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VOID EVOLUTION BEHAVIOR AND CLOSURE CRITERION INSIDE LARGE SHAFT FORGINGS DURING A FORGING PROCESS

OBNAŠANJE PRAZNIN IN KRITERIJ NJIHOVEGA ZAPIRANJA MED PROCESOM KOVANJA VELIKIH GREDI

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In this study, the effects of different void positions, void shapes and sizes on the evolution of voids were discussed in detail using experiments and simulations. The results show that the influence of the void size on the void closure can be ignored, while the void position and void shape have a great influence on the closure of a void. Considering the complexity of the void-shape change in a forging process, we proposed a quantitative expression of the void-shape coefficient, which is affected by the effective stress and effective strain. Meanwhile, the void-shape evaluation parameter, defined as a function of the stress deviator, effective strain and effective stress, was proposed to describe the changes in the void aspect ratio. Finally, WHF (wide die heavy blow) forging experiments were conducted using a 5MN hydraulic press to verify the numerical-simulation results. Based on the experimental and simulation results, a new mathematical model for void-closure determination was established during a forging process of large shaft forgings. The experimental results were consistent with the simulation results, showing that the void-closure model can accurately determine whether a void is closed or not.

Keywords: large shaft forgings, void evolution, finite elements, void-closure model

V študiji avtorji, s pomočjo eksperimentov in simulacij, natančno razpravljajo o vplivu različnih leg in oblik praznin na njihov razvoj med kovanjem. Rezultati študije kažejo, da lahko zanemarimo zapiranje praznin, medtem ko imata njihov položaj in oblika velik vpliv na njihovo zapiranje. Avtorji so predlagali kvantitativni koeficient oblike praznine, upoštevajoč kompleksnost spremembe oblike praznin med kovanjem, ki vpliva na efektivno napetost in efektivno deformacijo. Tako so predlagali za opis sprememb razmerja dimenzij praznin evaluacijski parameter oblike praznine, ki je definiran v odvisnosti od deviacijske napetosti, efektivne napetosti in deformacije. Nazadnje so izvedli še eksperimente kovanja WHF (angl.: Wide Die Heavy Blow) na 5MN hidravlični stiskalnici, da so lahko verificirali rezultate numeričnih simulacij. Na osnovi rezultatov eksperimentov in simulacij so postavili nov matematični model za določanje zapiranja praznin med kovanjem velikih odkovkov gredi. Eksperimentalni rezultati so se dobro ujeli z rezultati numeričnih simulacij, kar kaže na to, da novi model zapiranja praznin lahko natančno opredeli, ali se bo praznina zaprla ali ne.

Ključne besede: velike kovane gredi, razvoj praznin, metoda končnih elementov, model zapiranja praznine

1 INTRODUCTION

Large shaft forgings are the key components of major equipment, such as a nuclear-power main shaft, turbine rotor or generator rotor, whose quality directly affects the manufacturing level of large equipment. Due to the large size of large-scale shaft forgings, void defects inevitably occur in ingots during a casting process.[1–3] Void defects should be eliminated in the forging process, otherwise they affect the mechanical properties of the material.[4,5]

In order to reveal the mechanism of void closure, many researchers[6–8] analyzed the evolution behavior of void defects based on finite-element (FE) simulations and experiments. Tamura and Tajima[9] discussed the change of a surface void in the process of deformation with the aid of the FE simulation and put forward a method to remove the surface void defects. Kakimotoa et al.[10] used the FE numerical simulation to study the evolution law of a void on the central line in the forging process. Chbihi et al.[11] established a decision model to predict the evolution of a void based on the FE simulation.

During the forging of large items, it is very important to determine whether the void is closed or not. Keife and Ståhlberg[12] established a model to determine the closure of voids in plane-strain compression. Hwang et al.[13] and Nakasaki et al.[14] proposed to use parameter G_m, which represents the integration of the hydrostatic stress, to determine the closure of a void. Chen et al.[15] analyzed the influence of the void size, position and shape on the closure and established a new mathematical model of void closure. However, the current research mainly focuses on theoretical analysis, and there is a certain gap in the industrial practice. Therefore, it is still necessary to study the evolution of void defects in large ingots during multi-pass forging.

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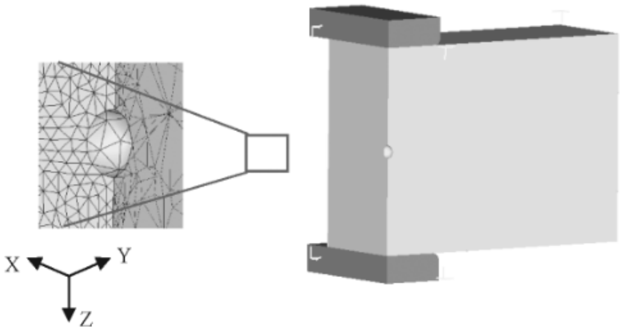


Figure 1: Compression schematic

In this study, numerical simulations were carried out when the void was in different positions, having different sizes and different shapes. Based on the simulation results, the mechanism of void closure was revealed and the mathematical model of void closure was established. Finally, taking the 30Cr2Ni4MoV steel as the research material, the simulation results were verified with a WHF (wide die heavy blow) drawing-forging experiment.

2 FINITE-ELEMENT SIMULATION PROCESS

The size of the simulated sample is 150 mm × 150 mm × 200 mm, and the size of the upper and lower molds is 200 mm × 200 mm × 90 mm, as shown in **Figure 1**. Considering the symmetry of loadings and geometry, only 1/4 of the billet is analyzed.

Simulation parameter setting: the environmental convection coefficient is set to 0.02 N/s/mm/°C, the blank grid is divided into 80000, the upper and lower dies are 8000, the heat-transfer coefficient of dies is 3 N/S/mm/°C, the preheating temperature of dies is 200 °C, the friction coefficient is 0.7, and the environmental temperature is 20 °C. After the numerical simulation, the change rules for different void sizes were analyzed, and the effective strain, hydrostatic stress and *Q*-value distribution around the void were observed.

3 RESULTS AND DISCUSSIONS

The shape of void is an important factor in the process of void-closure evolution, which mainly includes the original shape, size and location of the void. In order to find the quantitative relationship between these three factors and void closure, this paper puts forward a void-shape coefficient to describe the change in the void shape in the process of deformation. The void-shape coefficient for the three coordinate axes can be defined as:

$$\begin{cases} S_X = 2a/(b+c) \\ S_Y = 2b/(a+c) \\ S_Z = 2c/(a+b) \end{cases} \quad (1)$$

where S_X, S_Y and S_Z are the void-shape coefficients in the X, Y and Z directions, respectively, while a, b and c are the maximum dimensions of the voids in the X, Y and Z directions, respectively. When void coefficients S_X, S_Y and S_Z are zero, the void is closed.

3.1 Effects of the initial void size

The variation in the void-shape coefficients (S_X, S_Y and S_Z) for different void sizes with the increase of reduction is shown in **Figure 2**. **Figure 2a** shows that the influence of the void size on S_X is relatively large. When the deformation is less than 13 %, the variation of S_X is basically the same. With the increase in deformation, the S_X of a 3-mm-radius void continues to increase, while that of 4-mm and 5-mm-radius voids no longer continues to increase. When the deformation is more than 18 % and until the voids are closed, the S_X of the voids with different sizes continues to increase. The main reason for this is the fact that the void size in the X direction decreases, while the void size in the Y direction is basically unchanged, leading to an increase in S_X at this stage. **Figure 2b** shows that the void size has little effect on S_Y. With an increase in the reduction, S_Y gradually increases, which is because Y is the direction of a small deformation and the stress of the void in this direction is also relatively small. **Figure 2c** shows that S_Z decreases with the increase in reduction. When the reduction of the void size is 26 %, S_Z is zero, indicating that the void is closed. In **Figure 2**, it can be seen that both S_X and S_Y increase

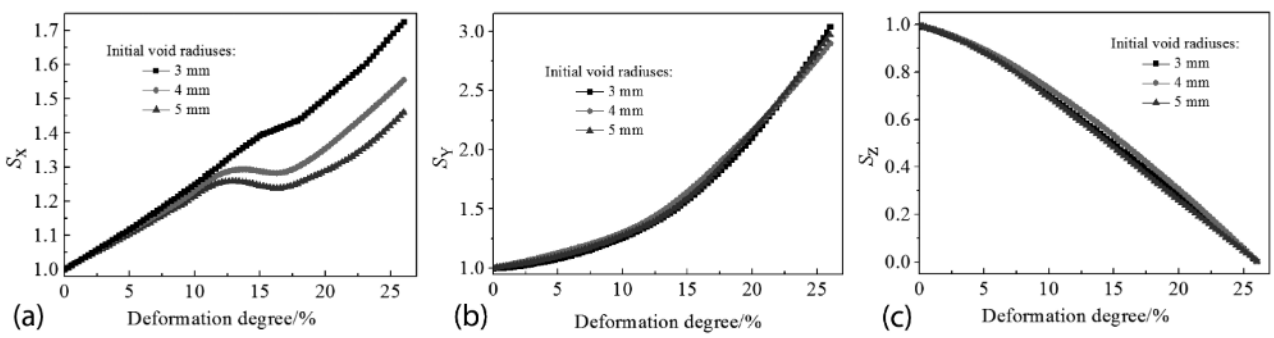


Figure 2: Variation of the void-shape coefficients with deformation for different sizes: a) S_X, b) S_Y, c) S_Z

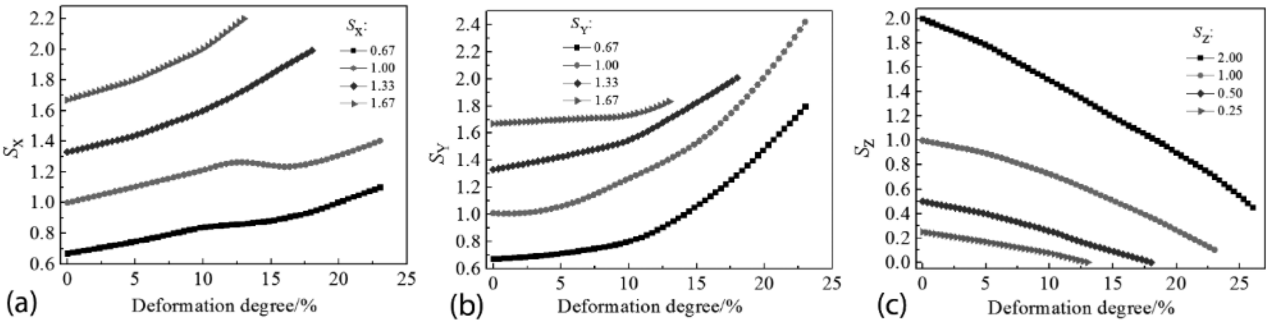


Figure 3: Variation of the void-shape coefficients with deformation for different shapes: a) S_X, b) S_Y, c) S_Z

with the increase in deformation. However, S_Z decreases with the increase in deformation, which means that the void closure occurs in the Z direction. In **Figure 2c**, the influence of the void size on S_Z is not significant, which shows that the void size can be ignored when compared with the workpiece size and the influence of the void size on the void closure can also be ignored.

3.2 Effects of the initial void shape

Figure 3 shows the variation in the void-shape coefficients (S_X, S_Y and S_Z) with different initial shapes. In **Figure 3a**, the initial S_X is 0.67, 1.00, 1.33 and 1.67, respectively, and the varying curve of S_X is basically parallel before the 13-% deformation. When the deformation is more than 13 %, the curve growth rate is different due to a different reduction rate of the void in the Z direction. **Figure 3b** shows that the initial shape of the void has an obvious influence on the change curve of S_Y. When the initial S_Y value is small, the growth rate of the curve is lower with the increase in deformation. In **Figure 3c**, the initial S_Z is 2.00, 1.00, 0.50 and 0.25, respectively. **Figure 3c** shows that the closure of the void occurs in the Z direction. The larger the initial S_Z, the greater is the reduction rate of the curve, increasing with the amount of deformation. Otherwise, the smaller S_Z, the easier is to close the void. Through the above analysis, it can be concluded that the initial void shape has an important influence on the void closure in the process of thermal deformation.

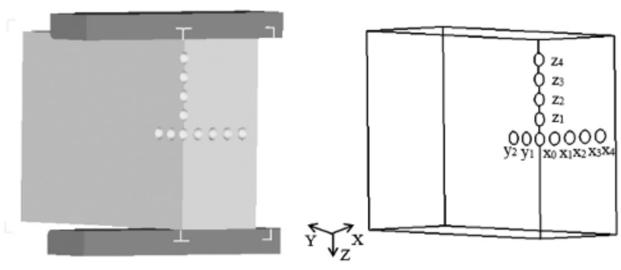


Figure 4: Void schematic for different locations

3.3 Effects of different void positions

Figure 4a shows FE models for the initial billet and a schematic of the positions of voids. The initial void radius is 5 mm, and they are at positions x_0-x_4, z_1-z_4 and y_1-y_2, as shown in **Figure 4b**. The distance between the voids is 15 mm.

Figure 5 shows the variation of the shape coefficient (S_Z) in different directions. As shown in **Figure 5a**, when the deformation is less than 5 %, the S_Z values at different positions in the X direction show little difference. As the deformation continues to increase, the reduction rate of S_Z near the center is faster. **Figure 5b** shows the variation of S_Z at the y_1 and y_2 positions with the increase in deformation. When the deformation is less than 15 %, S_Z decreases with the increase in deformation. Furthermore, the value of S_Z decreases faster at the y_1 and y_2 positions. When deformation exceeds 15 %, the value of S_Z at the y_1 position continues to decrease, but the rate of decrease gradually decreases. The S_Z value at the y_2 position basi-

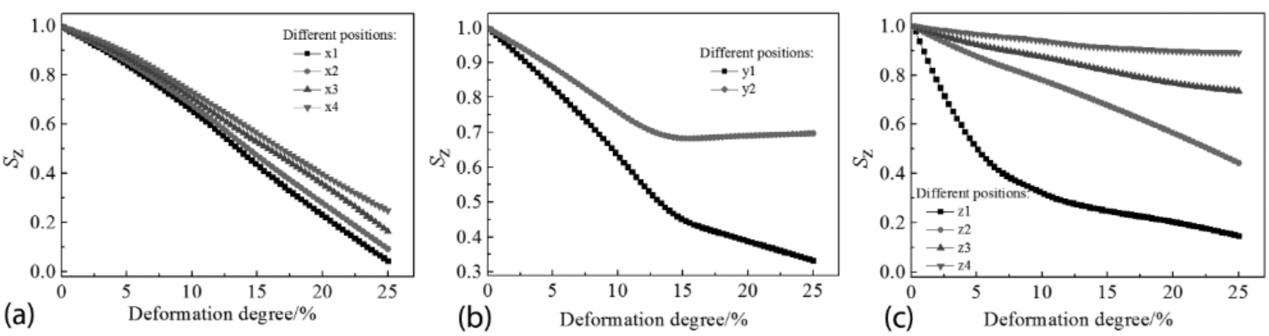


Figure 5: Variation of shape coefficient S_Z with deformation for different directions: a) X direction, b) Y direction, c) Z direction

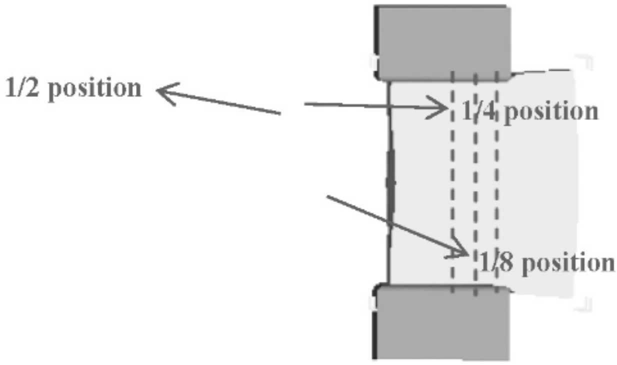


Figure 6: Sampling diagram

cally remains unchanged because the stress and strain around the void at the y_2 position are relatively low, basically remaining unchanged. From **Figure 5c**, it can be seen that S_Z decreases with the increase in deformation and its value at the z_1 position decreases fastest. When the deformation is more than 15 %, the S_Z value at the z_1 and z_2 positons continues to decrease, but the rate of decrease is very slow. The S_Z value at the z_3 and z_4 positons remains unchanged and does not decrease with the increase in reduction.

3.4 Comparison of the experimental and simulation results

3.4.1 Experimental process

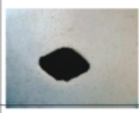
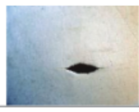
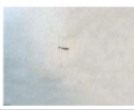
In this study, the accuracy of the simulation results was verified with four passes of the WHF drawing forging of an as-cast 30Cr2Ni4MoV ingot. The experiment was carried out on a 500-t hydraulic press. The size of the ingot was 150 mm × 150 mm × 120 mm. The compression temperature was 1200 °C. In the experiment, a 10-mm through hole was drilled into the center of the sample. The compression process was divided into four passes. After each compression, the test piece was turned by 90 degrees for the next compression. The forging ratios (FRs) were 1.1, 1.5, 1.8, 2.0 and 2.2, respectively. The sampling diagram is shown in **Figure 6**. The positions of 1/2, 1/4 and 1/8 of the specimen were cut to observe the void changes.

3.4.2 Comparison of the experiment and simulation results

Table 1 shows a comparison of the void shapes after the experiment and simulation at FRs 1.1, 1.5, 1.8, 2.0 and 2.2.

As shown in **Table 1**, when the FR is 1.1, the void at the 1/2 position is not closed and the circular void becomes ellipsoid. When the FR is 1.5, the void dimensions at the 1/2 position are 2679.53 µm and 752.14 µm in the *X* and *Z* directions, respectively. As the void moves away from the center, the size of the void increases. When the FR is 1.8, the deformation law for the void is the same as when the FR is 1.5. The void dimensions at the 1/2 position are 517.09 µm and 205.13 µm in the *X* and *Z* directions, respectively. When the FR is 2.0, the void at the 1/2 position disappears. The void at the 1/4 position becomes a crack with a width of 166 µm and the crack at the 1/8 position is 230 µm. When the FR is 2.2, the void is completely closed. The shape and size of the void are the same after the experiment and simulation, which shows the accuracy of the simulation results.

Table 1: Comparison of void shapes after the experiment and simulation

FR	1/2 position		1/4 position		1/8 position	
	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation
1.1						
1.5						
1.8						
2.0						
2.2						

4 ESTABLISHMENT AND VERIFICATION OF THE VOID-CLOSURE MODEL

In this study, the relationships between the void change and stress state, equivalent strain and the whole loading process are fully considered, and a model for evaluating the void-shape change is proposed, which can be expressed as follows:

$$Q_i^{'} = G(\bar{\varepsilon}_{\rm f}) = \int_0^{\bar{\varepsilon}_{\rm f}} \left(-\frac{\sigma_i^{'}}{\bar{\sigma}} \right) d\bar{\varepsilon} \quad (i = x, y, z) \tag{2}$$

where $Q_i^{'}$ ($i = x, y, z$) is the void-shape evaluation parameter in direction $\sigma_i^{'}$ ($i = x, y, z$) is the stress deviation $\sigma^{'}$ in different directions, which can be expressed as follows:

$$\sigma^{'} = \begin{bmatrix} \sigma_x^{'} & \sigma_{xy}^{'} & \sigma_{xz}^{'} \\ \sigma_{xy}^{'} & \sigma_y^{'} & \sigma_{yz}^{'} \\ \sigma_{xz}^{'} & \sigma_{yz}^{'} & \sigma_z^{'} \end{bmatrix} \tag{3}$$

In order to verify the accuracy of the void-shape evaluation parameter to determine the change of the void shape, the relationships between the Z-direction shape evaluation parameters and shape coefficients of voids with different positions and initial shapes are analyzed. If there is a one-to-one relationship between them, it shows that the void-shape evaluation parameters are feasible to determine the shape change. **Figure 7** shows the relationships between the estimated parameters and the shape coefficient of a circular void with a diameter of 10 mm at different positions.

Figure 8a shows the variation in the initial void-shape coefficients with the Z-direction shape evaluation parameters. From **Figure 8a**, it can be seen that the shape coefficient (S_Z) in the Z direction decreases with the increase in the evaluation parameter ($Q_Z^{'}$). The larger the initial S_Z value, the larger is the $Q_Z^{'}$ required for the complete closure of a void ($S_Z = 0$). In order to further study the evaluation of void closure with shape parameters, taking the initial circular void ($S_Z = 1$) as the target, curves with S_Z initial values of 0.25, 0.5 and 2 are translated horizontally along the right, right and left sides, respectively. The moving curves are shown in **Figure 8b**. The curves of different initial-shape coefficients coincide with the shape evaluation parameters, showing that there is a one-to-one relationship between the void-shape coefficients and the corresponding void-shape evaluation parameters. The shape-evaluation-parameter model can be used to determine the closure of a void that is not affected by the initial void shape.

Based on the analysis of the variation law for the void-shape coefficient with the void evaluation parameters, it can be seen that the void-shape coefficient (S_Z) at different positions basically coincides with the curve of the evaluation parameter ($Q_Z^{'}$). The curves of S_Z and evaluation parameter $Q_Z^{'}$ with different initial voids can always coincide with horizontal translation. The results show that the change curve of S_Z with the evaluation parameter $Q_Z^{'}$ at different positions and different initial shape coefficients is a group of similar curves, which can be expressed as a primary exponential function:

$$S_Z = A \exp\left(-\frac{Q_Z^{'}}{t} \right) + S_1 \tag{4}$$

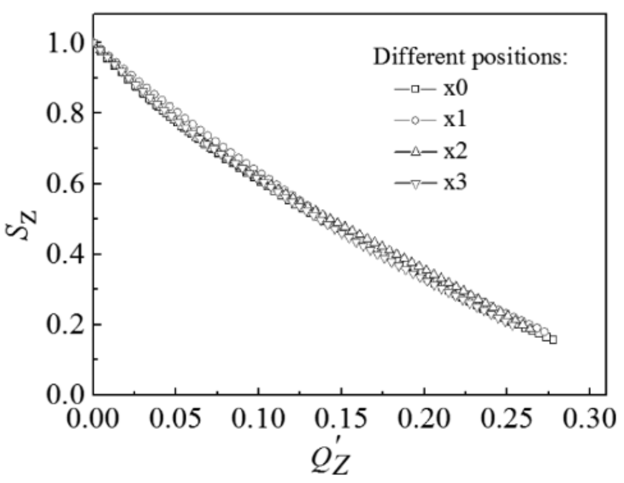


Figure 7: Relationships between void-shape evaluation parameters and shape coefficients in different positions

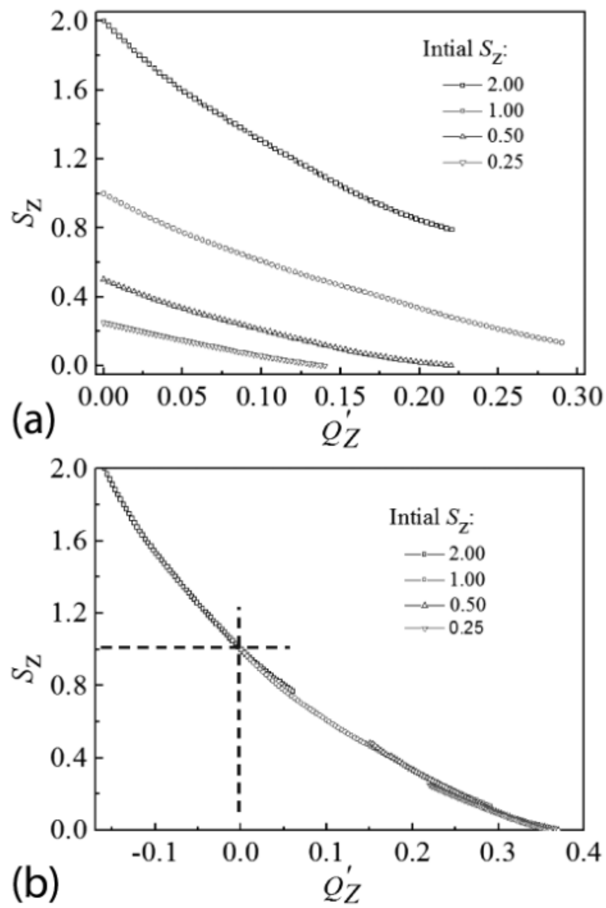


Figure 8: Relationships between void-shape coefficients and evaluation parameters with different initial shapes: a) before translation, b) after translation

where A, t and S_1 are coefficients. Based on the existing calculation data, the coefficients from Regression Equation (4) can be obtained, $S_1 = -0.469$, $t = 0.318$.

When $Q_Z' = 0$, Equation (4) can be simplified as:

$$S_{Z0} = A + S_1 \tag{5}$$

where S_{Z0} is the initial-shape coefficient of a void in the Z direction. According to Equation (5), coefficient A is the difference between S_1 and S_{Z0}.

By combining Equation (4) and Equation (5), based on the functional relationship between the void-shape evaluation parameters and the shape coefficient, a decision model for void closure is established.

$$S_Z = (S_{Z0} + 0.469)\exp\left(-\frac{Q_Z'}{0.318}\right) - 0.469 \tag{6}$$

The void-shape coefficient corresponds to the evaluation parameters one by one, and the functional relationship between them is not related to the position and initial shape of the void. Therefore, when S_Z is equal to zero, it means that the void is closed, and this model can determine the void closure.

Figure 9 shows the relationship between S_Z and Q_Z' the after numerical simulation and model calculation.

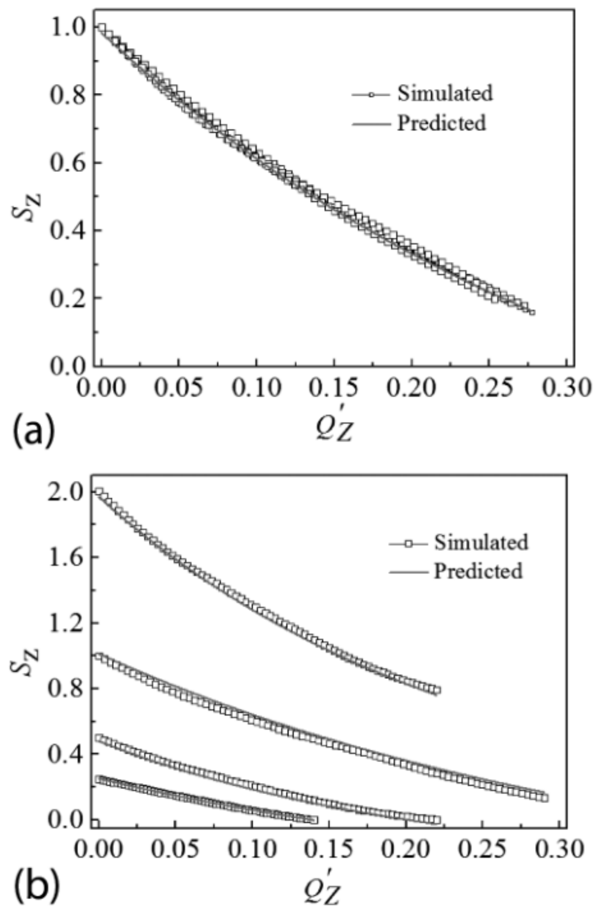


Figure 9: Comparison between the predicted and simulated void aspect ratios: a) different positions, b) different initial shapes

Figure 9a indicates voids at different positions and **Figure 9b** indicates voids with different initial shapes. As shown in **Figure 9**, it can be seen that the prediction results are consistent with the simulation results. The results show that the model established in this study can accurately determine the closure of voids. Compared with the existing void-closure criterion model, the new model is more suitable for void closure in a multi-pass deformation.

5 CONCLUSIONS

(1) The influence of the initial void size on the void-closure law can be ignored when the void size is small compared with the workpiece. However, the initial shape and position of a void have a great influence on the void closure. The effects of the initial void position on the evolution of void shape result from the variation in the stress and strain around the void.

(2) A void-shape coefficient is proposed for evaluating the change in the void shape. Meanwhile, a new void-shape evaluation parameter is established to predict the shape coefficient, which is defined as a function of the stress deviator, effective strain and effective stress. Moreover, the one-to-one relationship between the shape evaluation parameter and shape coefficient is established and the relationship can be represented as a first-order exponential function.

(3) The void evolution law is the same for both the experiment and the simulation, indicating that FE models can give an accurate estimation of void evolution. Finally, a void-closure decision model is established and the model calculation results are consistent with the simulation results.

Acknowledgments

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