). Its initial form was a cast ingot with the three zones typical of cast structures – columnar, chill, and equiaxed. Cylindrical specimens were machined from material in the equiaxed zone. These specimens were tested to determine the flow strength of the cast ingot material by hot compression testing using a hot deformation simulator, Thermecmaster-2™. Fig. 3 shows that the measured flow strength of the cast structure is quite different from that of the wrought material. The flow strength of the wrought material is over 30% greater than that of the cast material. Flow strengths were measured at three temperatures and three strain rates. These measured values were used in the DEFORM-3D™ simulations. Because of the difference in the flow strength values between cast and wrought material, it was important to use the appropriate values in the simulations. The use of the wrought properties for this study could have generated significant errors in the results from the FEM analysis.

#### 2.2. Void closure – initial upset

Fig. 4 shows the hexahedral cast-ingot that was used to investigate void closure, by experimental upset deformation and FEM analysis. The ingot was casted intentionally to include many kinds of voids so an investigation on variables, such as size and position could be conducted. The round ingot was machined from hexahedral cast-ingot into a cylindrical sample with a diameter of 90 mm due to scan limits of ferrous metals. The sample was scanned using an X-ray scanner (Vendo™ H-450CT) to determine if it had internal voids. When an internal void was found in the sample, the void was quantitatively characterized for incorporation into the simulation analysis. Table 1 and Fig. 5 show the size and shapes of the various voids.  

#### Fig. 8

External shape of upset specimen from experimental and analysis results.
voids that were found. Six representative void shapes were used in the three-dimensional FEM simulations. These shapes were of voids of different shapes and sizes and the voids were located at different positions in the ingot as well as different positions in the sample. The cylindrical sample with voids was upset (side pressed) and then it was rescanned to experimentally compare resulting changes in void geometry with the FEM analysis. Fig. 6 shows the shape and size of the internal voids after this initial upset. Fig. 7 shows the shape of the upset sample both experimentally and predicted by the simulation. After upsetting the large internal void on the right side of the sample decreased in width as compared to the void on the left side. These changes in void geometry were observed in both the experimental results and the FEM results. This match of results provided confirmation of the validity of the numerical simulations. Based on the favorable comparison for the laboratory experiments, it appears that an FEM analysis can accurately predict the deformation patterns and the void closure process during the upsetting of a cast ingot.

Fig. 9. Fine mesh system of workpiece and FE model.

Fig. 10. Temperature changes of workpiece from heating through transfer to hot forging on first upset.
2.3. Deformation behavior of voids – second upset

During open die forging, internal voids generally deform in various directions due to the multiple blows imparted during the upsetting or cogging stage. Each void may have a unique flow pattern. In this study, the sample with voids that was deformed by the initial simple upset was given additional plastic deformation after rotation of 90°. Fig. 8 shows how this second upset deformation was applied to the sample. Table 2 lists three types of void deformation patterns that were observed. In the first case, a void closed by first upsetting remained closed during the second step. In the second case, a closed void re-opened during the second step. In the third case, a void not closed during the first upset was not closed during the second upset.

3. FEM analysis

3.1. FE model and material properties

Fig. 5 shows the six voids that were analyzed by finite element analysis. The voids were assumed to be holes with vacuum. A very fine mesh system was used in the simulations in order to avoid remeshing. If the original mesh becomes too distorted and remeshing occurs, then the nodes on the deformed voids might be merged during the remeshing, causing an inappropriate closure during the simulation. If such remeshing is the cause of closure, then the critical conditions for void closure cannot be accurately predicted. Fig. 9 shows that the number of elements used in the simulations is on the order of 150,000. Table 3 lists the process conditions and material properties used in the simulations.
Table 3

<table>
<thead>
<tr>
<th>Process conditions</th>
<th>Material properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>AISI-4140</td>
</tr>
<tr>
<td>Billet temperature</td>
<td>1100 °C</td>
</tr>
<tr>
<td>Punch velocity</td>
<td>2 mm/s</td>
</tr>
<tr>
<td>Material model</td>
<td>Die: rigid</td>
</tr>
<tr>
<td></td>
<td>Workpiece: viscoplastic</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>205 GPa</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>12.2–14.6 μm/m °C</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>0.473–0.561 J/g °C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>33–42.6 W/mK</td>
</tr>
</tbody>
</table>

3.2. Plastic deformation of ingot – initial upset

The temperature of the workpiece decreased during the transfer from furnace to press. When the workpiece was deformed, the temperature increased due to the heat energy generated by the deformation process. Fig. 10 shows the temperature variation where the workpiece first decreased to between 900 and 1000 °C and then increased to temperatures up to 1120 °C. There was some local surface cooling where the workpiece was in contact with the die. The effective strain is largest in the interior of the forged billet and much smaller on the surface of the billet. As Fig. 11 shows, the applied load was 270 tons during the experimental tests. Whereas, the load predicted by the FEM simulation results was 290 tons. The difference in these loads is likely due to difference in the surface temperature of the billet. In production, the surface of a forged billet possesses an oxide layer, which can provide some insulation causing the interior temperatures to be a little higher than would be predicted by the simulation where the oxide surface layer is not part of the model. Due to this oxide layer, the higher applied load from the FEM analysis should be considered consistent with the experimental results.

3.3. Simulation of void closure – second upset

The largest void among the six that were analyzed by FEM is located in the right side of the sample as shown in Fig. 12. The others five voids are located in different positions. Shear stresses were present at these void locations during the initial upset step as well as during the second upset. The largest internal void evolved in a complex manner. In certain cross-sectional views the internal void appeared to re-open and in other cross-sectional views it appeared to close. For example, the cross-section no. 9 remained closed during the second upset, however, cross-section no. 1 was not closed even after the second upset.

Some of the small voids were closer during either the first or the second upset. Others voids were closed during the first upset and then re-opened during the second. The different closure behaviors during the deformation were influenced by the size and location of the individual void. Fig. 13 shows the detailed changes to the voids during the deformation.

4. Discussion

4.1. Criterion of void closure during a simple upset

Among voids that were investigated as part of this study, some closed and others did not close during the upsetting processes. Fig. 14 shows that three voids, P1, P2 and P3, were closed. The hydrostatic stress at these locations went from a tensile value through a compression value and then back to tensile. The transition of hydrostatic stress related to void closing is represented in P1, P2 and P3. Fig. 14 shows these hydrostatic stress changes. When the stress state was compressive, the value was near the flow strength of the material. The points near to the closed void were initially expanded in the direction of the upset and then they were compressed after the void closed. Fig. 15 provides a schematic drawing of this sequence. Based on these results, it can be suggested that a compressive stress equal to the flow strength of the materials should be applied in order to close voids. Practical FE simulations of cast-ingot forging are performed in the absence of voids because specifics of the voids are often unknown a priori. Therefore,
Various kinds of voids react to the upset differently. Table 1 classifies three forms of voids as how they deformed differently. Closure of the void occurred during plastic deformation when the local effective strain applied to the sample was greater than 0.6, as shown in Fig. 13(a). On the other hand, when the local effective strain of less than 0.6 was applied, the void did not close during either of the two upsets as illustrated in Fig. 13(b). Therefore, the threshold strain to achieve void closure is 0.6. Although volumes of P2 and P3 are almost same as shown in Table 1, the P3 void did not closed. Since the P3 void is located nearby the P6 void the accumulated effective strain on the P3 void is smaller than the P2 void. The local strain value is about 0.48 which is under the threshold deformation amount needed for void closure.

If a void is located on a surface, the void may not close. Fig. 13(c) shows surface voids that could not be closed during the two hot upsets. The applied effective strain was less than the threshold value needed for closure at both of these surface void sites.

The proposed criterion based on an effective strain value was confirmed again as shown in Fig. 17. Three cases are presented that
illustrate the importance of straining to a critical value in order to achieve void closure. Void closure is dependent on reaching the critical effective strain whether the void is a surface void or an internal void. A critical value of effective strain for void closure is a very efficient and practical parameter to base the criterion on. It is better than other parameters, such as the hydrostatic stress, since the strain value can be determined from FEM simulations of upsets even if the voids are not present in the simulation. The actual hydrostatic stress state for the material near a void would not be accurate in the FEM simulations if the void were not incorporated into the model. Parameters related to voids inside a cast ingot cannot be easily analyzed because it is difficult to know the specific size, shape, and location of the void prior to running the simulation.

5. Summary

The results from FEM simulations of void closure behavior during the forging of cast ingots have been compared with experimentally measured void geometries both before and after upset forings. An X-ray scanner can monitor voids experimentally. From the combined experimental and numerical results the amount of deformation needed to close a void closure was determined and a criterion has been proposed in terms of effective strain. Hydrostatic stress affects the void closure and previous studies have shown results related to the hydrostatic stress value. However, hydrostatic stress is not as useful for practical process design because the numerical analysis used during design may not give the correct hydrostatic stress distributions when internal voids in the ingot are not present in the simulations. Hence, effective strain, which is a parameter independent of the presence or the absence of an internal void in the simulation, is a more practical variable upon which to base a criterion for void closure.

In this study, changes of hydrostatic stress and effective strain during two upset steps were investigated to determine whether the void closed or not. From these results, we know that the transition points of hydrostatic stress related to void closing and that effective strain of 0.6 or greater provides an adequate condition for the closure of internal voids during forging. Other conclusions obtained from this study are as follows:

(1) During the upset the hydrostatic stress around the voids went from a tensile value through a compressive value back to a tensile condition. The compressive values were close to flow strength of the material. The material nearby a closed void initially expanded in the upset-direction and then compressed after the void closed. It is suggested that a compressive stress should be applied to close the voids. The criterion of an effective strain of over 0.6 achieves the conditions for void closure during forging.

(2) Various void behaviors can be observed during the upset forings. Three behavior types were found. The type of behavior exhibited by a single void depended on its size and location within the ingot.

(3) From the results, we propose that effective strain be used during forging process design. This measure allows numerical simulations for determination of void closure conditions to be performed without requiring the presence of an internal void within the simulation.

Acknowledgement

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References


