Topological Optimization of a Complex Shape Forming Stamp

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Abstract. The scientific research is devoted to the mathematical modeling of the optimal topology of stamps with a complex forming surface. Topological optimization is based on the SIMP method by creating a field of pseudo-densities and minimizing the pliability of the structure under the influence of load. When setting the problem, it is proposed to take into account the fatigue strength of polymers, taking into account the restrictions on the stress state. According to the results of the calculation in the ANSYS software package, an optimal redistribution of the stamp material and a reduction in volume due to the removal of elements that have little effect on the rigidity of the structure is obtained. The results of the study can be further applied in the field of hot and cold stamping by creating stamping tools of minimal volume.

1. Introduction

This study is devoted to modeling the optimal topology of dies of complex shape in view of a large number of non-standard parts, in particular, half-pipes associated with a change in diameter, channel branching. Due to such features, which distinguish complex types of dies from dies for the manufacture of parts of the "cup" type, where there is a precise zone of flanges and a "stream" of shaping, the most effective method of material redistribution is the method of topological optimization based on maximizing rigidity, where for a given decrease in volume the optimal configuration of elements that are deleted and saved in the stamp is selected.

In the study of dies, one of the important issues is to assess its wear by the criteria of low-cycle fatigue and plastic crushing, which is reflected in work [1]. Since the dies experience a long-term force impact, the issues of cyclic loading in the projection on the optimization of the topology of the dies were investigated in [2, 3]. The issues of reducing deformations of simple-shaped stamps during cold stamping, the design of stamps of the "cup" type were considered in the works [4, 5]. The study of the parameters of the "hemisphere" part shaping was studied in [6]. The problems of designing complex systems have been studied in sufficient detail in [7-10].

Since the problems of shaping are contact, important questions concern the study of the process of uneven loading of the punch, which is determined by the rate of loading from the press, the stiffness of
the workpiece and the elastic punch. The mechanics of the contact interaction of the punch, workpiece and punch was investigated in [11].

In view of the development of additive Technologies, the use of polymers in the manufacture of dies has gained widespread acceptance. The limiting state of polymers and composites under high-cycle loading was considered in [12]. Methods for non-destructive testing of polymers were studied in [13]. Stamping processes using polymers were studied in articles [14].

In view of the complexity of the forms and formulations of optimization problems for dies, it is very important to apply the methods of mathematical modeling and numerical analysis, which was studied in [15-17]. Optimization models taking into account power and thermal loads were considered in articles [18-20]. The problems of using the finite element method in assessing the stress-strain state in the problems of shaping were considered in the works [21, 22]. The application of optimization methods in the PAM-STAMP 2G software package was considered in [23]. Finite-element models of the optimal topology of shaping dies in the ANSYS program were considered in [24-26].

Optimization problems of contact interaction with uncertainties and the use of a probabilistic approach were considered in [27-29]. In addition, methods for optimizing the technology of manufacturing power aircraft structures were investigated in [30]. Optimization of operational reliability of stamping equipment was investigated in [31]. A mathematical model of the redistribution of the stamp material with the help of rod elements was constructed in [32]. Thus, according to the analysis of literature sources, the issues of die wear have begun to be considered from an optimization standpoint in recent years in view of the introduction of topological optimization methods into the finite element method, as well as the possibility of using composites in the manufacture of dies.

2. Numerical calculation method

The topological optimization of a complex shape forming stamp is considered in the paper on the basis of the SIMP method. The SIMP method of topological optimization is based on minimizing the malleability of the structure, which is divided into finite elements and a field of virtual pseudo-densities is created $\rho_l$ [33]:

$$ A_p = \int \{p\}^T \{u\} dS \rightarrow \min, $$

where $A_p$ – the work of external forces, $\{p\}$ – vector of external forces, $\{u\}$ – displacement vector.

The removal of an element is determined by the minimum stiffness by assigning a small value $E_{min}$ of the elastic modulus $E_i$ to the element [33]:

$$ E_i = \rho_i E_0 + (1 - \rho_i) E_{min}, $$

where $E_0$ – material elastic modulus.

The presence or absence of a material is determined by the pseudo-density parameter $\rho_i$, which takes the values: 0 or 1.

Thus, the mathematical formulation of the problem is determined by the relations, where the condition of the fatigue strength of the polymer is added to the main system of equations of topological optimization, taking into account the duration of the force action:

$$ \sum_{i=1}^{n} \rho_i v_i^T k_i v_i \rightarrow \min, $$

$$ k_i v_i - P_i = 0, $$

$$ \sum_{i=1}^{n} \rho_i V_i < V_0, $$
\[
\int_{0}^{t} \frac{1}{T_0} e^{\frac{U_0 - U}{k T_1}} dt = 1.
\]

where \( k_i \) – stiffness matrix, \( v_i \) – node movements, \( \bar{\sigma}_i \) – intensity of the stressed state, \( T_i \) – temperature, \( t \) – time, \( U_0, T_0, \gamma \) – experimental constants for a polymer, \( K \) – Boltzmann constant.

As a result, the search for the optimal redistribution of the material that satisfies the required restrictions on the volume and stress state is carried out on the basis of the presented relations.

### 3. Research results

The formulation of the topological optimization problem is shown in Figure 1: red color – the loading surface, the optimization-free zone; blue color – the internal optimization area of the stamp. 25653 elements were created when sampling the stamp volume, the size of one element is 2 mm. The surface load \( p=0.1 \) MPa was set as the pressure. Optimization limitations: the die volume should be more than 60%, and the stress state should not exceed 1 MPa.

The stress state of a solid die is shown in figure 2 based on the results of numerical calculation by the finite element method. The redistribution of the stamp material under the specified restrictions is shown in figure 3.

Figure 1. Areas of optimization and free from redistribution of the stamp material.

Figure 2. Stress state of a solid die under the influence of a surface load.
Figure 3. Optimal stamp topology.

4. The discussion of the results
According to the results of mathematical modeling of the volume of the solid stamp \( V_0 = 2.23 \cdot 10^5 \text{ mm}^3 \), the volume of the stamp optimized topology made up \( V_1 = 1.7 \cdot 10^5 \text{ mm}^3 \). As a result of optimization, the stamp volume was reduced by 24%. According to the analysis of the stress state of the solid die, the highest stress according to the Mises criterion is 0.5 MPa. The search for the optimal distribution is constructed iteratively and required 33 iterations for convergence. According to the calculation results, the distribution of pseudo-densities is obtained. The least loaded elements are the elements of the side faces of the stamp, the pseudo-density values of which are \( 0 \leq \rho \leq 0.4 \).

5. Conclusion
The formulation of the problem of topological optimization of a stamp of a complex shape of the "tee" type is presented according to the results of the study. The distribution of the material under the given restrictions on the volume and stress state is obtained as a result of mathematical modeling. The presented approach is of great practical importance for reducing the material costs for the production of all-metal stamps and their manual revision. The use of polymers and the possibility of using additive technologies will allow us to produce stamps with a complex internal structure and a minimized volume in practice.

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