The use of reliability indicators in the design of die tooling of technological processes of hot die forging

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Abstract. The article discusses the use of a number of indicators of the reliability of the functioning of the hot forming process to substantiate the choice of the number of die inserts (die streams) and selection of grades of tool steels for their manufacture. There are such used reliability indicators as the probability of the absence of typical defects in the shape of the stamped forgings, the probability of predominant types of exploitative refusals of the stamp, and the absence of failures in the implementation of the technological process as a whole. The rationale for the expediency of choosing a pre-stream of the die for stamping an axisymmetric forging with a high degree of complexity taking into account the possibility of occurrence of such shape defects as clamping, shooting, and incomplete forging radii during stamping, is considered. When the choice of the grade of tool steel for die inserts was taken into account, there was the occurrence of such typical types of their exploitative refusals as adhesion wear of die streams, the formation of hot cracks and plastic crushing of the forming elements of the stamp streams. The appropriate organizational and technical decisions are adopted on the basis of a comparison of cost indicators characterizing the production costs due to scrap forgings. They are caused by the formation of shape defects during stamping and the occurrence of exploitative refusals of dies. In addition, there are the costs for the manufacture of more complex die tooling and its exploitation, i.e. production quality costs.

1. Introduction

At present, a great deal of positive experience has been gained in designing die tools for hot die forging. At the same time, it should be noted that when designing this tool, reliability indicators are extremely rarely used, including its operation and the corresponding technological process as a whole [1-3]. Direct design of die tooling consists of a number of complex steps and procedures, which include the determination of the number of die streams and the choice of tool steel for tools manufacture. The solution of this kind of problems, despite the use of modern design tools, is often carried out by the designers on the basis of their own accumulated experience in this field, as well as using their well-known solutions - analogues provided by the databases of design tools. As a consequence, it is quite relevant to solve these problems when designing the tool in question, taking into account the estimates of the reliability indicators of its operation when stamping forgings.
2. Materials and methods

Often, decision makers in their activity use a comparative analysis of cost indicators characterizing a particular option for a possible solution to a task or problem. A similar approach is proposed to be used to select the number of forming die streams for hot stamping, as well as to determine the grade of die steel for their manufacture.

As part of the first task, which involves choosing between a die with one insert and a die with two inserts, it is advisable to verify the fulfillment of the following cost ratio (hereinafter, the subscript “1” of variables corresponds to a die with one insert, the lower index “2” variables - a die with two inserts):

\[
C_{1.1} \left[ (\gamma_{1.1} - \gamma_{2.1} + P_{1.1} - P_{2.1}) + (\gamma_{1.2} - \gamma_{2.2} + P_{1.2} - P_{2.2}) \right] + C_2 \left[ (N_{1.2})^2 - 1 \right] \geq 0.01059. \tag{1}
\]

Here \( C_{1.1} \), \( C_{1.2} \) - cost of producing one defective forging during stamping; \( \gamma_{1.1}, \gamma_{2.1} \) - proportions of rejects associated with the formation of mold defects, stamped forgings [2]; \( \gamma_{1.2}, \gamma_{2.2} \) - proportions of rejects of the forgings caused by the occurrence of predominant types of operational die failures [1]; \( P_{1.1}, P_{2.1} \) - probabilities of failures associated with the formation of defects in the shape of the stamped forging [2]; \( P_{1.2}, P_{2.2} \) - probabilities of failures that associated with the primary types of operational failure of the die [1]; \( N_{1.2}, N_{2.2} \) - estimated average die life [1]; \( C_3 \) - cost of ensuring the durability of both dies at a given level \( N_{d.1} \); \( C_4 \) is the cost of ensuring the durability of die with two inserts at a given level \( N_{d.2} \); \( P_{1.2} \) - probability of failure of the technological process of stamping forgings in a die with two inserts as a whole [2].

The expression on the left side of inequality (1) characterizes the cost savings at the expense of reducing forgings in die with two inserts with respect to marriage of forgings stamped in a die with one insert caused by the appearance of shape defects in the forgings. This includes non-completion of the rounding radii of protrusions, elements of the stamp, the formation of the defects type of “clamp”, “chamber” and “extrusion defect” [2, 4–7]) and the formation of the predominant types of failures of the die tool during its operation [1, 4, 8-12]. The first term in the right-hand side of inequality (1) characterizes the costs associated with the production of defective forgings, which is caused by the failure of the die with two inserts due to the occurrence of predominant types of failures in it. The second term (1) estimates the costs associated with measures to increase the average resistance of the stamp from the level of \( N_{d.1} \) to the desired level of \( N_{d.2} \).

The probability of the absence of predominant types of failures \( P_{st} \) and during operation of the inserts die for hot stamping is estimated by the following expression [1, 2]:

\[
P_{st} = (B)^{-1} \left[ 1 + (B-1) \exp(-B) \right] = \sum_{j=1}^{J} \left( P_{st,j} \right)^{-1} - (J - 1). \tag{2}
\]

Here \( J \) is the total number of predominant types of operational failures of the die inserts for hot stamping; \( l_j \) is the number of die insertion elements most critical to the occurrence of the \( j \)-th type of primary failure; \( N_{0,j} \) - number of forgings, stamping of which is possible before the occurrence of the \( j \)-th type of primary failure of the die insert; \( N_0 \) - batch of stamped forgings.

The predominant types of failures of the die insert of the preliminary stream are plastic deformation of the elements of the die impression (\( j = 1 \)) and the formation of high-pressure cracks in the die impression (\( j = 2 \)) [3, 6-8, 10-12]. For the final die impression, in addition to those already indicated, adhesive wear of the adhesive wear of the die bridge of the final creek of the stamp (\( j = 3 \)) is also possible [1, 3, 6-11].

The values \( N_{d.1}, N_{d.2} \) are proposed to be estimated by the following dependence [1, 2]:

\[
\beta_j^* = \frac{N_{0,j}}{l_j/C_j}. \tag{3}
\]
where $J_{f(1,2)}$ is the number of preferred types of failures of the corresponding type of stamp, the occurrence of which is possible during stamping; $N_{0,f(1,2)}$ - number of forgings, stamping of which is possible before the occurrence of the $j$-th type of preemptive failure in the corresponding type of stamp; $I_{f(1,2)}$ is the number of elements of the corresponding type of stamp that are most critical to the occurrence of the $j$-th type of primary failures; $P_{u,f(1,2)}$ - probability of the absence of the $j$-th type of primary failures during stamping of forgings in a die with one insert and in a die with two inserts (4).

The proportions of rejects of forgings $\gamma_{sh,1}$, $\gamma_{sh,2}$, $\gamma_{st,1}$, $\gamma_{st,2}$, caused by the formation of shape defects during stamping of the forgings and the occurrence of primary types failures of the die tool, are determined by the dependencies:

$$\gamma_{sh(1,2)} = (1 - P_{sh(1,2)}) \left(P_{sh(1,2)} \right)^{-1}; \gamma_{st(1,2)} = \left(1 - P_{st(1,2)} \right) \left(P_{st(1,2)} \right)^{-1}. \quad (6)$$

If inequality (1) holds, then the inclusion of a preliminary stream in the stamp design seems rational.

When solving the second task associated with the selection or replacement of die steel used in the manufacture of die inserts, it is proposed to use the following dependence:

$$Q \gamma_{st} \left(1 - P_y \right) C_5 \left(P_{new} - P_{old} \right) + \sum_{\lambda=1}^{m} \left(C_4 \bar{x}_i \left(\sigma_{hi} \right)^{-1} \right) \left(C_4 Q \left(N_{h} \right)^{-1} \left(N_{0,new} \left(N_{0,norm} \right)^{-1} - 1 \right) \right). \quad (7)$$

Here $Q$ - forgings release program; $C_5$ - cost of producing one defective forgings; $N_{0,norm}$ - standard resistance of die tooling in the considered technological operation; $N_{0,new}$ - average resistance of die tooling from the stamp steel grade proposed for replacement; $C_4$ - cost required to increase the durability of die tooling: $N_{0,new} > N_{0,norm}$; $\bar{x}_i$ - average values of technological parameters that affect die tool failures; $\sigma_{hi}$ - standard deviations of $x_i$; $C_i$ - expenses for providing a unit value $\bar{x}_i$ for the $i$-th technological parameter of the stamping operation; $\gamma_{st}$ is the proportion of forgings defective due to failures in die tooling, which is determined similarly to (6); $P_y$ - probability of failure of the technological process of stamping forgings as a whole [2]; $P_{new}, P_{old}$ are the probabilities of failure-free operation of die tooling from the steel proposed for replacement and the replaceable initial tool steel (2,3).

The left-hand side of inequality (7) characterizes the cost effect of reducing the marriage of manufactured forgings, which is caused by failures of die tooling. The expression on the right-hand side of inequality (7), in turn, characterizes the costs associated with replacing the grade of tool steel used for the manufacture of die inserts.

The average durability of die tooling $N_{0,new}$ is the proposed for the replacement of stamped steel grades is determined by the dependence [1]:

$$N_{d(1,2)} = \min_{j \in d} \left\{ N_{0,j(1,2)} \left(F_{i(j,1,2)}N_{h} \right)^{-1} - \left(N_{0,j(1,2)} \left(N_{h} \right)^{-1} - 1 \right) P_{u,j(1,2)} \right\}, \quad (4)$$
where \( P_{st,j,new} \) is the probability of the absence of the \( j \)-th type of primary failures of die inserts from the proposed die steel replacement; \( N_{0,j,new} \) - number of forgings, stamping of which is possible before the occurrence of the \( j \)-th type of primary failure of the die insert from the stamp steel proposed for replacement.

If condition (7) is met, the decision to replace the stamped steel grade is justified.

3. The rationale for the choice of the number of die forge inserts for die of hot forging and tool steel for their manufacture

Let us consider now the feasibility of making a decision on the use of the blocking impression of the die for stamping forging, a sketch of which is shown in Figure 1.

**Figure 1. Sketch of the forging**

The calculated values of the parameters included in the dependence (1 - 6) are given in tables 1 - 2.
Table 1. Probabilities of the absence of shape defects in the forgings (table 1), stamped in dies with one insert and two inserts [2].

| $f$ | Types of failures associated with defects form of the forgings | Probabilities absence of the failures |
|-----|---------------------------------------------------------------|-------------------------------------|
| 1   | Non-completion of the rounding radii of the protruding forgings elements | $P_{sh,1.1} = 0,987$ $P_{sh,1.2} = 0,993$ |
| 2   | The formation in a forging of the defects of the clamp     | $P_{sh,2.1} = 1^*$ $P_{sh,2.2} = 1^*$ |
| 3   | The formation in a forging of the defects of the type "chamber". | $P_{sh,3.1} = 0,996$ $P_{sh,3.2} = 0,999$ |
| 4   | The formation in a forging of the defects of the type "extrusion defect" | $P_{sh,4.1} = 1^*$ $P_{sh,4.2} = 1^*$ |

* - The probability value of the absence of this defect during stamping of the considered forging is 1, because there are no elements in the forging configuration where the formation of this defect is possible.

The probability of failure-free operation of the technological process of stamping forgings in a die with two insert according to [2] is equal to $P_{tp.2} = 0,988$. Values of the quantities $\gamma_{sh,(1,2)}$ and $\gamma_{st,(1,2)}$ for dies with one insert and two inserts according (6) respectively equal $\gamma_{sh,1} = 0,0132$; $\gamma_{sh,2} = 0,004$; $\gamma_{st,1} = 0,1135$; $\gamma_{st,2} = 0,004$. In turn, the average durability $N_{d,(1,2)}$ of each type of dies in accordance with (4) is equal to: $N_{d,1} = 1800$ die, $N_{d,2} = 2400$ pcs. Substituting the calculated and accepted values of the corresponding variables into the dependence (1) we obtain: 232,9 rubles > 101,4 rubles. When taking into account the size of the production program $Q$, it is obvious that the use of a preliminary brook is economically profitable, and the costs associated with its manufacture and operation of more complex die tooling are compensated by reducing costs due to failures during stamping of forgings.

Table 2. Probabilities of the absence of primary failure modes in the die with one insert and in the die with two inserts [1, 2]

| $j$ | Preferred types of die insert failures | Forging in the die with one insert | Forging in the die with two inserts |
|-----|----------------------------------------|----------------------------------|----------------------------------|
|     | $N_{d,j,1}$, pcs $P_{st,j,1}$ | $N_{d,j,2}$, pcs $P_{st,j,2}$ |
| 1   | Plastic deformation of the elements of the die impression | 4000 0,924 | 5700 0,991 |
| 2   | Adhesive wear of the die bridge | 6000 0,994 | 7400 0,999 |
| 3   | Formation of high-pressure cracks in the die impression | 3400 0,88 | 4700 0,974 |

Now we consider the feasibility of replacing 4KhMFS steel used in the manufacture of die inserts with 4Kh5V2FS steel ($C 0,35…0,45; Si 0,8…1,2; Mn 0,15…0,45; Ni up to 0,4; S up to 0,03; P up to 0,03; Cr 4,5…5,5; W 1,6…2,2; V 0,6…0,9; Cu up to 0,3), which has higher wear resistance. Forgings are stamped in a die with one insert. Physico - mechanical properties of the steel 4Kh5V2FS 41...46 HRC [4, 8, 12, 13] are as follows: the tensile strength at a temperature of $20^\circ$C is $\sigma_\nu = 1780$ MPa; the temperature of the beginning of intense softening is $T_\nu = 500^\circ$C; $\sigma_{T_\nu} = 1200$ MPa. In this case, the predominant types of failure of die inserts during stamping of forgings are also plastic deformation of the elements of the die impression ($j = 1$), adhesive wear of the die bridge ($j = 2$) [3, 6-8, 10-12] and
the formation of high-pressure cracks in the die impression \((j = 3)\) \([1, 3, 6-11]\). The predominant types of failures of die inserts (Table 3) are similar to those considered earlier (Table 2).

**Table 3.** The calculated values of durability and the probability of the absence of primary types of failures of die tooling from replaceable and proposed for replacement die steel \([1, 2]\)

| Preferred types of die insert failures | The calculated values of the die tooling life (8), pcs. | Estimated probability of failure's absence of the die (2) |
|----------------------------------------|--------------------------------------------------------|--------------------------------------------------------|
|                                        | 4HMFS | 4Kh5V2FS | 4HMFS | 4Kh5V2FS |
| 1 Plastic deformation of the elements of the die impression | \(N_{0.1,\text{old}} = 4000\) | \(N_{0.1,\text{new}} = 5000\) | \(P_{st.1,\text{old}} = 0.924\) | \(P_{st.1,\text{new}} = 0.995\) |
| 2 Adhesive wear of the die bridge | \(N_{0.2,\text{old}} = 6000\) | \(N_{0.2,\text{new}} = 7000\) | \(P_{st.2,\text{old}} = 0.994\) | \(P_{st.2,\text{new}} = 0.999\) |
| 3 The formation of high-pressure cracks in the die impression | \(N_{0.3,\text{old}} = 3400\) | \(N_{0.3,\text{new}} = 4200\) | \(P_{st.3,\text{old}} = 0.88\) | \(P_{st.3,\text{new}} = 0.974\) |
| The average resistance of the die tooling | \(N_{0,\text{old}} = 3500\) | \(N_{0,\text{new}} = 4500\) | \(P_{st,\text{old}} = 0.898\) | \(P_{st,\text{new}} = 0.978\) |

We take the following values of a number of variables of dependence (7): \(\gamma = 0.1135\) \((6)\); \(C_5 = 20000\) RUB; \(C_6 = 60000\) RUB; \(N_{0,u} = N_{0,norm} = 2500\) pcs; \(P_{st,\text{old}} = 0.898\); \(P_{st,\text{new}} = 0.978\) (Table 3); \(P_{q} = 0.982\) \([2]\); \(N_{0,\text{old}} = 3500\) pcs; \(N_{0,\text{new}} = 4500\) pcs (Table 3).

Since the organizational and technological infrastructure of production does not change with respect to the use of both steels for the production of die inserts, we can assume that the value of the term \(\sum_{i=1}^{n} C_i x_i (\sigma_x)^{-1}\) expression (7) for both steel grades is the same and may not be taken into account in the calculations. Given there are values of the variables, we obtain the estimate of the left side of expression (7): 2.73 105 rubles. The value of the right side of this expression is 3.42 105 rubles. Thus, the cost effect of reducing forgery rejects due to failures in die tooling does not exceed the costs associated with replacing the grade of tool steel used to manufacture this tooling. Consequently, the decision to replace the tool (die) steel for the manufacture of die inserts is not advisable.

4. Conclusion

The results allow us to conclude that it is advisable to use such indicators of the reliability of the hot forming process as the probability of failure in terms of quality of manufactured forgings and the absence of primary types of operational failures of die tooling at the design stage. Along with this, the use of these reliability indicators is also relevant at the stage of supporting the technological process, for example, in developing organizational and technical solutions for replacing die steel for the manufacture of die inserts.

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