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Multiobjective robust optimization method for drawbead design in sheet metal forming

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ABSTRACT

It is recognized that fracture and wrinkling in sheet metal forming can be eliminated via an appropriate drawbead design. Although deterministic multiobjective optimization algorithms and finite element analysis (FEA) have been applied in this respect to improve formability and shorten design cycle, the design could become less meaningful or even unacceptable when considering practical variation in design variables and noises of system parameters. To tackle this problem, we present a multiobjective robust optimization methodology to address the effects of parametric uncertainties on drawbead design, where the six sigma principle is adopted to measure the variations, a dual response surface method is used to construct surrogate model and a multiobjective particle swarm optimization is developed to generate robust Pareto solutions. In this paper, the procedure of drawbead design is divided into two stages: firstly, equivalent drawbead restraining forces (DBRF) are obtained by developing a multiobjective robust particle swarm optimization, and secondly the DBRF model is integrated into a single-objective particle swarm optimization (PSO) to optimize geometric parameters of drawbead. The optimal design showed a good agreement with the physical drawbead geometry and remarkably improve the formability and robust. Thus, the presented method provides an effective solution to geometric design of drawbead for improving product quality.

1. Introduction

With increasing requirements in functions and aesthetics, highly sophisticated designs of sheet metal workpieces have made its manufacturability more and more demanding. Design of sheet metal forming process has become one of the major concerns in manufacturing engineering, which determines quality and cost of product. Conventional process design is largely based upon experience available by incorporating with a trial and error procedure. As a result, the development of a new die often requires numerous prototype tests, leading to a long design cycle and significant cost. Development of advanced computational technology, represented by finite element analysis (FEA), has been changing such philosophy, which enables us to precisely predict a forming process and detect such defects as wrinkling and fracture in a design stage, thereby reducing design and prototyping costs to a considerable extent. In this respect, Makinouchi [1] adopted finite element method (FEM) to predict the defects of fracture, wrinkling and springback of the sheet successfully. Panthi et al. [2] utilized FEM to analyze springback in sheet metal bending process. Dong and Lin [3] explored the formability of a Santana 200 exterior panel and achieved well-correlated results with the experiment. Chen et al. [4] investigated the effects of blank holder gap and shell element type on the formability of a washing-trough. It was found that the extent of wrinkling in the flange region of the blank became severer with the increase in the blank holder and thus an optimal blank holder gap was recommended for the given process parameters. Nevertheless, these abovementioned practical industrial applications appeared to usually employ FEA in an iterative fashion, where the improvement of forming process still somewhat relied on designer's experience. To attain a satisfactory result, many FEA runs may be needed to manually alter the design model parameters and then re-evaluate the results, whereas this by no means guarantees a global optimum. In this sense, the capacity of computer aided engineering (CAE) may have not be fully taken up yet. Therefore, some research attempts have been made on how to transform FEA from a passive verification tool to a more active design tool in the sheet metal forming process recently.

Computational optimization signifies a more effective tool by seeking for an optimal design systematically, which helps engineers to attain the best possible formability of sheet metal production. For example, Ohata et al. [5] incorporated the sweeping simplex method with FEA to optimize the punch travel and

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forming stages for obtaining a uniform thickness distribution. Naceur et al. [6] employed a mathematical programming algorithm in the inverse procedure to optimize the restraining forces and then to design the drawbead. Azaouzi et al. [7] developed an automatic design procedure within commercial FEA program and adopted a Heuristic Optimization Algorithm (HOA) for the blank shape design of high precision metallic parts in a special stamping process. Guo et al. [8] combined an inverse procedure with a sequential quadratic programming (SQP) technique to optimize the blank shape. Although these algorithms that directly incorporate with sheet metal forming FEA are capable of optimizing the forming processes, the implicit relationship and the great complexity of sensitivity analysis in a context of material and geometric nonlinearities as well as frictional contact dynamics could largely compromises the feasibility and precision in practical applications of prevalent mathematical programming techniques [9].

As an effective alternative, such surrogate or metamodel techniques as response surface method (RSM) have been exhaustively adopted in sheet metal forming optimization. In this regard, Chengzhi et al. [10] presented a new method integrating the finite element method with adaptive response surface method (ARSM) to determine an optimum blank holder force during box deep drawing process. Naceur et al. [11] developed a new RSM involving Moving Least Squares regression models and pattern search optimization for the rapid design of aluminum sheet metal forming parameters. Kok and Stander [12] adopted successive response surface method (SRSM) to optimize the preforming die shape in terms of the blank weight, thereby minimizing the difference in workpiece thickness. Kayabasi and Ekici [13] integrated FEA, RSM and genetic algorithm together to find the most appropriate values of forming process parameters. Huang et al. [14] used RSM to optimize the intermediate tool surfaces in the multi-step sheet metal stamping process to obtain improved quality of a final product. Ohata et al. [15] employed RSM to optimize the annealing temperature and time for thickness uniformity of stamping part. Hu et al. [16] adopted an adaptive RSM to design blank shape and blank hold forces for thickness uniformity, in which a significant improvement was made. Breitkopf et al. [17] developed a new RSM involving Moving Least Squares regression models and pattern search algorithms for achieving uniform thickness, where a one step solver is used in optimization procedure and the incremental solver for final verification. Jansson et al. [18] employed RSM to optimize draw bead restraining force, whose combination with a space mapping technique largely enhanced computing efficiency. Later, they further improved this by using an iterative RSM [19]. Tang et al. [20] also addressed the design of restraining force for minimizing the thickness difference subject to the constraints of failure criteria, where the one step method was adopted in constructing response functions. Jakumeit et al. [21] utilized Kriging model to optimize blank holder force, whose objective was to form fracture and wrinkling free workpiece with an acceptable thinning and springback.

These above mentioned sheet metal forming studies are restricted on deterministic optimization, where it is assumed that all the design variables and parameters involved are certain [22]. It is noted that the optimal solutions are often pushed to limits of design constraints, leaving no room for tolerances/uncertainties in modeling, simulation and/or manufacturing capabilities available. Practically, all real-life sheet metal forming are indeed nondeterministic, which involve some degree of uncertainties in lubricative situation, material properties, geometries, manufacturing precision and actual usage, etc. Consequently, nondeterministic optimization problems solved by deterministic optimization algorithms may result in unreliable designs. In order to take into account various uncertainties in sheet metal forming process, Li et al. [23–25] presented a CAE-based six sigma robust optimization procedure, which integrated probability optimization, six sigma criterion and robust design concept. Demir et al. [26] proposed an effective design strategy, which integrates FEA, approximate model, numerical optimization algorithm and probabilistic design method (Monte Carlo simulation) into an automated design tool to design sheet metal die for reducing stress and increase fatigue life of sheet metal die. However, these algorithms involve only single-objective function. Sheet metal forming is typically characterized by a number of quality and/or performance indices, for example, cracking, wrinkling and springback [27], some of which could conflict with each other. Despite its significant practical value, the development of multiobjective robust optimization methods for sheet metal forming process has been under-studied.

In sheet metal forming process, the initial blank (thickness, contour and surface), process parameters (boundary conditions, holding forces, lubrication conditions, drawbead types and positions, etc.) and the material properties (yield stress, hardening, anisotropy, etc.) can also affect the forming quality of workpiece [19]. In these parameters, the drawbead is one of the most important parameters to control the material flow and final quality. Very heavy restraining forces can prevent the sheet from drawing-in but may cause fracture, whereas insufficient forces may lead to wrinkling (Fig. 1). Therefore, drawbead should be optimized in die design. It is noted that there has been some published work available about the optimization design of drawbead. For example, Wang et al. [28] developed response surface methodology based on a so-called intelligent sampling to optimize drawbead. Naceur et al. [29] integrated an inverse approach, BFGS algorithm and analytical sensitivity analysis into optimization of restraining forces. However, these studies are mainly optimizing drawbead restraining forces with single-objective and without considering fluctuations of variables and design parameters. In practice, a series of modifications on the drawbead positions and dimensions are necessary in order to adjust these restraining forces. Furthermore, sheet metal forming process is essentially a multiobjective optimization problem, in which the requirements of avoiding fracture and wrinkling are often contradictory from each other. Moreover, variations of design variables and system parameters affect the formability. Under the circumstance, the effectiveness of a single and/or deterministic design optimization may be problematical.

This paper aims to address two abovementioned major issues of (1) multicriteria and (2) nondeterministic design for sheeting metal forming process. An effective multiobjective robust optimization method will be developed and applied to a real-life drawbead design based on dual response surface models. To deal with this problem, the design procedure is divided into two stages herein: firstly, the optimal equivalent drawbead restraining forces are obtained through a multiobjective robust optimization; and secondly, the equivalent restraining force model is integrated into a particle swarm optimization to optimize the geometric parameters of drawbead.

2. Methods and materials

To develop multiobjective robust optimization for sheet metal forming, we firstly establish the objective functions with respect to the drawbead forces by using a dual response surface approach, one for mean and another for standard deviation in each objective. Following this, a multiobjective particle swarm optimization procedure is applied to optimize the drawbead forces. Then, a single-objective particle swarm optimization is carried out to inversely determine the geometric parameters of drawbead for generating the desirable optimal drawbead forces. This section will introduce these relevant methods.