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Preform die shape design for uniformity of deformation in forging based on preform sensitivity analysis

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Abstract

A finite element based sensitivity analysis method for preform die shape design in metal forging by controlling the deformation uniformity is developed in this paper. The optimization problem is to minimize the effective strain variation within the final forging through optimizing the preform die shape, so that a more uniform deformation within the final forging can be obtained. The preform die shapes are presented by cubic B-spline curves. The control points of the B-spline curves are used as the design variables. The objective function expressed by the effective strain variation is constructed. For two-dimensional forging problems, the sensitivity equations of the objective function, elemental volume, elemental effective strain-rate and the elemental strain-rate with respect to the design variables are developed. The optimization procedures of the method are given. The preform die shapes of two H-shaped forging processes in axisymmetric and plane-strain deformation are designed using the method.
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Keywords: Metal forging; Preform design; Sensitivity analysis; Uniform deformation; Strain variance

1. Introduction

Metal forging technology plays an important role in manufacturing industry. Most forging processes are complex. Two or more forging stages are usually used to realize a sound final forging product. Die design, especially preform die design, is an important and also a difficult part in forging process design. With the introduction of the finite element method (FEM) and the development of computer technology, computer aided simulation of manufacturing processes became available and has developed very quickly. However, the current simulation is an error-and-trial method in searching for an optimal design because the initial process and die designs still depend on empirical guidelines or the experiences of designers. The optimization of a metal forming process as a multi-discipline system becomes more important due to the increasing requirement of high quality products. The optimization of metal forming processes has been researched only recently.

Badrinarayanan and Zabaras [1,2] developed a sensitivity analysis method for the large deformation of a hyper-elastic visco-plastic solid that can be applied to preform design problems in metal forming. This method designs the preform or intermediate shape of the workpiece instead of the preform dies. The method was applied to an axisymmetric disk upsetting problem where the preform was designed such that a final forging with a minimum barreling effect was achieved. However, the axisymmetric preform shape had a concave lateral shape that is difficult to forge in practical production.

Fourment and Chenot [3,4] described a method to design preform shapes. The disparity between the achieved and required parts is used as the objective function to be minimized. The shapes are discretized using spline functions. The design variables of optimization problem are the displacements of selected characteristic points of the spline in the normal direction. The gradients are calculated analytically where the friction on the tool–workpiece interface is considered as an exponential function of the sliding velocity. The shape optimizations for both one- and two-stage forging processes were performed using this method.

Zhao et al. [5–8] described a method to design the preform die shapes instead of the preform shapes. The preform die shapes are represented using piecewise cubic B-spline functions. The objective is to reduce the zone where the actual final forging shape and the desired final forging shape do not coincide. The coordinates of B-spline control points are considered as the design variables for the sensitivity analysis and optimization problem. By minimizing the objective function, the obtained optimal preform die shape can realize the net-shape manufacturing of the final forging. Two kinds of axisymmetric forgings with net-shape manufacturing were performed using this method.

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Chung and Hwang [9] presented an approach to optimal design in non-steady-state metal forming. In this approach, the optimal design problem is formulated on the basis of an integrated thermo-mechanical finite element process model so as to cover diverse objective functions and design variables, and a derivative-based approach is adopted for conducting optimization. The process model, the formulation for process optimization design, the schemes for the evaluation of the design sensitivity and an iterative procedure for optimization are described. The validity of the schemes for the evaluation of the design sensitivity is examined by performing several numerical tests. The capability of the approach to deal with diverse process parameters and objective functions is demonstrated through applications to some selected process design problems.

Joun and Hwang [10] conducted the optimization of the die shapes in terms of the forming load. Various shapes such as polygons, T-shapes and half round–half ellipse shapes of extrusion were considered. Through optimization, the forming load was decreased remarkably. At the same time, more homogeneity of the effective strain distribution in the part was obtained.

Renping [11] presented a new approach to optimal design using an improved micro-genetic algorithm, and set up a prototype system for computer aided preform design optimization based on the design-oriented function integration of CAD/CAE. Using this system, both two-dimensional and three-dimensional metal forming processes were optimized.

The above literature mainly focused on the shape optimization of forging processes. However, a metal forming process is a complex manufacturing process related to many parameters and performance measures. The perfect forging usually contains the following characteristics: (1) the shape of the forging satisfies the design desire very well; (2) the material used in forging is least; (3) there is no defect in the forging and the streamline and composition of the forging are perfect; (4) the deformation force or energy is least; (5) the deformation with the forging is as uniform as possible.

Therefore, the objective used to optimize the actual forging process should be multiple instead of single. The multiple objective function should include the forging shape, the deformation uniformity, the deformation force or energy and so on. However, most of the recent research works focus on a single objective function and mainly on the shape optimization or control. Therefore, other single objectives or measures are also needed to be studied in advance in order to be able to carry out the multiple objective optimization of metal forging processes.

Due to the limitation of the material and the working requirements of some products, extensively large deformation of local zones in forging should be avoided. Thus deformation control is often desired in order to obtain a deformation as uniform as possible.

Cheng et al. [12] tackled the problem of forging process design by taking the velocity and the initial die temperature as optimization parameters in order to control the effective strain-rate and temperature of the process. The control procedure is based on a state space model. Huang and Kobayashi [13] designed preform shapes of an axisymmetric disk forging process using finite element based backward simulation. The design purpose is to form a uniformly deformed flat disk without lateral barreling using designed preform shapes. Using the direct differentiation method, a plane-strain flashless forging process with a C-shaped cross-section was carried out by Chung and Hwang [9].

In this paper, a new sensitivity analysis method for preform die shape design in metal forging was developed by means of controlling the deformation uniformity in the final forging. The optimization goal is to minimize the effective strain variation within the final forging so that a more uniform deformation can be obtained. In this optimization method, the preform die shapes are presented by cubic B-spline curves. The control points of the B-spline curves are used as the design variables. The sensitivity of the objective function, the elemental effective strain and the strain-rates with respect to the design variables were developed. Using this method, the preform die shape of an axisymmetric H-shaped forging process was designed.

2. Objective function and design variables

The effective strain variation of the deformed workpiece, as a good measure of deformation uniformity, is used as the objective function for the optimization problem in this paper. For the FEM, the effective strain variation is defined as the volume-weighted square summation of the difference between the effective strain of an arbitrary element and the average effective strain over all elements in the entire domain of the deformed body. An elemental volume weighting is included to account for the various element sizes after deformation. Therefore, the optimization problem is to minimize the objective function through optimizing the preform die shapes so as to obtain a more uniformly deformed forging.

According to the above definition, the objective function can be described as follows:

$$\psi = \frac{\sum_{i=1}^{N} V_i(\bar{\varepsilon}_i - \bar{\varepsilon}_{\mathrm{av}})^2}{N} \tag{1}$$

where ψ is the objective function or effective strain variation. V_i the volume of the ith element.$\bar{\varepsilon}_i$ the effective strain of an arbitrary element. $\bar{\varepsilon}_{\mathrm{av}} = 1/N\sum_{i=1}^{N}\bar{\varepsilon}_i$ is the average effective strain over all elements in the entire domain of the deformed body. N is the total number of elements.

The smaller is the objective function ψ, the more uniform is the forging's deformation. Therefore, the optimization problem is also stated as defining a preform operation that will minimize the objective function.

The preform die shapes for a two-dimensional forging problem are presented using cubic B-spline functions. The B-spline shapes are controlled through varying the coefficients or the coordinates of the control points. For each

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