Development of the Sequential Voids Creation Approach in Axisymmetric Forming Dies

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Abstract. The study deals with the problem of topological optimization of forming dies with a limitation on fatigue strength. As a model of a stamp, a typical geometric configuration of stamps for the manufacture of parts of the "cup" type is considered. The algorithm for finding the optimal topology is proposed to be built separately in the internal areas under the stamp flanges and under the bottom of the "cup" of forming. Mathematical regularities are presented, according to which elements that fall into the area of predicted removal have a very small elastic modulus, which is widely used in topological optimization methods, then the stress state level is analyzed according to the fatigue strength curve. In the area of the flanges, there is a "build-up" of the mass according to the quadratic law with a variation in the depth of removal of the material. In the area of the bottom of the "cup" of forming, a step-by-step addition of rod elements is proposed until the level of the stress state meets the specified restrictions. Thus, this study is a modification of the topological optimization method. The novelty of the research lies in the construction of a new geometric scheme for determining the area of stored and deleted elements. The results of the study can be further developed in the development of methods for effective redistribution of material, as well as significantly reduce the material costs for the production of metal forming dies.

1. Introduction

At the present stage of development of aircraft and machine-building production, the manufacture of parts of complex shapes is inextricably linked with the processes of metal forming. In this regard, a special place is occupied by the study of stamping tools as objects subjected to periodic power and heat loads. In most scientific studies, the use of dies is considered from the position of rigid non-deformable bodies, which is not always acceptable, especially when considering dies with an optimized shape and made of plastic. A variety of types of stamps is described in sufficient detail in [1-3], the structural features of stamping tools and the influence of the geometry of stamps on the stress-strain state of workpieces in the process of shaping are described in works [4,5].

Questions of static and impulse sheet stamping, distribution were investigated in works [6,7]. In the processes of long-term operation of dies, an important issue is to assess the frequency of loading and the nature of the stress-strain state under cyclic loading, which was reflected in works [8-10]. In view of the use of polymers in stamping processes, which is reflected in [11], it is important to study the
rheological properties of materials, the development of creep processes, which was considered in [12-14]. Numerical analysis of the deformation behavior of stamping elements, assessment of the stress-strain state during plastic hardening, thermal strength criteria were considered in the works [15-19]. The issues of applying lubricant during stamping were investigated in [20].

Technological capabilities of alloys in the process of drawing, structural changes in materials were studied in [21, 22]. The use of the energy criterion of destruction in the study of drawing processes was discussed in the article [23].

The development of computer technologies in recent years has made it possible to actively use methods of numerical analysis to solve stamping problems. Aspects of physical and mathematical modeling of shaping processes were considered in [24-28]. Topological optimization methods, which can significantly reduce the material resource, in the manufacture of products using three-dimensional printing methods are reflected in the works [29-31].

2. Problem statement
The paper proposes to develop a step-by-step algorithm for "building up" the die material from the minimum volume with the maximum removal of elements to the most effective volume that meets the fatigue strength requirement. The relevance of the study is due to the widespread use of standard dies in the field of metal forming, which requires the development of approaches for a more economical use of material. A feature of axisymmetric dies is a typical geometrical configuration, namely: the presence of a flange area, as well as a "cup" of shaping.

When building a step-by-step algorithm, it is proposed to remove the areas of the side faces under the flanges, as well as the area under the bottom of the shaping cup. However, the main question is how to determine the reaming of the remote areas so that they meet the fatigue strength requirement.

When removing the area under the flange, the main load: bending and compressive is imposed on the wall. The novelty of the research lies in the development of a new numerical technique and an algorithm for finding the optimal topology of stamps with a constraint on the stress state.

3. Numerical calculation method
A numerical technique for finding the optimal topology is developed separately for the area of flanges and the bottom of the "cup" of shaping. The area to be removed under the flanges is proposed to be described by a quadratic function with the possibility of varying the removal depth. The area of removal in the area of the flanges is determined by the ratio:

\[ x_i = 4\Delta^{(k)}z_i \frac{(z_i + H)}{H}, \]

where \( \Delta^{(k)} \) — removal depth given in successive approximations, \( H \) — die height, \( x_i, z_i \) — element coordinates at \( y = \text{const} \), \( k \) — iteration number.

The iterative process is built in successive approximations with a decrease in the depth of the removed region and is accompanied by an analysis of the stress level at each iteration step

\[ \Delta^{(k+1)} = \alpha \Delta^{(k)}, 0 < \alpha < 1, \]

\[ \sigma_i^{\text{max}} < f(N^*). \]

Then for elements that satisfy the conditions:

\[ f_1: Hx_i - 4\Delta^{(k)}z_i(z_i + H) < 0, \]
\[ f_2: x_i - \Delta^{(k+1)} < 0 \]

the modulus of elasticity is determined by the ratio according to the method of topological optimization [32]
\[ E_i = (E_0 - E_{\text{min}})\rho_i + E_{\text{min}} \]

where \( E_0 \) – elastic modulus of material, \( E_{\text{min}} > 0 \) – small value, \( \rho_i \) – pseudo-density determining the presence or absence of material:

\[ \rho(f_1; f_2) = \begin{cases} 1, & f_1 \geq 0 \land f_2 \geq 0 \lor f_1 \cdot f_2 \leq 0 \\ 0, & f_1 < 0 \land f_2 < 0 \end{cases} \]

In the area of the bottom of the glass, it is proposed to create bar elements with a step-by-step analysis of the stress level. At each iteration step, the number of supports increases until the stress state level satisfies the fatigue strength requirement. Coordinates of the bar elements to be saved

\[ m_j = x_- + \frac{x_+ - x_-}{k + 1} j, \]

where \( j \) – stored item number, \([x_-; x_+]\) – optimization area.

The area of the saved elements under the glass bottom is determined by:

\[ |x_i| \leq m_j + \Delta_x, \]

where \( 2\Delta_x \) – set width of the bar element.

When constructing a step-by-step algorithm for finding the optimal topology, the desired topology of a stamp of minimum volume is set as an initial approximation, and the level of the stress state is analyzed. If the stresses in the die from the action of the load from the elastic punch do not satisfy the fatigue strength criterion, the mass "builds up" in the area of the flanges due to the decrease in the depth of the removed area and the addition of rod elements in the area of the bottom of the "cup" of the die. Next, the stress level of the new topology is analyzed again under the condition \( V_0 > V^{(k+1)} > V^{(k)} \). The cycle continues until the stress state level meets the strength requirements.

As a result of a step-by-step increase in the die volume, the optimal combination of the smallest die volume and the required number of loading cycles is selected. One of the important questions is to choose the value of the coefficient \( \alpha \). The closer the value is to 1, the more iterations are required to find the optimal volume, but the more accurate the process of finding the optimal topology in the area of the flanges will be. Similarly, in the region of the bottom of the "cup", the slower the number of rod elements increases, the more accurate the iterative process of finding the optimal topology.

4. Research results

An example of a numerical calculation is shown in Fig. 1. The lower base of the stamp was fixed as the boundary conditions, and the forming surface was loaded with a pressure \( p = 2\text{MPa} \). Plastic pla was considered as a material. As the constraints, the condition was set, according to which the stress state should not exceed 0.8 MPa. The step-by-step algorithm for increasing the mass in the area of the stamp flanges is shown in the block diagram (Fig. 2), in the area of the bottom of the "cup" - in the block diagram (Fig. 3).
Figure 1. Stress state of stamps with optimal topology with step-by-step "material build-up": A) one-piece stamp, B) stamp of minimum volume, C) topology of stamp at k = 1, D) topology of stamp at k = 2.
Figure 2. Block diagram of the subroutine for removing material in the area of the stamp flanges.

Figure 3. The block diagram of the subroutine for removing the material of the inner area is given to the "cup" of the stamp.
5. The discussion of the results
The stress state of the dies at different stages of optimization was assessed according to the Mises criterion. The maximum stress in the solid die at the current pressure was 0.6 MPa. With extreme material removal in the area of the flanges and the bottom of the nozzle, the highest stress was 3 MPa. With a change in the depth of removal $\Delta^{(1)} = 0.5\Delta^{(0)}$ and the addition of one rod element in the area of the bottom of the “cup”, the maximum stresses in the punch reached 0.9 MPa. With a change in the depth of removal $\Delta^{(2)} = 0.5\Delta^{(1)}$ and the addition of 2 bar elements in the area of the bottom of the “cup”, the maximum stresses in the stamp reached 0.7 MPa. Thus, at the second iteration step, the distribution of the material is obtained at which the stress state does not exceed the specified limit of 0.8 MPa.

6. Conclusion
The research results can be effectively used for topological optimization of standard dies for shaping products of the "glass" model. Reducing the volume of the stamp while meeting the required strength criteria under conditions of long-term use will significantly reduce the waste of material in the production of stamping tools in the field of metal forming.

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