Finite element analysis of a plate forging considering air-pocketing phenomena

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Abstract: In this paper, a three-stage plate-forging process is simulated considering air-pockets enclosed by material, dies, or tools and a plane of symmetry. A new basic approach is presented to deal with the air-pocketing phenomena. The volumetric strain of each cavity of an air-pocket is traced when it has no air hole and its pressure, which is a function of the volumetric strain multiplied by the bulk modulus of elasticity of the air-pocket and maximum normal stresses of the neighbouring contact interfaces, is exerted onto the surface of the material inside the air-pocket. This approach is applied to a three-stage plate forging process in which the air-pocketing phenomena can be sensitive to the plastic deformation of the material. The predictions are
compared with experimental data and the effect of the bulk modulus of elasticity on the size of air-pocket is evaluated to examine the stability of the present approach.

**Keywords:** plate forging; air-pocket; finite element predictions; experiments; bulk modulus of elasticity.


**Biographical notes:** Bongsu Kim is a graduate student. His major is metal forming engineering and the related simulation technology. He is very interested in applying the simulation technology to special incremental metal forming processes including ring rolling processes, Mannesmann roll piercing processes and the like.

Jaehun Chung graduated from Seoul National University for his Bachelor’s degree. He is a Senior Researcher and has worked for Schaeffler Korea nearly for 25 years. He has very peculiar experience that he applied the metal forming simulation technology first in Korean industry. He has written many papers about finite element simulation technologies for the application to bearing part manufacturing processes for about 15 years with Prof. Joun’s research laboratory. Recently, he is studying material fracture occurring in rotary forming of hub bearing units using AFDEX, which has been developed by Joun’s research group.

Sangwook Lee graduated from Gyeongsang National University for his Master’s degree. He is a Research of Schaeffler Korea. He majored in metal forming engineering for his Master’s degree. For more than ten years, he has worked for optimisation of metal forming process designs for bearing parts using metal forming simulation technology.

Jaegun Eom graduated from Gyeongsang National University (GNU) in South Korea for his Master’s degree. He is currently working for Technology Innovation Center (TIC) of GNU. He was involved in developing a powerful algorithm for material identification using FEM for his Master’s degree. He is also studying metal forming technology for his PhD degree as a part-time student. He is interested mainly in simulation of fracture occurring in cold forging. He has published many papers in the learned journals including *Mechanics of Material, Computational Material Science*, etc.

Mansoo Joun is a Professor of Gyeongsang National University (GNU) in South Korea. He is in charge of Technology Innovation Center (TIC) of GNU, which is the only TIC specialised at metal forming and powder forging in Korea. He is interested in developing intelligent metal forming simulation technologies based on finite element method. He graduated from Seoul National University for his Bachelor’s degree from KAIST for his Master’s degree and from POSTECH for his PhD degree. His PhD thesis topic was the optimal die shape design in extrusion or drawing. After his PhD course, he has developed and commercialised a metal forming simulator called AFDEX, which is competitive in terms of solution accuracy and user-friendliness.
1 Introduction

Enclosed spaces constructed by material and dies or tools frequently appear in metal forming, especially in forging. These enclosed spaces, sometimes called air-pockets, can involve a mixture of oil, lubricant, air, debris and even unidentifiable impurities, and they can cause under-filling or surface defects of the products if not properly controlled. These defects are known as air-pocketing phenomena. In thus paper, the terminology ‘air’ implies the material inside the air-pocket, that is, the mixture.

The easiest way to avoid problems due to air-pocketing phenomena is to place appropriate air holes in the dies or die parting lines, which increase die costs and decrease die structural strengths and confidence in service lives. While some air-pocketed cavities may not deteriorate the metal-forming process and/or the product, other processes may include special dies in which no air holes are allowed or can be applied. There may also be some special cases in which under-filling due to air-pocketing is desired; that is, under-filling due to air-pocketing can be a requirement of the process design.

Optimised positions of these air holes or parting lines can be found using finite element simulation technologies; i.e., finite element predictions for cases without air-pockets can give valuable information about air-hole designs. Therefore, for many real situations, finite element simulations of metal-forming processes considering air-pocketing phenomena could be of great importance. The necessity of finite element simulations considering air-pocketing cannot be overemphasised, particularly in plate forging (Mori et al., 2011; Mori, 2012; Nakano, 2012; Orita, 2012; Kobayashi, 2012; Kim et al., 2010), for which applications have gradually increased. Here, plate forging refers to special forging of material with a large radius-to-thickness ratio that is not large enough to be considered sheet metal forming.

There have been only a few studies on air-pocketing phenomena, despite its importance. Hwang et al. (2006) and Koo et al. (2008) studied air or fluid flow characteristics inside air-pockets during sheet metal forming. However, their interests were focused mainly on the air flow inside an air-pocket with air holes, because in sheet metal forming, the pressure inside the air-pocket is relatively small and the air-pocket is inherently large. This is not well aligned with the concerns of forging process design engineers, who are interested mainly in the necessity and position of air holes.

In this paper, a new approach to finite element simulation considering air-pocketing phenomena is presented and applied to an example of a three-stage plate-forging process. These predictions are compared with experimentally obtained under-filling defects caused by air-pocketing phenomena to verify the validity of the approach.
2 Finite element approach to air-pocketing

A common plastic flow analysis problem in metal forming requires finding the velocity field \( \mathbf{v} \) and the hydrostatic pressure \( p \) that satisfy the following boundary value problem (Lee and Kobayashi, 1973; Lee et al., 2009). The material is denoted as domain \( V \) with boundary \( S \). The boundary \( S \) can be divided into a velocity-prescribed boundary \( S_v \), where the velocity is given as \( \mathbf{v} = \mathbf{v}_i \); a traction-prescribed boundary \( S_t \), where the stress vector is given as \( \mathbf{t}^{(n)} = \mathbf{t}^{(n)}_i \); and a die-workpiece interface \( S_c \), where the no-penetration condition, \( \mathbf{n} \mathbf{v} = \mathbf{n} \mathbf{v}_i \), must be maintained when the interface is in compression. In the above, \( \mathbf{v}_i \) and \( \mathbf{v}_n \) are the given velocity components, \( \mathbf{t}^{(n)}_i \) is the traction vector component, \( \mathbf{n} \) is the normal unit vector on boundary \( S \), and the variables with subscript \( n \) denote their related normal components.

To model the air-pocketing phenomena, a kind of traction-prescribed boundary condition should be considered additionally as follows:

\[
\mathbf{t}_n^{(n)} = -p_{\text{air}} \quad \text{on} \quad S_n
\]

where \( p_{\text{air}} \) is the pressure due to the air-pocketing phenomena, which is a function of volumetric strain of the air-pocket. The material inside the air-pocket has thus a large influence on the pressure.

It is assumed that the material to be formed is incompressible, isotropic, and rigid-viscoplastic and that it obeys the von Mises yield criterion and its associated flow rule (Hill, 1998).

Figure 1 conceptually shows the air-pocketing phenomena in a two-dimensional domain. Air-pocketing occurs when the free surface of the material, dies or tools, and/or planes of symmetry make an enclosed cavity in a three-dimensional problem and a closed loop in a two-dimensional problem. The volume of an air-pocket varies with the stroke, and the varying pressure is exerted inside the air-pockets. The magnitude of the pressure is a function of the volumetric change of the air-pocket. The function may be greatly affected by the material inside the air-pocket. For example, if the process occurs in water or oil environments, there must be considerable water or fluid inside the air-pocket, which increases the bulk modulus of elasticity of the air-pocket. In this study, it is assumed that the material inside the air-pocket is uniform; i.e., the bulk modulus of elasticity of the material inside the air-pocket is constant, even though it can be affected by the volumetric strain of the air-pocket. Note that the material inside the air-pocket may vary with the stroke, especially when leakage through the die-material interface takes place.
Let us confine our explanation to two-dimensional problems to clarify the new approach. A closed loop is constructed on a two-dimensional plane when both ends of a free surface of material contact the same die. In finite element simulation of a process having a line of symmetry, a cavity also belongs to the set of closed loops if it is enclosed by the free surface of the material, a line of symmetry, and a die profile. All closed loops without air holes on their perimeters are considered air-pockets.

The $j^{th}$ increment of volumetric strain, denoted as $\Delta \varepsilon_v^j$, is defined as follows:

$$\Delta \varepsilon_v^j = \int_{V_j}^{V_j + \Delta V_j} \frac{dV}{V} = \ln \left( 1 + \frac{\Delta V_j}{V_j} \right)$$

where $V_j$ is the volume of an air-pocket at the $j^{th}$ increment and $\Delta V_j$ is its increment. The volumetric compression ratio of an air-pocket is:

$$\varepsilon_v^j = \varepsilon_v^{j-1} - \Delta \varepsilon_v^j$$

where $\varepsilon_v^j$ is the volumetric compression ratio at the $j^{th}$ increment, which is the negative of the volumetric strain.

It should be noted that the pressure inside the air-pocket is dependent on the die normal stress of neighbouring contact interfaces as well as on the volumetric compression ratio. In this paper, it is assumed that the inside pressure $p_{\text{air}}$ is linearly proportional to the volumetric compression ratio when the calculated inside pressure is less than the maximum die normal stress of the neighbouring contact interfaces, i.e.,

$$p_{\text{air}} = B \varepsilon_v^j \quad \text{when} \quad B \varepsilon_v^j < p_{mp}$$

$$p_{\text{air}} = p_{mp} \quad \text{when} \quad B \varepsilon_v^j \geq p_{mp}$$

where $B$ is bulk modulus of elasticity and $p_{mp}$ is the minimum peak pressure in the neighbouring contact interfaces.
When the calculated inside pressure exceeds the maximum die normal stress of the neighbouring contact interfaces, the volumetric compression ratio is purposely lowered to make the two values identical. In fact, when the inside pressure increases and exceeds the limit as the volumetric compression ratio increases, there must be air leakage and a corresponding pressure drop to make the inside pressure identical to the maximum normal pressure of the neighbouring contact interfaces. During finite element simulation, the air trap conditions are checked at each solution step to ensure that the above requirement is satisfied. The solution step must be small enough to minimise the cumulative volumetric strain.

3 Application example

We applied our approach to an axisymmetric cold plate forging process composed of three stages. Figure 2 shows the process design of the application example. The initial material was a disk with a diameter and thickness of 86.0 mm and 1.5 mm, respectively; i.e., the diameter-to-thickness ratio of the material was relatively small compared to common sheet metal-forming processes. Try-out was conducted under oil mist environments for proper lubrication.

**Figure 2**  Process design of test example, (a) stage 1 (b) stage 2 (c) stage 3
The experiments are shown in Figure 3 where an under-filling defect can be detected with ease because there is a distinct difference in surface roughness between the under-filling defect, that is, a free surface and the material surfaces on the die-material contact interfaces. Note that another under-filling defect due to air-pocket phenomena was observed on the inside of the forged material.

In most real situations, it is very rare to make air holes or die partition lines on the smooth die corners with small curvature to avoid the under-filling defects due to air-pocket phenomena because they can leave some surface defects on the forged material or deteriorate die structural rigidity.

It is noteworthy that the plate forging process can be sensitive to the air-pocketing phenomena because its deformation is much dependent on bending deformation of plates. Of course, finite element method is very powerful to solve this kind of mechanically complicated problems. However, there is no remarkable application to revealing air-pocketing phenomena occurring in plate forging.

The present finite element approach is applied to the plate forging process. The process information used for finite element analysis is as follows:

- Flow stress: \( \sigma = 580.0 \left( 1.0 + \frac{\varepsilon}{0.024} \right)^{0.14} \) MPa.
- Friction law: Coulomb friction (coefficient of Coulomb friction, \( \mu = 0.05 \)).

Because the material is not rate-dependent, the punch velocity was assumed to be unity.

**Figure 3** Experiments of the test example problem, (a) stage 1 (b) stage 2 (c) stage 3 (see online version for colours)

It should be noted that one of the most influential parameters affecting the finite element predictions of the air-pocketing phenomena is the bulk modulus of elasticity of the material inside the cavity. It is not easy to measure the mechanics inside the cavity or to estimate theoretically the value because of complexity of the material, that is, a mixture of air, water, debris, lubricant, etc. Therefore, the bulk modulus of elasticity was first predicted by comparing the predicted under-filling defect with a corresponding experimental defect for a wide range of test bulk modulus of elasticity. Let us focus the
outside air-pocket at stage 3, as shown in Figure 3. The shape of under-filling defect, that is, air-pocket at the final stroke at stage 3 is a circular band and thus its width was measured at four places using a profile measuring machine and it was 2.78 mm on average and the distance from the top to the lowest point of the air-pocket is 7.81 mm. Similarly, the averaged distance from the top to the lowest point of the air-pocket defined in Figure 6 is 7.54 mm.

Figure 4 shows the variation of the size of under-filling defect, that is, air-pocket width with the bulk modulus of elasticity, which was obtained by finite element predictions of the air-pocket widths for the sampled bulk moduli. The predicted width of an air-pocket was measured by the distance between the two end nodes of the air-pocket on which the normal stresses exert.

It can be seen from Figure 4 that the air-pocket width varies linearly with the bulk modulus of elasticity in the case of $B < 650$ MPa and that the value of $B = 500$ MPa is deemed appropriate for predicting nearly the same air-pocket width as measured in the experiments. It is interesting to note that the air-pocket width converges to 3.5 mm when the bulk modulus of elasticity is greater than 650 MPa, indicating that the internal pressure became greater than the lower peak pressure, that is, lower absolute value between the two peak normal stresses at the two neighbouring contact interfaces and that leakage of the internal cavity material occurred. It is also noteworthy that a quite wide range of the bulk modulus of elasticity (450–550 MPa) gives acceptable predictions of which accuracy is greater than 90% in terms of air-pocket width in the axisymmetric process.

Figure 4  Variation of air-pocket width with bulk modulus of elasticity (see online version for colours)

To reveal the effect of air-pocketing phenomena on the plastic deformation in plate forging, two cases of finite element analyses were considered. First, the test process was simulated without applying the air-pocketing treatment scheme. The predictions of deformed shapes together with normal stresses for the first case are shown in Figure 5, indicating that the metal flows around the die corner were quite sound and that there is no enclosed cavity between the material and die. However, distinct difference between the predictions for the first case and the experiments shown in Figure 3 was observed, especially around the die corners.
Figure 5  Finite element predictions of the test example without the air-pocketing treatment scheme applied, (a) stage 1 (b) stage 2 (c) stage 3 (see online version for colours)

Figure 6  Finite element predictions of the test example with the air-pocketing treatment scheme applied, (a) stage 1 (b) stage 2 (c) stage 3 (see online version for colours)
Figure 7  Comparison of the metal flow lines, (a) without air-pocketing considered (b) with air-pocketing considered (see online version for colours)

For the second case, the predictions shown in Figure 6 were obtained with the air-pocketing treatment scheme applied; they were very close to the experiments in terms of the defect position defined by the distance from the top and the lowest point of the air-pocket as well as the air-pocket width defined in Figure 4. To exaggerate the difference of the two predictions, the two cases are compared in Figure 7 with an emphasis on the variation of metal flow lines (Joun et al., 1998) which mean the deformation of initially horizontal lines inside the material. It can be seen that the predictions obtained with the air-pocketing phenomenon considered have the distinct thinned thicknesses at the die corners while the normal stresses in the predictions obtained without air-pocketing phenomena considered imply the sound material-die contact.

In the above, the air-pocket marked ‘D’ in Figure 8 was investigated in detail because it can be seen outside as shown in Figure 3. In Figure 8, however, the internal pressures of all the air-pockets occurring in stage 3 were traced. During the simulation, four air-pockets occurred and two air-pockets marked ‘A’ or ‘B’ disappeared in turn before final stroke. For the two disappeared air-pockets, internal pressures increase almost linearly with the stroke even at the final disappearing instant. To the contrary, the internal pressures of the two survived air-pockets marked ‘C’ and ‘D’ increase rapidly as the punch approaches to its destination.
It should be noted that any user intervention was not needed during the whole simulation and that the practical process simulation with air-pocket phenomena considered is too complex to be conducted in a manual way. This point has prevented the related technology from being employed by process design engineers as well as researchers.

Figure 8  Pressure variation of the all air-pockets occurring in stage 3, (a) position of air-pocket (b) variation of internal pressure with stroke at stage 3 (see online version for colours)

4 Conclusions

A new finite element approach to simulating metalforming processes considering air-pocketing phenomena was presented in this paper. The internal pressure of an air-pocket was assumed to be a linear function of the volumetric compression ratio of the air-pocket when it was less than the lower absolute value between peak die normal stresses of the neighbouring contact interfaces of the air-pocket. When it exceeded the value, the accumulated volumetric compression ratio was purposely lowered to make the internal pressure identical to the minimum peak die normal pressure of the neighbouring contact interfaces. Note that the proportional constant is defined as the bulk modulus of elasticity.

The approach was implemented into the commercial metal forming simulation software AFDEX (Joun et al., 2011), which has a special remeshing capability for simulating the air-pocketing phenomena. The approach was then used to simulate a plate forging process with emphasis on analysis of under-filling defects due to the air-pocketing phenomena near the smooth die corners. The validity of the results was verified using experimental data. The comparisons between the predicted and experimental data were in good agreement.

The importance of bulk modulus of elasticity was emphasised, which may vary from situation to situation. A practical approach to find the bulk modulus of elasticity was given with the application example. It was shown that a quite wide range of the value gives acceptable predictions and that the linearity between the modulus of elasticity and air-pocket width in an axisymmetric plate forging process was observed, indicating that the present approach and the related software are numerically stable.
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