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Studies on optimization of metal forming processes using sensitivity analysis methods

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Abstract

In this paper, an optimization method for metal forming processes, especially for forging process designs using finite element based sensitivity analysis method is briefly introduced. On the basis of the authors' previous studies, this paper gives further improvements concerning several critical techniques of the optimization method. An approach for improving the computational efficiency is introduced and demonstrated. After introducing the optimization method of multi-stage forming processes, the paper presents an optimization method for single stage forming processes. The initial billet dimension is optimized for achieving a net-shape final forging. Besides, the paper also gives a method for dealing with the velocity sensitivity boundary conditions for both moving upper dies and stationary lower dies. Using this boundary condition treatment method, not only can we optimize the upper die shape but also the lower die shape, even if both of the dies have different shapes. The paper also extends the optimization to the more complex forming processes with multiple cavities.

Keywords: Preform design; Optimization; Sensitivity analysis; Forging process

1. Introduction

Net-shape forging processes have been the goal pursued by the manufacturing industry. The various forging shapes usually have very complex geometrical shapes. Net-shape forging to a large extent depends on the exactness of the die design, especially the preform shape design. Therefore, the process or sequence design for forging processes is the main focus for the forging quality control, material saving and reduction of manufacturing cost. It is known that the forging process design for a given forged part is non-unique. In these different forging process designs, choosing an optimal process is the designer's desire. The metal forming process is characterized by forming equipment, process geometries and process conditions. Making proper selections regarding various process parameters is the main problem that a process designer is concerned with.

However, in most cases, a designer will mainly work with the die shapes and perhaps with the number of stages as well as intermediate die shapes for a multi-stage operation. Consequently, die shape optimal design is one of the most important aspects in forming process design since the rest of the process variables may often serve as the constraints imposed by the customers and manufacturers' need. The research on integration of optimization methods, finite element simulation techniques, and forming process and die designs becomes the first choice for studying the optimization methodology of metal forming.

Optimization of the forming process can be performed on the basis of reliable modeling capability available now. Rigid–plastic and rigid–viscoplastic finite element methods developed by Kobayashi [1,2] have provided an effective numerical method and been applied to process simulations for various metal forming processes. Recent efforts have been made to develop a more efficient methodology for process optimal design.

For the preform design, the methodology presented in [3] starts with the final state of the product and traces backward the deformation process by the finite element method. The method was also extended to non-isothermal deformation and applied to many non-steady forming processes [4–7]. The backward tracing method is not an optimization method since the multiple deformation processes and preform shapes could be obtained depending on the different boundary conditions during backward tracing which must be chosen before by designers.

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Recent research mainly focuses on the direct differentiation of equilibrium equations and optimal metal forging process design. This method is a derivative based approach in which the derivatives of the state variables with respect to the design variables are calculated by solving the matrix equations resulting from the differential form of the perturbed finite element equations. The values of these derivatives are then used for the evaluation of the current design sensitivity based on which design iteration is performed. Kusak and Thompson [8] applied the method for die shape optimal design in steady state forming. Later, the method was applied to optimization of the preform shapes in non-steady forming by Badrinarayanan and Zabaras [9–11] and preform die shapes by Chenot and coworkers [12,13]. In steady forming problems, the design sensitivity may be evaluated with better computational efficiency if the adjoint variable method is employed [14,15]. The direct differentiation method seems to be the only feasible derivative based approach, for non-steady forming problems.

Zhao et al. [16–18] also developed a sensitivity analysis based optimization method for forging preform optimal design using rigid–plastic and rigid–viscoplastic finite element formulations and applied it to various forging process designs. Grandhi and co-workers [19,20] extended this method to a thermo-mechanically coupled analysis. Numerous iterations of coupled thermo-mechanical analysis are performed to determine an optimum preform shape based on a given criterion of minimizing the objective function on effective strain variance within the final forging. Also, Gao and Grandhi [21] extended the sensitivity analysis based optimization method to optimal microstructure development during the forging process. The objective function was to minimize a function describing the variance of mean grain size and the average value of mean grain size in the whole final product. Two design variables including state parameter (initial shape of billet) and process parameter (die velocity) were considered. Doltsinis and Rodic [22] gave a comprehensive review of computational concepts applicable to the optimization of process design in metal forming. Srikanth and Zabaras [23] also reviewed the sensitivity analysis method and the applications in metal forming process design.

After reviewing the above literature, it can be found that the sensitivity analysis based design method still has some application issues to be addressed. (a) For a complex die's cavity, there are a relatively large number of design variables. Therefore, the improvement of the computational efficiency is a critical point for the wider industrial application of the method. (b) All of the works done before focus on the multi-stage forging processes, especially two-stage forging processes, but there are also a number of forging processes performed by single stage forging processes. In single stage forging processes, the initial billet dimension (ratio of height to diameter/width) design for a net-shape final forging is the main optimization goal. Since the initial billet usually has a standard dimension, the upsetting process is usually needed for a single stage forging process if the initial billet's diameter or width does not match the standard one. Therefore, it is necessary to optimize the upsetting reduction, that is, the ratio of height to diameter/width of the upset. (c) Most applications in optimal process design were applied to one-die (the upper die) shape optimal design. It is necessary to impose the nodal velocity sensitivity condition on a workpiece boundary in contact with the stationary lower die so both the upper and lower die shapes can be optimized simultaneously. (d) The die shapes designed optimally before were relatively simple forming processes, such as simple upsetting and H-shape forging. Complex forging processes with multiple cavities have not yet been optimized until now.

This paper extends the research works to the above issues and presents the methods for dealing with the above problems. The method is applied to complex forging processes with multiple cavities. The boundary condition is improved so both the upper and lower die can be optimized even if they have different shapes. An approach for improving the computational efficiency is given. The guidelines for selecting the initial guess of preform die shape are also proposed. An approach for the optimal initial billet design is proposed, and the effectiveness of the methods is demonstrated by using several optimization applications.

2. Sensitivity analysis based optimization method

To realize a net-shape forging process, the preform die shape for multi-stage forging process and the billet dimension (ratio of height to diameter/width) are the main design parameters. For a two-dimensional metal forming processes, suppose that the ideal preform die shape design achieves a net-shape forging named as the *desired* final forging shape. The final forging shape achieved using an arbitrary preform die shape is named as the actually *achieved* shape that may not be net-shaped. The shape design objective is to minimize the preform die shape to make the achieved final forging shape approach the desired one as much as possible. It is indicated that process and sequence designs are ideal if these two shapes coincide. But this does not usually occur. The area ψ of the zone where the two shapes do not coincide is used as the objective function for optimization. When ψ approaches zero, the achieved shape will be consistent with the desired shape. Therefore, the optimization problem is to define a preforming operation that will minimize the objective function ψ. The shapes of the preform dies are represented using cubic B-spline function [24]. The coordinates of the control points define the B-spline shapes (x_i, y_i) which are used as the design variables p_l. So the optimization problem can be expressed as

$$\text{minimize } \psi = \psi(p_l), \quad p_l = (x_1, y_1, x_2, y_2, \ldots, x_K, y_K) \tag{1}$$

where K is the total number of the control points of B-spline curves.