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Structural design of aircraft skin stretch-forming die using topology optimization

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ABSTRACT

This paper demonstrates a topology optimization method for the large scale stretch-forming die design. The implementation of the topology optimization depends on the surface loads obtained from the numerical simulation of the sheet metal stretch-forming process. Typically, the design variables are defined based on a linear interpolation to generate directional structures satisfying the manufacturing requirement. To further validate the design procedure, mathematical derivations have proved that the design sensitivities are strictly continuous. More explanations and numerical tests are presented to show the variation of the surface loads versus the stiffness of the die.

A stretch-forming die design example is solved on account of gravity and surface loads. The final solution is compared with the traditional design. The numerical results have shown that the topology design can improve the stiffness and strength of the stretch-forming die significantly.

1. Introduction

In the past two decades, the techniques of topology optimization were developed to generate reasonable structural configurations by re-distributing the material in the design domains with the prescribed loads and boundary conditions [1–4]. Till now, one of the most challenging works involved in the research of topology optimization is the industrial application, where complex practical load cases have to be taken into account and different manufacturing constraints have to be satisfied.

The skin stretch forming die discussed in this paper is one of the key equipments of aircraft manufacturing. It basically consists of a certain stretch working surface of specific form and the supporting structure that interconnects the working surface for its integrity. Nowadays, the development of large cargo and passenger aircraft has brought a series of new challenges. On the one hand, the size and weight of the stretch-forming dies increase significantly. As the traditional die is always designed extremely stiff, it results in excessive costs as well as difficulties in transportation and installation. On the other hand, the structural design of the die must ensure the accuracy of the stretch-forming process. As a result, the light-weight design of the large scaled stretch-forming die using the structural optimization methods becomes necessarily important. In this paper, the topology optimization method is used to design the supporting structures on account of the gravity of the die itself and the surface loads obtained from the numerical stretch forming procedure.

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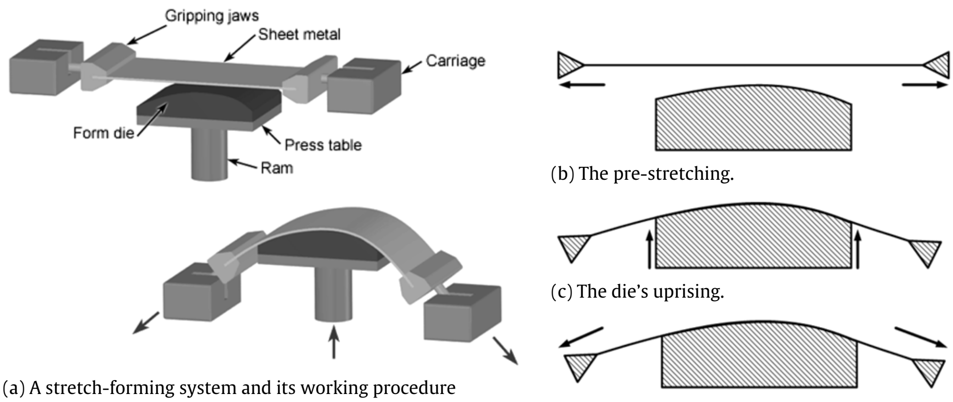

(a) A stretch-forming system and its working procedure (www.custompartnet.com).

(b) The pre-stretching.

(c) The die's uprising.

(d) The final stretching.

Fig. 1. An illustration of stretch-forming procedure.

The structural optimization design of the stretch-forming die proposed in this paper is actually carried out as a two-step way. First, the surface loads on the die have to be numerically predicted with the performing of non-linear finite element analysis. Some typical and extreme load cases will be selected for the topology optimization. Currently, most of the existing works on the stretch-forming were concentrated on the numerical simulation of different kinds of forming process to improve the forming precision [5]. For example, Yan and Klappka [6] studied the spring-back behaviors of panel forming productions using the multi-point stretch forming technique. Wang et al. [7] carried out a series of numerical simulations. The shape error and non-uniformity in thickness distribution of the sheet part were analyzed. Jiang et al. [8] combined the stretch forming with the roll forming procedure. The non-linear Finite Element simulation had shown more benefits that better forming precision and lower stress level were obtained. Till now, the development of the numerical simulation of the metal sheet stretch forming procedure has been satisfied. As a result, we choose to use the explicit time-integration method in the platform of ABAQUS to obtain the different surface load cases.

Second, based on the contact forces, topology optimization will be implemented to design the supporting structure satisfying the stiffness of the die and the requirement of weight-saving.

Currently, the application of topology optimization to the contact problems is not a new issue. For example, Petersson and Patriksson [9] proposed a subgradient algorithm to solve the topology optimization of sheets in contact. The convergence and the computational efficiency of the optimization were in-depth discussed. Recently, in the work of Strömberg and Klarbring [10], the unilaterally constraints were simulated with contact conditions. Both 2D and 3D problems were optimized and reasonable results were obtained.

In the existing works, the structural optimizations of the metal forming dies are mostly found designing the stamping die. For example, Sheu and Yang [11] predicted the pressures on the working surface of a stamping die. The inner structures were then designed by modifying the size and layout of the stiffeners. The optimized results turned out to be completely different from the traditional design, i.e. a uniform distribution of the stiffeners. Nilsson and Birath [12] simulated the variation of the surface loads during the stamping process by means of time integration, where the process of lifting and stamping are taken into account. Topology optimization was then applied to save the weight by maintaining the structure rigidity and strength. Similarly, Xu and Tang [13] developed the topology optimization procedure for the inner structure design of the stamping die based on the platform of LS-Dyna and Hyperworks, where 28% of the total weight is saved.

Based on the previous works, a stretch-forming die of a large cargo aircraft is designed in this paper. The stretch-forming process is first simulated based on ABAQUS to obtain the surface loads which will be defined as numbers of weighted load cases. By deriving the design sensitivities and applying the constraints on the material distribution and the total material cost, topology optimization of the inner structure is then carried out to find the optimized structural layout.

2. Basic formulation

2.1. Stretch-forming simulation

A typical stretch-forming procedure as illustrated in Fig. 1 can be subdivided into three stages, i.e. the pre-stretching, the die's uprising and the final stretching. During the pre-stretching, the metal skin is stretched horizontally to generate the pre-stress. Then the die rises and pushes the skin to generate a curved surface. Finally, the skin is pulled along the clamping direction to accomplish the final stretching. The simulation of the stretch-forming procedure can be solved by standard non-linear finite element method. In this paper, we choose to use ABAQUS solver with central difference method and explicit