Minimization of dies volume using uniform distribution of hollows in the conditions of multi-cycle fatigue dependence on temperature

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The research is devoted to development of a model of dies of optimized shape used in the field of metal forming. Use of solid-cast metal dies at the present stage of production requires large material resources, which makes it actual to develop dies models with minimal volume of material due to effective distribution of hollows in correspondence with the required strength resource. The dies mainly experience compressive non-uniform loading in the conditions of drawing and forming, which can lead to the accumulation of damages and lowering of its strength resource in the conditions of long-term operation of a die at high temperatures; therefore, the optimized area is represented in this work by alternating rod elements and hollows. The paper considers the problem of optimizing the volume of a metal die, presents a model for minimizing the die volume with restrictions on multi-cycle fatigue at various temperature conditions. The dependence between the volume of the optimized area and the number of loading cycles is obtained, taking into account the non-uniform loading of the die for axisymmetric forming. The main approach to reducing the die volume due to distribution of hollows was concluded in increase the stress state of the rod elements experiencing compressive stress to the limit values in accordance with the restriction on multi-cycle fatigue. The number of elements providing the required die stress state is calculated for different temperature conditions and preset geometrical parameters of the rod elements. When calculating the configuration of the optimized die area for axisymmetric forming, experimental curves of dependence between stress state and number of cycles for 12Kh1MF1 steel were considered at the constant temperature. The variants of the material distribution in the internal die area at preset temperatures are presented. Reduction of the optimized die volume was compared with a solid cast die. The constructed mathematical model and the results of calculation of the optimized die volume will significantly reduce the material costs for production of metal forming dies and can be used for further development of the methods for topological optimization of stamping tools, taking into account the features and duration of power and thermal loading.

Key words: metal forming, die, multi-cycle fatigue, topological optimization, stress, temperature, stamping, non-uniform loading.
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Introduction

The modern aviation and automotive production are tightly connected with metal forming processes, due to use of wide range of thin-walled components manufactured by sheet stamping. The main stamping tools (dies, punches, reversing gears, clamps) are fabricated mainly via cold and hot stamping from different steel grades. The problems of steel wear resistance for durable operation are rather important, owing to influence of die surface on quality of the component manufactured via metal forming. Deformability of steel at different temperatures, analysis of steel state at variable thermal conditions play important role in forming of thin-walled components [1]. The problems of steels state at different temperatures were widely investigated; dependence of steel deformation on presence of non-metallic inclusions was researched in [2], while the problems of state of metal alloys at constant high temperature were reflected in [3].

Most of metallic dies accumulate surface defects in the process of durable operation; irregularities and dents occurred during metal forming can lead to billet deviation from the required shape. In this connection, very important issues are connected with dies surface quality evaluation and surface roughness [4]. Investigations of lubrication materials for resistance increase of dies and coatings are described in [5, 6]. The problems related to mathematical description of metal forming processes are observed in [7], while mathematical methods of correlation analysis for evaluation of availability of die materials are examined in [8]. Application of finite element analysis for simulation of metal forming processes ere researched in [9, 10].

As soon as dies are experiencing power and thermal loadings, examination of temperature and mechanical stresses and deformations is very important [11. 12]. Evaluation of the conditions of power effect on die surface and longevity of dies during cyclic operation are reflected in [13, 14] and [15, 16] respectively. Destruction criteria of materials at multi-cycle fatigue and for complicated stresses state is examined in [17]. Multiple use of dies in metal forming processes stipulates calculation of their optimal shape with reducing material volume. These questions were partly solved using the methods of topological optimization [18]. The methods of stiffness improvement via material redistribution were investigated in [19-21]. Die material redistribution, taking into account its fatigue strength, is described in [22]. Variation of rheological properties was examined in [23].

Target setting

It was required in the framework of this research to build the model of hollows distribution within internal space of a metallic die, taking into account the curves of multi-cycle fatigue for steels at different temperatures, as well as to evaluate the effect of temperature conditions during operation of a steel die on its volume minimization. Actuality of this research is stipulated by active use of dies, punches, reversing gears in multi-serial production for the aircraft and automotive industries, where they are subjected to cyclic loadings. Conditions of dies operation during cold and hot stamping require taking into account the effect of temperature on stress-strain state of these dies. This question is especially important in the cases, when die mass is minimizing owing to inclusion of hollows, in order to reduce material expenses. It creates additional loading on remained die areas: stresses in a die body and temperatures are substantially increased, and these factors should be tied together by special mathematic regularities to determine internal configuration of a steel die during preset loading cycles. The research novelty is concluded in development of the new approach and mathematical model of material distribution within the internal area of stamping tools due to creation of hollows with their distribution depending on loading kind and temperature. Possibility of transition from solid metal dies to dies with optimized volume is also the new idea; stress state of dies then increases in the conditions of long-term operation up to ultimate level of allowable area boundaries.

This work considers optimization of a die internal area during axisymmetric drawing or forming, using rod elements which are operating in compression mode. In this case the stress-strain state of the surface forming area is not considered. The boundary die surfaces are free from optimization. According to the target setting, it is required to optimize the internal die area using alternating rod elements and hollows in the conditions of restrictions for multi-cycle fatigue. The volume of internal die part is considered as the goal function:

$$V=\sum_{i=1}^{n}\Gamma(x_i,\,y_i)\Delta S_{ij}\rightarrow \min$$

$$V_0=\sum_{i=1}^{n}\Gamma(x_i,\,y_i)\Delta S_{ij}+\sum_{i=1}^{n-1}\overline{V}_j$$

$$\sigma_{ij}\leq\overline{\sigma}$$

$$\overline{\sigma}=f(N,\,T),$$

where $z=\Gamma(x_i,\,y_i)$ – the function describing the die forming boundary surface, x_i, y_i – distribution coordinates of rod elements along the die base, ΔS_{ij} – cross section square of a rod element, σ_{ij} – stress in a rod element, $\overline{\sigma}$ – ultimate stress, being a function of loading cycles N and temperature T, $\overline{V}_j$ – volume of removed area, V_0 – initial volume of a solid die.

Methods and materials

The main approach to reducing the die volume via distribution of hollows is based on the proposal to increase stress state of rod elements, being under compressive loading, to ultimate values in correspondence with restriction for multicycle fatigue. As a result, the minimal die volume will be determined according to the following condition:

$$V_*=\min_{\sigma\leq\overline{\sigma}}V=V\big|_{\sigma=\overline{\sigma}(N,\,T)}. \tag{1}$$

Evaluation of optimal material distribution in the internal die area requires use of approaches for stress state analysis of the main bearing components depending on loading type and operation time. Relationship between stress state and number of cycles is determined for metals by Weibull ratio. If $T=$ const, the fatigue curve of stress / cycles number relationship looks like [24]:

$$\overline{\sigma}=(\sigma_B-\sigma_R)e^{-\alpha(\ln N)^m}+\sigma_R\,, \tag{2}$$

where σ – maximal stress, σ_R – fatigue stress, σ_B – tensile strength, $\alpha=\alpha(T)$, $m=m(T)$ – experimental constants for preset temperature.

As soon as liquid, elastic or rigid media can be used as punches in the field of sheet stamping, die loading on the forming surface can be non-uniform. For example, the following dies can be used for axisymmetric drawing and forming (typical model is presented on the **Fig. 1**).

Respectively, compressive loading on rod elements in the die internal area has different values for flanges, walls and bottom of forming surface in the case of use of rubber punch. Let's describe the equation for die surface $F_s(x,\,y,\,z)$ (Fig. 1) at $x\geq 0$, $y=$ const for axisymmetric drawing and forming by the following relationships:

$$F_s(x,\,y,\,z):\begin{cases} z-h=0, \quad 0\leq x\leq r-r_a \\ z-h-r_a+\sqrt{r_a^2-(x-r)^2}=0, \;\; r-r_a\leq x\leq r \\ x-r=0, \quad h+r_a\leq z\leq H-r_a \\ z-H+r_a-\sqrt{r_a^2-(x-r-r_a)^2}=0, \\ r\leq x\leq r+r_a \\ z-H=0, \quad r+r_a\leq x\leq R \end{cases} \tag{3}$$

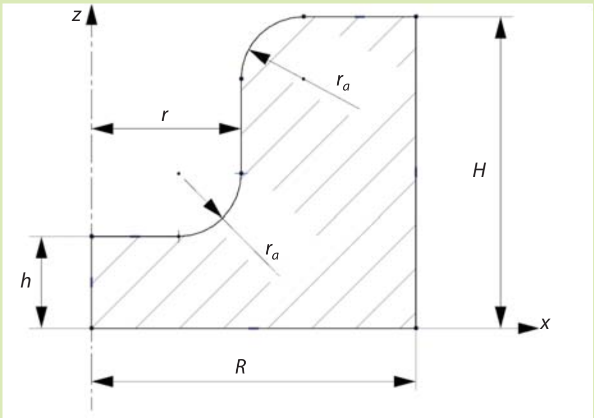


Fig. 1. Die model for axisymmetric forming

To evaluate the stress state of rod elements under the effect of compressive loading in the die internal area, let's consider its projection on z axis:

$$p = p^* \cdot \frac{|\vec{k} \cdot \overrightarrow{\mathrm{grad}} F_s(x, y, z)|}{|\vec{k}| \cdot |\overrightarrow{\mathrm{grad}} F_s(x, y, z)|}, \qquad (4)$$

where p^* – normal pressure in a surface point from the side of elastic punch, $\vec{k}$ – unit vector along z axis.

The pressure from the side of elastic punch for the forming surface areas (3) can be determined in projection according to (4) as:

- in the die bottom and flange:

$$p_f = p^*, \qquad (5)$$

- on die rib in transition from bottom to wall:

$$p_a = \frac{p^*}{r_a}(r_a^2 - (x - r)^2)^{\frac{1}{2}}, \qquad (6)$$

- on die wall area:

$$p_w = 0, \qquad (7)$$

- on die rib in transition from wall to flange:

$$p_b = \frac{p}{r_a}(r_a^2 - (x - r - r_a)^2)^{\frac{1}{2}}, \qquad (8)$$

The work suggests to build the model at fixed size of rod element cross section; this model will determine number of elements and their distribution along die base. The number of remained rod elements for separate areas is determined as follows for preset conditions $N = N^*$, $\Delta S = \Delta S^*$:

- for $0 \le x \le r - r_a$; $r + r_a \le x \le R$:

$$n_f = \frac{p^* S_p}{\Delta S^* \left((\sigma_B - \sigma_R)e^{-\alpha(\ln N^*)^m} + \sigma_R\right)}, \qquad (9)$$

- for $r - r_a \le x \le r$:

$$n_a = \frac{p^* S_p (r_a^2 - (x - r)^2)^{\frac{1}{2}}}{r_a \Delta S^* \left((\sigma_B - \sigma_R)e^{-\alpha(\ln N^*)^m} + \sigma_R\right)}, \qquad (10)$$

- for $r \le x \le r + r_a$:

$$n_b = \frac{p^* S_p (r_a^2 - (x - r - r_a)^2)^{\frac{1}{2}}}{r_a \Delta S^* \left((\sigma_B - \sigma_R)e^{-\alpha(\ln N^*)^m} + \sigma_R\right)}, \qquad (11)$$

where S_p – surface square of die forming.

Distribution of the elements along the die base is determined according to coordinates:

$$\begin{Bmatrix} x_i \\ y_i \end{Bmatrix} = \begin{Bmatrix} \frac{1}{2}\Delta x + i\left(\Delta\bar{x} + \frac{\Delta x}{2}\right) \\ \frac{1}{2}\Delta y + i\left(\Delta\bar{y} + \frac{\Delta y}{2}\right) \end{Bmatrix}$$

where Δx, Δy – cross section size of the saved element with square ΔS^*, $\Delta\bar{x}$, $\Delta\bar{y}$ – cross section size of deleted element.

As a result and taking into account (1), (2) and (5) - (11) relationships, optimal die volume V^* in the process of axisymmetric forming can be determined (with restrictions for multi-cycle fatigue) by the following expression:

$$V_* = \frac{1}{(\sigma_B - \sigma_R)e^{-\alpha(\ln N^*)^m} + \sigma_R)}\left[(h + H)p^* S_p + \frac{p_a S_p}{n_a}\left(\sum_{i=1}^{n_a}\Gamma(x_i)\right)_{r - r_a \le x \le r} + \frac{p_b S_p}{n_b}\left(\sum_{i=1}^{n_b}\Gamma(x_i)\right)_{r \le x \le r + r_a}\right].$$

The obtained relationship displays connection between optimal die volume (from one side) and required number of loading cycles and operation temperature procedure (from other side).

Calculation results

Calculation of optimal die volume for low-alloyed steel 12Kh1MF1 was carried out as an example, taking into account multi-cycle fatigue depending on temperature, with external pressure from elastic punch $p^* = 20$ Mpa. Selection of this steel grade was stipulated by its thermal stability and possibility to use dies from this material in hot forming, as well as its fatigue longevity. Calculation of minimal material volume was conducted for the axisymmetric forming die according to the Fig. 1. Selection of such die kind was based on the most frequent forming of sleeve-type components in fabrication of semi-connections, especially in the field of aircraft production.

Fig. 2 shows dependence between relationship of optimized die volume to its initial volume and number of loading cycles for the following temperature conditions: 20 ºC, 450 ºC, 500 ºC, 565 ºC.

Additionally, the reverse problem was also solved in this research: it was required to calculate distribution of hollows and rod elements along the die base for preset number of loading cycles. As soon as dies are used in hot stamping, their stress-strain state under long-term thermal and power effect

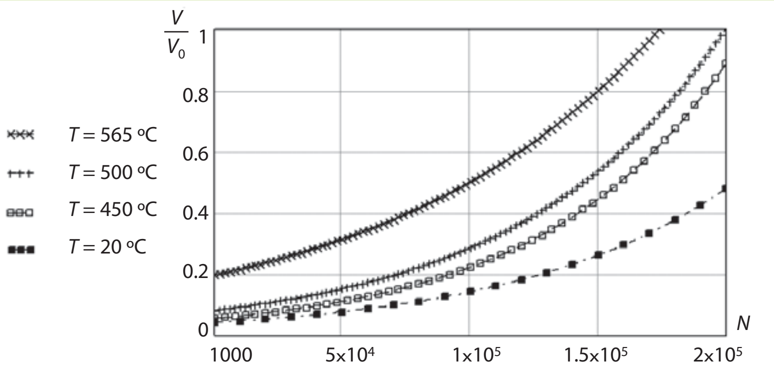
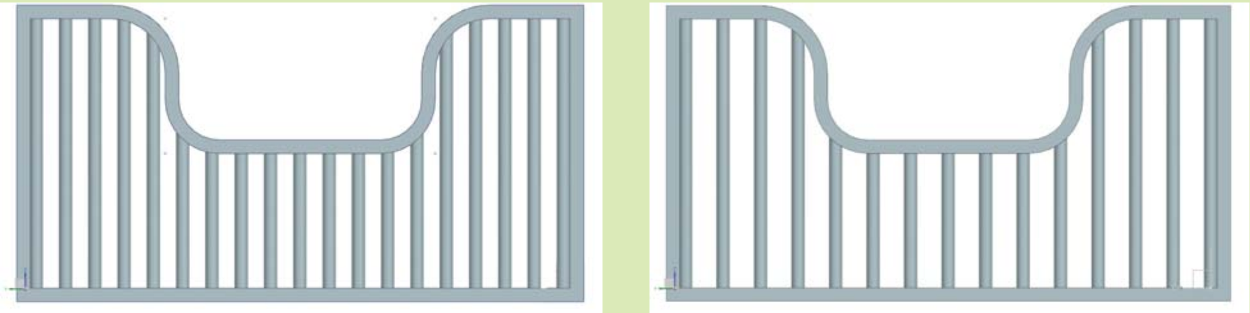
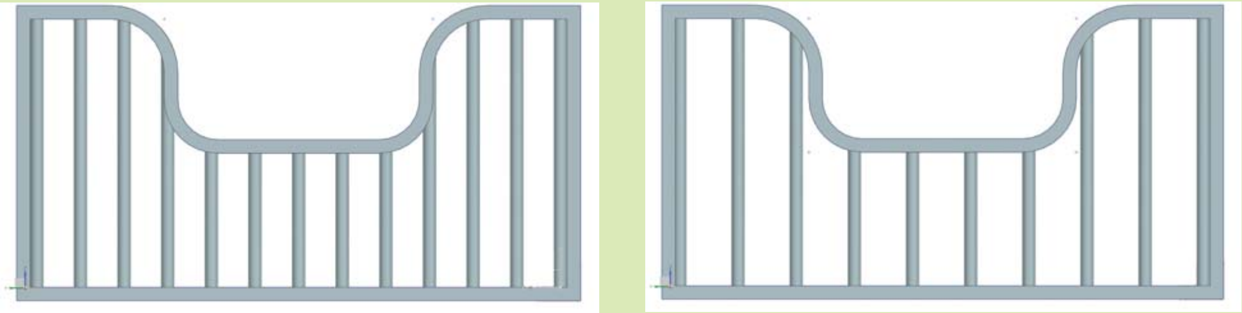


Fig. 2. Dependence between relationship of optimized die volume to its initial volume and number of loading cycles



$T = 565$ °C

$T = 500$ °C



$T = 450$ °C

$T = 20$ °C

Fig. 3. Variants of die optimization during forming at different temperature conditions

can vary substantially; it needs to consider the die models for different temperature conditions:20 °C, 450 °C, 500 °C, 565 °C. The variants of die internal area images for axisymmetric forming with $y = \text{const}$ and for different temperatures are presented on the **Fig. 3** (the required number of loading cycles before destruction made 10^5).

The results of calculation showed that optimal distribution of hollows allowed to reduce the volume of die internal part: $V_1 = 0.46V_0$ at $T = 565$ °C, $V_2 = 0.3V_0$ at $T = 500$ °C, $V_3 = 0.23V_0$ at $T = 450$ °C, $V_4 = 0.18V_0$ at $T = 20$ °C.

The numerical experiment using the finite elements method was conducted as a verifying calculation for evaluation of fatigue longevity for the die with volume $V_1 = 0.46V_0$ at $T = 565$ °C in the software complex Ansys 19 (**Fig. 4** and **5**). The die base was fixing after overlapping of the boundary conditions. Discretization of the die model represents the finite elements net from 26192 elements and 50256 nodes.

Results and discussion

According to the calculation results, obtained relationships between volume variation and number of loading cycles allowed to choose the most rational correlation die volume / loading conditions. The areas below the curves (see Fig. 2) can be accompanied by appearance of defects in the process of long-term die operation; the points on these curves correspond to the most effective reducing of a die volume after reaching the ultimate thermal stress state in remained die elements.

Stress intensity in a die is presented according to the Mises criterion, based on conduction of verifying finite element calculation. Average stress in rod elements makes 21 MPa (see Fig. 4). According to evaluation of cyclic longevity, number of cycles until destruction in the elements constitutes $1.2 \cdot 10^5$ cycles (see Fig. 5). The results of analytical calculation and numerical experiment via the finite element method are mutually agreed.

Practical importance of this research is concluded in the fact that the developed model of die volume minimization can be used for manufacture of the main stamping tools, such as dies and punches, in the aircraft and automotive industries, what will allow to reduce metal consumption for fabrication of such tools. In this connection, financial profit of metal consumption economy was conducted. If material price was 120,000 rub/t, fabrication of solid die with mass $m_0 = 54$ kg will cost $S_0 = 6{,}500$ rub. For the dies with optimized material distribution, price will make: $S_1 = 2{,}900$ rub. at $T = 565$ °C, $S_2 = 1{,}900$ rub. at $T = 545$ °C, $S_3 = 1{,}500$ rub. at $T = 500$ °C, $S_1 = 1{,}200$ rub. at $T = 20$ °C. In accordance with the developed model and calculation results, the price reduces depending on the operating temperature conditions. The expenses connected with die fabrication were not considered in this research. Practically fabrication of such dies can be realized via steel remelting, casting of molten metal in a mould with consequent crystallization and cooling. Manufacture of dies with optimized shape via casting can be done with creation of solid longitudinal ribs which are alternated along the base width. In the case of rod elements structure design on chess board principle,

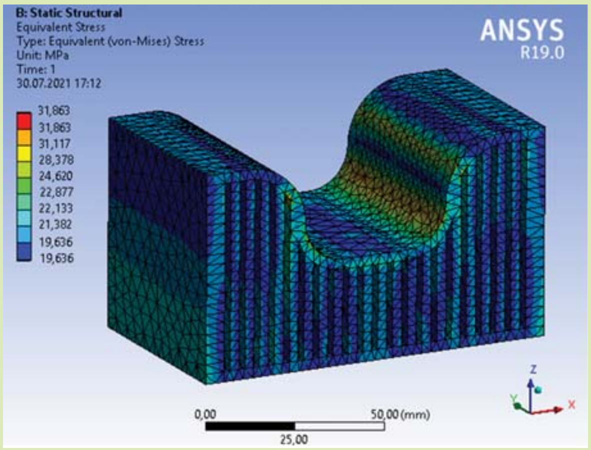


Fig.4. Die stress state

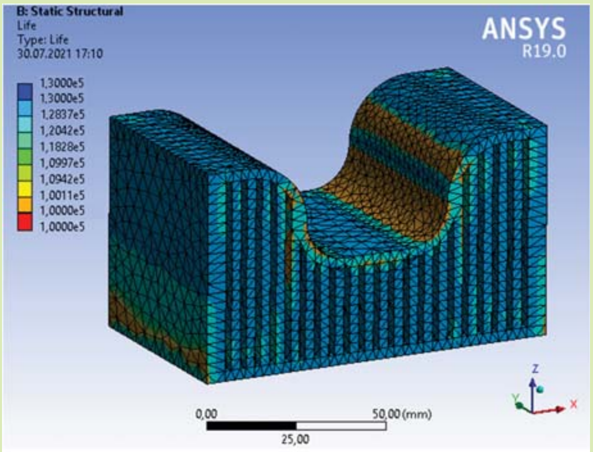


Fig.5. Distribution of the fatigue longevity cycles

manufacture of the die with hollows can be realized using 3D printers, via additive melting technologies, both for metals and plastics. Sheet billets from the following materials can be used in plastic forming during stamping: AMg2M, 12KH18N10T, V95pchAM, as well as polymers PEVD, PEND etc.

Conclusion

Influence of operating temperature conditions for steel die on optimal material distribution in the die internal area with minimization of its volume is reflected. Obtained mathematical relationship between die volume and number of loading cycles takes into account features of non-uniform loading in the areas of flanges, bottom and walls of forming surface sleeve, as well as temperature conditions of loading. The results of this investigation allow to reduce substantially expenses for manufacture of forming metal dies and can be used for consequent development of topological optimization methods for stamping tools, taking into account their features and loading duration. Redistribution of die material from the point of view of topological optimization is considered as perspective for the further researches. In this case preset reducing of volume takes place in order to maximize die stiffness, and previously unknown areas of material deleting and saving are determined. Putting into industrial practice dies with optimized topology, manufactured via 3D printing, is rather prospective, because it allows to expand dies fabrication with minimized material consumption and to increase speed of dies and punches manufacture.

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