Numerical and experimental study of the process parameters effect on the void evolution in the cold extrusion of rods

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Abstract

Elimination of defects such as voids and internal cavities is required in metal forming processes to avoid premature failure of mechanical components during service. In this paper, the effect of different parameters on the void closure behavior is studied in the cold extrusion of rods. A three dimensional nonlinear dynamic finite element model is developed for this purpose. Experiments are also performed on aluminum samples to verify the accuracy of the finite element model. Results of the developed model are in good agreement with experimental findings. It is observed that voids contract in all directions during the direct extrusion which is in contrast to some other metal forming processes like forging and rolling. Effect of parameters such as die semi-angle, friction coefficient and void location on the void evolution is systematically investigated and discussed. The results of this study can help industries using metal extrusion for optimized design and control of the process to reduce voids and porosity and increase the strength of their product.

Keywords: Void evolution; Cold extrusion; Finite element method; Die geometry; Void location
1 Introduction

Internal defects such as voids and porosity usually occur due to shrinkage and gas progression during the solidification of the casting ingots [1],[2]. The presence of these defects in the final product adversely affects its mechanical properties and may disturb its performance and shorten its life [3]. Consequently, reduction of these defects is of prime importance for the industrial applications [4],[5],[6].

Void elimination is usually performed by applying large compressive plastic deformation in the material by means of different metal forming processes [7],[8],[9]. Direct extrusion, in which the billets are subjected to high compressive and shear stresses, is capable of reducing the defects in the metal structure [10] and can be effectively used for void elimination during manufacture of mechanical parts.

The void closure behavior during metal forming processes has been the subject of many studies in recent years. Kakimoto et al. [9] examined the closing behavior of internal voids in different configurations of the cold forging process by a deformation analysis involving the finite element method (FEM). To confirm the accuracy of the deformation analysis, experiments were carried out on pure aluminum billets through which cylindrical hole was drilled. Chen et al. [8] developed a procedure based on finite element analysis and neural network to predict the degree of void closure in cold rolling. Experiments were conducted on aluminum sheets to validate the developed model. Two types of voids, namely a cylinder void (a longitudinal hole through the width of the sheet) and a spherical void, were considered in their study. Kim et al. [11] carried out a numerical analysis to explore various parameters, such as the ratio of height to diameter of ingot, pressing depth, and void location, effect on the void evolution in forging process. Pure lead specimens containing spherical voids were employed to perform verification tests. Chen et al. [12] proposed a mathematical methodology from the view of strain function for analyzing void closure in the forging process of steel ingots. They obtained a mathematical criterion for on-center and off-center void closure and verified the criterion by finite element simulations. Chen et al. [13] employed a nonlinear coupled finite element model to investigate deformation mechanism of internal spherical void defects during the hot radial forging process. They investigated the effect of void location, die shape, and reduction of the tube thickness on the void
closure behavior. Chen and Lin [14] examined the evolution mechanisms for the spherical or spheroidal voids during hot working by finite element simulations and experiments. They discussed the effect of the initial void size, aspect ratio and position on the void evolution and argued that the strain and stress fields around voids are the key factors influencing the void closure. Park [15] investigated the closure phenomenon of cylindrical voids in flat-die forging by rigid-plastic finite element analysis and experiments using plasticine specimens. Saby et al. [16] used a Representative Volume Element for simulation of spherical and ellipsoidal voids at the meso-scale. They performed a sensitivity study to mechanical parameters and concluded that strain-rate has no major influence on the closure of real void. Saby et al. [6] presented a geometry-dependent model for void closure in hot metal forming that was capable of accounting for the void's geometry and orientation, as well as the mechanical state during deformation.

The review of the existing literature reveals that most of the reported studies on the void closure phenomenon in metal forming problems focused on forging or rolling [7]. This is common since forging and rolling are the most efficient methods for elimination of internal voids and porosity. Nevertheless, investigation of the void evolution in other metal forming processes like extrusion can provide useful information and help industry to optimize design and control of forming processes. Considering this fact, in the present study, the effect of process parameters on the void closure behavior is investigated in the cold extrusion process. A three-dimensional nonlinear dynamic finite element model is used for this purpose. Experiments are performed to validate the accuracy of the developed finite element model. The void reduction predictions by the developed model are in good agreement with experimental results.

2 Description of the analysis procedure

2.1 Void geometry

The void cross section is assumed to have initially a circular shape which turns into an elliptical shape after extrusion. Figure 1 shows the void dimensions before and after deformation. $d$ is the void initial diameter while $h$ and $l$ are its final height and length.

In order to characterize the void evolution during extrusion, three parameters, i.e. void height reduction ($r_h$), void length reduction ($r_l$) and void area reduction ($r_A$), are defined as follows [13]:

$$r_h = \frac{h - d}{d}, \quad r_l = \frac{l}{d}, \quad r_A = \frac{\pi h l}{4 d^2}$$
\[ r_h = \frac{h-d}{d}, \quad r_i = \frac{l-d}{d}, \quad r_A = \frac{A_f - A_i}{A_i} \]

(1)

where \( A_i \) and \( A_f \) are the void initial and final cross-sectional areas, respectively. From these relations, it can be seen that the void is completely closed when \( r_A \) reaches its limiting value (i.e. \( r_h = -1 \) and/or \( r_i = -1 \)). Furthermore, a lower value is favorable for these parameters as it corresponds to a smaller void after extrusion.

2.2 Finite element modeling

A schematic of direct extrusion of rods is shown in Fig. 2. The die semi-angle is depicted by \( \alpha \) in this figure.

A three-dimensional nonlinear dynamic finite element model has been developed using Abaqus/explicit finite element software to examine the void evolution behavior in the cold direct extrusion. The formulation for the dynamic finite element analysis can be written as:

\[
\begin{bmatrix} M^e \end{bmatrix} \{ \ddot{u}^e \} + \begin{bmatrix} K^e \end{bmatrix} \{ u^e \} = \{ F^e \}
\]

(2)

where

\[
\begin{bmatrix} M^e \end{bmatrix} = \int_V \rho \left[ \begin{bmatrix} N \end{bmatrix}^T \right] \left[ N \right] dV, \quad \begin{bmatrix} K^e \end{bmatrix} = \int_V \left[ B \right]^T \left[ C \right] \left[ B \right] dV
\]

(3)

In these equations \( \{ u^e \} \) and \( \{ F^e \} \) are the displacement and force vectors, respectively. \( \begin{bmatrix} M^e \end{bmatrix} \) is the mass matrix and \( \begin{bmatrix} K^e \end{bmatrix} \) is the stiffness matrix. \( \rho \) denotes the material density and \( \begin{bmatrix} C \end{bmatrix} \) represents the elastic-plastic stiffness tensor. \( \begin{bmatrix} N \end{bmatrix} \) is the element shape function matrix and \( \begin{bmatrix} B \end{bmatrix} \) refers to the element strain-displacement matrix.

The explicit central difference integration rule is used to integrate Eq. (2). This gives:
\[
\{\ddot{u}^e\}_{(i)} = \left[ M^e \right]^{-1} \left( \left\{ F^e \right\}_{(i)} - \left[ K^e \right] \left\{ u^e \right\}_{(i)} \right)
\]

\[
\{\dot{u}^e\}_{(i+1/2)} = \{\dot{u}^e\}_{(i-1/2)} + \frac{\Delta t_{(i+1)} + \Delta t_{(i)}}{2} \{\ddot{u}^e\}_{(i)}
\]

\[
\{u^e\}_{(i+1)} = \{u^e\}_{(i)} + \Delta t_{(i+1)} \{\dot{u}^e\}_{(i+1/2)}
\]

(4)

Subscript \( i \) in the above equations denotes the increment number in an explicit dynamics step.

The workpiece material is aluminum 5010 alloy which is annealed at 350\( ^0 \text{C} \) for 1 hour and then cooled down to room temperature to decrease its flow stress and increase its formability. A standard compression test is performed on a sample made from the resulted material at room temperature and the following power law is obtained for the relationship between the stress and the amount of plastic strain:

\[
\sigma = 520\varepsilon_p^{0.22}
\]

(5)

Similar power law equations have been previously used in many related studies, e.g. in [17],[18],[19]. The associated strain-stress curve is shown in Fig. 3. It should be noted that since the process is performed at room temperature and the ram velocity is low (0.1 mm/s), it’s fair assuming the process to be quasi-static and neglect the strain rate effect [20],[21]. An elastic-plastic material model created from the von Mises yield surface and associated flow rule is used to describe workpiece deformation. The temperature rise is also ignored because the heat generated by the mechanical work is transferred to the surroundings and the material does not experience any changes in its microstructure. [22],[23]. In fact in the cold extrusion, the temperature rise is important only if the extrusion ratio or ram speed are very high or when the process is adiabatic which is not the case here [24]. Eight-node brick elements with reduced integration and hourglass control are used to mesh the workpiece model.

Die and punch are modeled as rigid bodies in the FEM simulations since their deformation is negligible. Four-node three dimensional bilinear rigid quadrilateral elements are used to create their FEM mesh. A constant friction coefficient is assumed between workpiece and die in the range of \( \mu = 0.05 \) to \( \mu = 0.2 \) which is a common assumption in cold metal forming processes.
The Coulomb friction law is used to define the friction in the contact areas. The voids are assumed to be cylindrical with circular cross-section and to be positioned on-center or off-center of the workpiece cross section as shown in Fig. 4. In order to reduce the computational cost, a quarter model is used for the workpiece with on-center void and a half model for the workpiece with off-center void. The dimensions of workpiece and die and the size of voids are based on the parameters of the experimental tests which are given in the following sections.

2.3 Model verification

The described finite element model was verified by results of experiments performed on two cylindrical samples of 30 mm diameter and 60 mm length. A void with radius of about 2.2 mm was drilled through the length of each sample. The void was on-center in one of the samples and off-center in the other one as shown in Fig. 5. The voids diameter was accurately measured by a microscope with a micrometer scale eyepiece. A microscopic view of the voids cross-section is provided in Fig. 6.

Samples were then extruded in a die with semi-angle of $\alpha = 30^\circ$. Subsequently, the extruded products were wire-cut by an electric discharge machine near their tips. Figure 7 shows the products after the wire-cut process. A microscopic view of the voids in the wire-cut surface is provided in Fig. 8.

The void dimensions were measured in the wire-cut surface under microscope. Table 1 presents the experimental and finite element results for the voids dimensions after extrusion. The results show that the difference between experimental and FEM data for void area reduction is about 1.4% for the on-center and 7.6% for the off-center void. This indicates good agreement between experimental and simulation results. The friction coefficient was assumed to be $\mu = 0.15$ for both on-center and off-center cases. This value gave the best agreement between experimental and finite element predicted ram force.

3 Results and discussion

The finite element model of workpieces with on-center and off-center voids before and after simulation are shown in Fig. 9. It should be noted that the quarter model of the workpiece with on-center void is mirrored to a half model in Fig. 9a to have a better view of the workpiece and
3.1 effect of the die semi-angle and friction coefficient

Figure 10 shows the variation of the void area reduction $r_A$ with die semi-angle and friction coefficient for on-center and off-center voids. As this figure shows, regardless of the void position in the workpiece, the void reduction increases with reduction of die angle and friction coefficient.

The plastic effective strain distribution in workpieces extruded by dies with $\alpha = 10^\circ$ and $\alpha = 40^\circ$ is presented in Fig. 11. It can be seen that the workpiece experiences a larger plastic strain when extruded by a die with a greater semi-angle. However, the maximum plastic deformation occurs in regions near the workpiece surface in this case. But extrusion in dies with a small semi-angle creates a more uniform deformation in the workpiece and the maximum plastic strain occurs inside the workpiece where internal voids and other defects are located. Consequently, dies with smaller semi-angle lead to greater void area reduction and are recommended for better void closure.

A pattern of material deformation in the workpiece cross-section obtained by a coarse mesh is plotted in Fig. 12 for low and high friction conditions in blue and red colors, respectively. This pattern clearly shows that in the low friction condition the deformation is uniform throughout the workpiece and it can contribute to closure of voids located everywhere in the workpiece. However, in higher friction conditions, the plastic deformation is less uniform and is more concentrated near the contact area between die and workpiece. Consequently, it has a less profound effect on the internal voids closure as Fig. 10 predicts.

3.2 effect of the void position

Figure 13 shows variation of the on-center and off-center voids area reduction with die semi-angle for friction coefficients of $\mu = 0.05$ and $\mu = 0.2$. It is seen in this figure that $r_A$ for on-center void is more sensitive to the die semi-angle. In other words, variation of the die semi-angle has a greater effect on the closure of voids located on or near center of the workpiece.

Figure 14 shows $r_h$ and $r_l$ variation by die semi-angle for workpiece with off-center void in friction coefficients of $\mu = 0.05$ and $\mu = 0.2$, respectively. According to these figures, when

void geometry and deformation. The mesh independence study was conducted in both cases to ensure that the mesh size is not influencing results.
friction is small, absolute value of $r_l$ is greater than that of $r_h$. This means that the void contraction in hoop direction is greater than its contraction in radial direction. This, however, changes as the friction coefficient increases. In higher frictions, absolute value of $r_l$ is getting smaller than that of $r_h$ especially in dies with bigger semi-angles. In other words, the void contraction in the radial direction exceeds its contraction in the hoop direction as friction increases between die and workpiece. It is worth noting that both $r_h$ and $r_l$ are negative in all conditions for both on-center and off-center voids. This indicates that the voids contract in all directions during direct extrusion. This is in contrast to many other forming processes like rolling and forging in which void contraction in one direction is accompanied by expansion in the perpendicular direction as demonstrated in previous studies like [6],[8].

4 Conclusions

A three dimensional nonlinear dynamic finite element model was developed in this paper to study the effect of different parameters on the void evolution in the clod extrusion of rods. The accuracy of the model was confirmed by experiments performed on the aluminum samples containing longitudinal on-center and off-center voids with circular cross-section. It was observed that in contrast to some other metal forming processes like forging and rolling, the voids contract in all directions during direct extrusion. Furthermore, regardless of the void position, the void reduction increases with reduction of die semi-angle and friction coefficient. However, voids that are closer to the workpiece center are more sensitive to the die semi-angle. Moreover, it was found that when friction is small the contraction of off-center voids in hoop direction is greater than its contraction in the radial direction. But in high friction condition, the void contraction in the radial direction exceeds its contraction in the hoop direction, especially in dies with bigger semi-angle.

Conflict of interest

None declared.

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References


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**Fig. 4** Different positions of voids in the workpiece

**Fig. 5** Samples used in the experimental tests

**Fig. 6** A microscopic view of the voids before extrusion
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**Fig. 8** A view of voids under microscope after extrusion

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**Fig. 12** Pattern of workpiece deformation on a coarse mesh in low (blue) and high (red) friction conditions

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Table 1 Comparison of finite element and experimental results

<table>
<thead>
<tr>
<th>Void position</th>
<th>Void initial diameter (mm)</th>
<th>Void final dimensions (mm)</th>
<th>Void area reduction %</th>
<th>Error %</th>
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<td></td>
<td></td>
<td>Experimental</td>
<td>FEM</td>
<td>Experimental</td>
</tr>
<tr>
<td>On-center</td>
<td>4.48</td>
<td>2.40</td>
<td>2.40</td>
<td>2.44</td>
</tr>
<tr>
<td>Off-center</td>
<td>4.32</td>
<td>3.80</td>
<td>3.48</td>
<td>3.66</td>
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