Forging preform design for simple shapes

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ABSTRACT: Material flow in the forging process has crucial effect on the final product quality. One of the most important factors that dominate this flow is optimum preform design. In this study by applying the minimum potential energy principle and considering volume consistency and maximum homogeneity of deformation conditions, it has been tried to predict preforms for non-proportional loading condition. In this way, based on proposed formulation, an inverse FEM code has been developed for 3D preform design prediction. The simulation results have been examined through experimental testing of a conical and cylindrical lead samples and the comparisons of data prove the ability of the developed technique.

Key words: preform design, inverse FEM, forging

1 INTRODUCTION

One of the most important steps of the forging process is preform (or blockers) design for succeeding proper metal distribution. With proper preform design, defect-free metal flow and complete die fill can be achieved in the final forging operation and metal losses into flash can be minimized [1]. Also in complicated forging product usually, two or more preform design stages are needed. In the past, preform shapes were generally determined through the trial and error, during which various combination of process parameters were tried out experimentally. Today with development of computers and numerical methods, applications of computer simulations have increased in order to predict preform in metal forming processes. Among various numerical methods, FEM is a prominent one that can be divided into forward and backward techniques. In the forward simulation, shape of initial preform is guessed based on the designer's experience and physical modelling tests. Then by applying proper boundary conditions closed to really, solutions are searched forwardly. Finally, by change of the preform shape, possible defects are minimized. These steps are continued to achieve optimum preform design [2-3].

In the backward simulation, by using final shape, boundary conditions and some kind of optimization criterion, it has been tried to traverse deformation path inversely in order to obtain optimum preform. Also the preform can be modified by forward simulation. Because of the efficiency of backward simulation, some methods have been developed based on the backward procedure to acquire optimum preform design. These methods are Backward tracing method [4], shape complexity factor [5] and ideal forming theory [2]. In this paper, brief discussions of forging perform design formulation based on the minimum potential energy principle and maximum homogeneity of deformation will be presented. On the basis of the derived formulation a program is developed and used to predict required initial simple shape for non-proportional loading condition. Finally, numerical results of developed program will be compared with experimental results for simple shapes.

2 THEORY AND FORMULATION

Of the all geometrically possible shapes that a body can assume, true one should minimize the minimum potential energy, in the stable equilibrium condition of the body. This will be satisfied when total potential energy (W) acquirers a minimum value [6]. In preform design, after part discretization and surface traction approximation by point forces, since final configurations x are acquainted, with assumption of knowing deformation path, the total potential energy becomes just a function of initial configuration X. Therefore its variation can be written as equation (1).

$$\delta W_{total} = \frac{\partial W_{total}}{\partial X_1}\delta X_1 + \frac{\partial W_{total}}{\partial X_2}\delta X_2 + \frac{\partial W_{total}}{\partial X_3}\delta X_3 = 0 \qquad (1)$$

Where ∂X_i are partial differential of initial point position. The independency between X variable in the above equation results in nullifying each partial derivative, as follow:

$$\frac{\partial W_{total}}{\partial X_i} = 0 \quad i = 1,3 \qquad (2)$$

W_{total} is defined as sum of the plastic energy (W_{st}) and the external energy (W_{ex}):

$$W_{total} = W_{st} + W_{ex} \qquad (3)$$

According to equations (2) and (3), we have:

$$f_i = \frac{\partial W_{st}}{\partial X_i} \qquad (4)$$

Knowing external forces (f_i) and by solving the above system of equations, preform coordinates will be obtained. Based on the Ideal forming theory f_i are equal to zero when the total plastic energy is extremum. Thus all external forces to nodes are normal to surface and there is no tangential friction force. In fact this condition is satisfied just in final forged specimen. So in the first solution f_i are considered to be equal to zero:

$$\frac{\partial W_{st}}{\partial X_i} = 0 \qquad (5)$$

For solving the non-linear equation (5) Newton Raphson method is used [2].

$$\frac{\partial W_{st}}{\partial X_i} = -\sum_{i=1,3} \frac{\partial^2 W_{st}}{\partial X_i \partial X_j}\delta X_j \qquad (6)$$

where:

$$\frac{\partial^2 W_{st}}{\partial X_i \partial X_j} = -\int \left[\bar{\sigma}(\bar{\varepsilon},\dot{\varepsilon})\frac{\partial^2 \bar{\varepsilon}}{\partial X_i \partial X_j} + \left(\frac{\partial \bar{\sigma}}{\partial \bar{\varepsilon}} + {}^1/_t \frac{\partial \bar{\sigma}}{\partial \dot{\varepsilon}}\right)\frac{\partial \bar{\varepsilon}}{\partial X_i}\frac{\partial \bar{\varepsilon}}{\partial X_j}\right] dV_0 \qquad (7)$$

Because, in present FEM, tetrahedral elements with 4 nodes are applied, i varies between 1 and 12. Since existence of friction in metal forming is inevitable, after preliminary calculation of preform without considering of friction, frictional effects are evaluated using derivative of W respect to final configuration X, as follow:

$$\frac{\partial W_{st}}{\partial x} \cdot n = f_n \qquad (8)$$

$$f_\mu = \mu \times f_n \qquad (9)$$

Where f, f_μ and μ are the applied external forces on the initial configuration, friction forces and friction coefficient respectively. f_n are normal components of f. In second loop of solution f_i in equation (4) is replaced by f_μ and corresponding f_n then inverse solution is searched. These iterations are carried out until the obtained performs from two sequential iteration differ only through very small value.

For establishing the relationships between initial and final coordinates and enforcing the deformation path dependency, deformation gradient tensors are employed [7]:

$$F_{ij} = \begin{bmatrix} \frac{\partial x_1}{\partial X_1} & \frac{\partial x_1}{\partial X_2} & \frac{\partial x_1}{\partial X_3} \\ \frac{\partial x_2}{\partial X_1} & \frac{\partial x_2}{\partial X_2} & \frac{\partial x_2}{\partial X_3} \\ \frac{\partial x_3}{\partial X_1} & \frac{\partial x_3}{\partial X_2} & \frac{\partial x_3}{\partial X_3} \end{bmatrix} \qquad (10)$$

Using tetrahedral elements and assumption of linear relation between x and X leads to constancy of deformation gradient tensor in each step.

$$x_{ij} = F_{j1}X_{i1} + F_{j2}X_{i2} + F_{j3}X_{i3} + c_i \quad i = 1,4 \;\&\; j = 1,3 \qquad (11)$$

According to equation (11), F is function of x and X. Velocity gradient can be calculated using equation (12).

$$L_{ij} = \dot{F}_{im}F^{-1}_{mj} \qquad (12)$$

Where L_{ij}, $\dot{F}_{im}$ are spatial gradients of the velocity and time derivative of F_{ij} respectively. In this formulation, time independency of deformation is assumed and all of the time steps are considered to be the same [8].

$$\dot{F} = \frac{\Delta F}{\Delta t} = \Delta F \qquad (13)$$

$$F_{(\Delta t)} = I + \dot{F}\Delta t = I + \Delta F \qquad (14)$$

Using equations (12), (13) and (14), equation (15) is obtained:

$$L_{ij} = (F - I)_{im}F^{-1}_{mj} \qquad (15)$$

L is written as sum of symmetric tensor D, called the rate of deformation tensor and a skew-symmetric tensor W, called the spin tensor [7]. It is assumed that relation between strain and the rate of deformation tensor can be expressed as:

$$D_{ij} = \frac{d\varepsilon_{ij}}{dt} \quad (16)$$

$d\varepsilon_{ij}$ is the increment of strain. Then by considering $\Delta t = 1$, equation (17) is derived.

$$\Delta\varepsilon_{ij} \approx D_{ij} \quad (17)$$

In a large deformation, principal axes of rate of deformation tensors rotate during the deformation. Therefore, total strain cannot be obtained directly. However, deformation should be calculated in several steps and in each step, rate of spatial deformation tensor D should be converted into rate of material deformation tensor D^m using rotation tensor R. So principal axes of D^m tensor are constant during the all deformation and in this way, total rotationless strain is obtained [7-9].
Therefore partial derivatives of strain with respect to initial X can be obtained.

$$\frac{\partial\bar{\varepsilon}}{\partial X_i} = \sum_{\propto=1,6} \frac{\partial\bar{\varepsilon}}{\partial\varepsilon_\propto} \times \frac{\partial\varepsilon_\propto}{\partial X_i} \quad (18)$$

$$\frac{\partial^2\bar{\varepsilon}}{\partial X_i \partial X_j} = \frac{\partial\left(\frac{\partial\bar{\varepsilon}}{\partial\varepsilon_i} \times \frac{\partial\varepsilon}{\partial X_i}\right)}{\partial X_j} = \sum_{\propto=1,6} \sum_{\beta=1,6} \frac{\partial^2\bar{\varepsilon}}{\partial\varepsilon_\alpha \partial\varepsilon_\beta} \times \frac{\partial\varepsilon_\alpha}{\partial X_i} \times \frac{\partial\varepsilon_\beta}{\partial X_j} + \sum_{\alpha=1,6} \frac{\partial\bar{\varepsilon}}{\partial\varepsilon_\alpha} \times \frac{\partial^2\varepsilon_\alpha}{\partial X_i \partial X_j} \quad (19)$$

Where $\bar{\varepsilon}$ is the effective strain, X is initial configuration tensor consisted of 12 components (4 nodes in three directions) and ε is a symmetry tensor with 9 components that is converted to tensor with 6 components consisted of three normal and three shear.

3 MATERAIL BEHAVIOR:

It is assumed that the hardening behaviour of used material can be expressed using swift relation [9].

$$\sigma = H(\varepsilon_s + \varepsilon)^n \quad (20)$$

Where ε_s and n are previously stored strain and strain-hardening power coefficient respectively.

4 DEFORMATION PATH CONDITIONS:

By ignoring the elastic deformation, volume constancy can be assumed during metal forming processes (equation (21)).

$$det(F) = \frac{\rho_2}{\rho_1} = 1 \quad (21)$$

Where $\rho_1$is initial density and $\rho_2$is final density in each step, then equation (22) can be derived by considering volume constancy and applying it through penalty function. C_1 is penalty coefficient.

$$K_1 = C_1 \times \left[\frac{\partial^2((det(F) - 1)^2)}{\partial X_i \partial X_j}\right] \quad (22)$$

Because of the existence of friction in metal forming processes, it is almost impossible to attain perfect homogenous strain. Therefore, by imposing a penalty function, for attaining maximum homogeneity of deformation in formulation through minimizing the difference of current strain ε and average effective strain ε_{avrg} , it has been tried to find the best perform. In this way, average effective strain (ε_{avrg}) is calculated from initial iteration and then for subsequence one, nodes are displaced in the path that effective strains of elements prone to that average in prior iteration. Such assumption leads to equation (23). C_2 is penalty coefficient.

$$K_2 = C_2 \times \left[\frac{\partial}{\partial X_i}\left(\frac{\partial\left(\left(\bar{\varepsilon} - \varepsilon_{avrg}\right)^2\right)}{\partial X_j}\right)\right] \quad (23)$$

Finally total stiffness matrix (K_T), for each element is obtained:

$$K_T = K + K_1 + K_2 \quad (24)$$

Where K, K_1 and K_2 are stiffness matrix, volume constancy matrix and homogeneous strain matrix respectively.

5 RESULT AND DISCUSSION

In the following, the results of the presented formulation that is converted into an inverse FEM for calculation of initial shapes for simple forgings will be presented. Calculated results will be compared with experimental outcomes. In the calculations, the effects of friction are neglected.
In calculations and experiments, cylindrical and a conical lead specimen are considered. In the experiments, specimens are subjected to cold upsetting and the effect of friction is reduced to its minimum possible value by using of PTFE and oil lubricants.
The cylindrical specimens before and after upsetting test are shown in figure 1. While figure 2 presents the initial and compressed conical specimens.

Fig. 1. Cylindrical specimen, (a) preform specimen, (b) forged specimen

Fig. 2. Conical specimen, (a) preform specimen, (b forged specimen.

Predicted initial shapes for cylindrical and conical specimens are shown in figure 3 and figure 4 respectively.

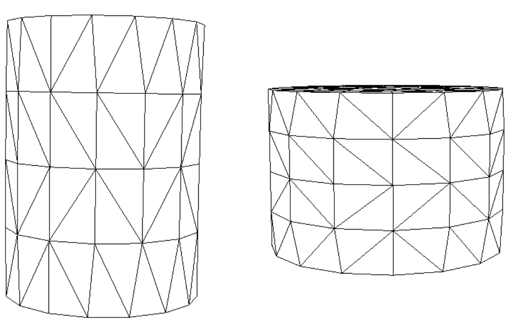

Fig. 3. Predicted FEM results from cylindrical specimen, (a) preform specimen, (b) forged specimen

Comparison of numerical result and experimental work indicates to the high ability of the developed program for prediction of initial shape for simple shapes.

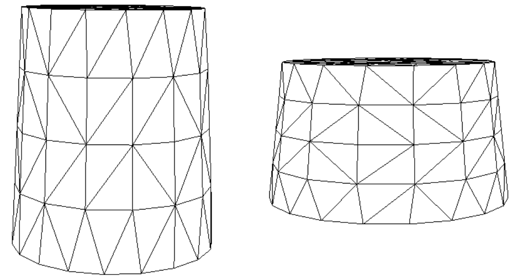

Fig. 4. Predicted FEM results from conical specimen, (a) preform specimen, (b) forged specimen

6 CONCLUSIONS

A formulation based on the minimum potential energy principle and maximum homogeneity of deformation has been introduced. The main goal of the presented formulation is an attempt for predicting of preform design for complicate shapes which deformations are path dependent and non-proportional. As a first step, application of this formulation for simple shapes lead to satisfactory results.

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