Creation of a design methodology for crank punching machines of specified durability

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Abstract. The article discusses the main aspects of designing large-forging equipment of given durability on the example of crank punching machines. A scientifically based algorithm is proposed to ensure reliable operation of the structure operating in the field of high-cycle fatigue. An example of calculations is given when designing a bed for a crank hot forging press (CHFP) and a crank plate forging press defined durability on the basis of existing structures.

Keywords: crank punching machines, durability, high-cycle fatigue, stress concentrator, structural rigidity.

1. Introduction

Under market conditions, economic feasibility strictly dictates the production of the need to reduce production costs. One of the ways to reduce costs is the design and manufacture of equipment and tools by a strictly limited program of durability ordering (specified life), for example [1-8]. Figure 1 shows the dynamics of publications on the topic specified life over the past 10 years. Figure 2 shows the dynamics of patenting over the past 10 years on this topic in the countries of the world. Obviously, it is the industrialized countries that are most active in this direction, which indirectly indicates the cost-effectiveness of this approach.

Figure 1. Dynamics of publications on the topic "specified life" over the past 10 years.

Figure 2. Dynamics of patenting on the topic "specified life" over the past 10 years in the world.
There are a number of works on designing die tools with limited durability [1-5], metallurgical equipment and aircraft structures [9]. However, such approaches are practically not applied to large metal-consuming forging equipment. But it is in this area that they can provide greater economic efficiency by reducing metal consumption, manufacturing time for large parts, reducing the load on the foundations, reducing transport costs. This is especially interesting for the industry of the Republic of the Union of Myanmar, since it does not yet have the capacity to create large parts, and the need for domestic technological machines of large forces is increasing. Therefore, the way to create technological machines of limited durability with low metal consumption is one of the options for the development of this industry in Myanmar. The same approaches can be implemented when modernizing equipment in Russian conditions, when existing machines increase the nominal force while maintaining metal-intensive basic parts (the main direction of modernizing press-forging equipment in Russia) [8].

2. Materials and Methods
As part of this work, the press frame CHFP (AJAX-CECO) with a nominal force of 20 MN and an open-type frame KD2130 with a force of 1 MN were simulated to increase the level of cyclic strength (durability) with constant metal intensity and rigidity (figure 3).

For calculation using numerical methods, the Solid-Works system was used to automate mechanical design and create solid-state parametric models of parts, assemblies and drawings. The system works in the MS Windows operating environment. Solid-Works software, that includes finite element analysis, which corresponds to a high accuracy class, proved by the International Association for Engineering Modeling, Analysis and Simulation NAFEMS.

![Figure 3](image)

**Figure 3.** a, c — the distribution of equivalent stresses (according to IV theory of strength), b, d — displacements along the vertical axis; a, b — relate to the CHFP (AJAX-CECO) press frame with a nominal force of 20 MN; c, d — to the open-type KD 2130 press frame with a force of 1 MN.

3. Results and Discussions
The calculation by the numerical method (finite element method) allowed us to reveal the optimal parameters of the design concentrators for the structures under consideration according to the criterion of cyclic strength and zones, the most dangerous according to the criterion of possible origin and growth of macro-cracks. It is assumed that the limiting states regulated in [10], PLS3 (*primary limit state*) can
be realized in the supports of the main shaft of the press and the guides of the slide. However, it is removable by replacements and registers. Therefore, in the future, only 3 limit states are taken into account: PLS2 — failure to operate due to the formation of fatigue cracks in metal parts at the moment of cyclic loading, ALS1 (additional limit state) — occurrence of fragile, quasi-brittle or viscous type with process initiation from a technological defect. In this paper, for the crank hot forging press (CHFP) we propose to take account ALS4 - the occurrence of specific degradation processes in the material of the frame during operational thermal cycling due to the influence of thermal load from the workpiece when performing technological operations on the die zone [11-13]. When designing power parts of forge-and-press machines for a given durability, the main tasks are the problems of fatigue damage accumulation under loads (PLS2), whose maximum values do not reach \( \sigma \) (yield strength) values, but there is a significant amount of loads with amplitudes greater than fatigue limit with cyclical loading [14-16].

The calculations were carried out only for the optimal according to the criterion of the cyclic strength of the concentrator with a given number of cycles to failure. The allowable stresses are calculated using the data analysis function “goal seek” in Microsoft Excel software. Accepted in the calculation of the primary data and the calculated values of some parameters are summarized in table 1. Stresses are found corresponding to the known values of the endurance limit of the frame from the table 1. The obtained values are presented in column 3 of the table 2.

| Primary data                                      | CHFP  | KD 2130 |
|--------------------------------------------------|-------|---------|
| Tensile strength \( \sigma_B \) (reference value) | 491 MPa | 300 MPa |
| The value of the sensitivity of the material to the cycle asymmetry by dependencies [17] | 0.12  | 0.08    |
| The endurance limit of the frame \( \sigma_{1c} \) taking into account all downward factors according to [17] | 61 MPa | 72 MPa |

Table 2. Results of stress calculation by a given number of cycles to failure.

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-----|---|---|---|---|---|---|---|
|     | The number of cycles to failure (specified) | \( \times 10^7 \) basic number of cycles according to [17] | \( 6 \times 10^6 \) | \( 6 \times 10^5 \) | \( 6 \times 10^4 \) | \( 5 \times 10^4 \) |
| 1   | N | 109.11<sup>a</sup> | 128.59<sup>a</sup> | 216.41<sup>a</sup> | 304.23<sup>a</sup> | 311.18<sup>a</sup> |
|     | The maximum stress allowed by the condition of ensuring a specified number of loading cycles, MPa | \( \sigma_{\text{max}} \) | 133.33<sup>b</sup> | 145.66<sup>b</sup> | 201.21<sup>b</sup> | 256.77<sup>b</sup> | 261.17<sup>b</sup> |
| 2   | \( \sigma_{\text{res}} \) in a symmetrical loading cycle, MPa | 61<sup>a</sup> | 71.9<sup>a</sup> | 120.99<sup>a</sup> | 170.1<sup>a</sup> | 173.98<sup>a</sup> |
| 3   | \( \sigma_{\text{res}} \) in a symmetrical loading cycle, MPa | 72<sup>b</sup> | 78.66<sup>b</sup> | 108.66<sup>b</sup> | 138.66<sup>b</sup> | 141.03<sup>b</sup> |

<sup>a</sup> Values for press frame CHFP.
<sup>b</sup> Values for press frame KD2130.

Then the dependences of equivalent static stresses (MPa) on the number of loading cycles were constructed (figure 4). The graph was plotted only for the region of multi-cycle fatigue in semilogarithmic coordinates. There is a linear relationship between stress and the number of cycles before failure. With this dependence, it is possible to determine which stress level corresponds to a given number of loading cycles, and then, based on the dependence connecting the stresses and the force causing them (with the optimal parameters of the concentrator defined above), designate the declared...
when designing for a given durability. That is, the declared force in the design (modernization) of the “specified life” system proposes to call the force that provides the specified value of durability.

**Figure 4.** The influence of stresses (MPa) on the number of loading cycles (high-cycle area of fatigue) at optimal concentrators.

**Table 3.** Calculated performance with an increase in nominal forces.

| Press   | k | 1  | 1.5 | 2  | 2.5 | 3  | 3.5 | 4  | 4.5 | 5  |
|---------|---|----|-----|----|-----|----|-----|----|-----|----|
| CHFP    | k×10^7/M | 1.42 | 2.14 | 2.85 | 3.56 | 4.27 | 4.98 | 5.7 | 6.41 | 7.12 |
|         | N×10^3    | 5300 | 920  | 160 | 27.7 | 4.81 | 0.84 | 0.15 | 0.025 | 0.004 |
| KD2130  | k×10^7/M | 12.82 | 19.23 | 25.64 | 32.05 | 38.46 | 44.87 | 51.28 | 57.69 | 64.1 |
|         | N×10^3    | ∞    | ∞    | ∞   | 3650 | 990  | 268 | 73  | 20   | 5.3  |

A further calculation was the number of cycles to failure with an increase in technological forces with the existing version of the bed considered above CHFP and KD2130. The values of stresses in each variant were determined by calculation by numerical methods. The data are summarized in table 3. The following notation k – the coefficient of increase of nominal power (P_n), M – the mass of the frame (70237 kg 7800 kg CHFP and KD2130 respectively).

The ratio of the applied force to the mass of the structure, as a target function, should tend to the maximum when imposing restrictions on rigidity and the required (specified) durability. Next, you need to find out the nature of the influence of technological forces on the durability of the forging and pressing machine on which the operation is performed. Low-cycle fatigue is limited to N≤5 · 10^5, presses designed according to “specified life” and crank punching machines that have been modernized with an increase in the declared technological forces should not work in the area of low-cycle fatigue. On universal forming presses, the main operation is cutting / punching, the technological strength of which depends on the shear resistance and the area of the cut [18]. A graphic representation of the dependence of force on the parameters of separation operations is given in figure 5.

To ensure a specified number of cycles to failure during a technological operation on the press KD2130, it is accepted by approximating the calculated data using the P → σ_{eq} (FEM) → σ_{res} (according to [17]) → N. We obtain the following:

$$N = 4 \cdot 10^6 \cdot P^2 - 16.315 \cdot P + 2 \cdot 10^7$$

(1)

The main operation at the CHFP accept hot upsetting [18]. The dependence of the force of hot upsetting of a billet of steel 45 on the height of the billet H_{ups} and diameter of the billet D_{ups} after hot upsetting is shown in figure 6.

Similarly, we obtain the following expression for the number of cycles to the destruction of the CHFP bed from process operations of hot sludge:
\[ N = 1.39 \cdot 10^{-6} D_{oc}^4 \cdot \left( 1 + 0.17 \frac{D_{oc}}{H_{oc}} - 0.33 \frac{H_{oc}^2}{D_{oc}^2} \right)^2 - 9.8 D_{oc}^2 \cdot \left( 1 + 0.17 \frac{D_{oc}}{H_{oc}} - 0.33 \frac{H_{oc}^2}{D_{oc}^2} \right) + 2 \cdot 10^7 \] (2)

Figure 5. Graphical representation of the calculated data for the separation operations.

Figure 6. Graphic representation of the ratio of hot upsetting force, height and diameter of the work-piece after hot upsetting for steel 45.

Graphic representation (2) is shown in figure 7.

Figure 7. Graphic representation of the expression (2).
Thus, a calculation procedure has been developed, which makes it possible to ensure the durability set by the technical specification (the number of cycles to failure) of the basic parts of the crank punching machines. The main stages of calculations:

- Determination of the loads acting on the base parts of the press in the process of loading with a nominal force.
- Calculation of the finite-element model of the objects under study by numeral methods (finite element method) under the action of nominal force.
- Optimization of all structural stress concentrators of the base part by the criterion of maximum cyclic strength with a constant metal intensity: determination of the dependence of stresses and displacements on the magnitude of the applied force at various parameters of concentrators by the finite element method, calculation of loading cycles to failure at various parameters of the concentrator, according to calculations plotting the number of loading cycles to failure from the geometry/dimensions of the concentrator, optimization of the obtained dependence of n on the criterion for obtaining the maximum loading cycles by the simplex method with the imposition of restrictions on constructive considerations.
- Construction of the calculated dependence of the voltages, reduced to a symmetrical cycle, on the applied technological forces, other than the nominal, adopted in the original calculation.
- Construction of the dependence of the stresses reduced to a symmetric cycle on the number of loading cycles (inverse problem).
- Determination of the corresponding values of stresses to symmetric cycles according to the graph of the dependence of the stresses to symmetric cycles from the number of cycles to failure, according to a given number of cycles to failure.
- Determination of the dependence of the stresses, reduced to symmetrical cycles, on the applied forces, the force, allowing to ensure the specified durability. We assign this force nominal.
- Determination of stiffness and comparison of the obtained stiffness with empirical stiffness according to recommendations substantiated in the works of Lansky E.N., Banketov A.N. and Krupa A.T. Comparison of obtained stiffness with recommended values for nominal force. If the resulting value is less than the recommended, then change the design to obtain the desired values (by iterative approximation or optimization with the imposition of restrictions on stiffness / displacement).
- Determination of the order of loading (loading history) according to the hypotheses of Henry, Guts, Serensen S.V. and Manson, giving the maximum value of the residual life of the base part at the end of the load block. This will provide a minimum scientifically based margin on fatigue life, which will allow parts to work out all the load cycles specified in its design without cracking with the minimum ratio of metal intensity / technological force.
- Determination of the number of cycles to failure with increasing technological forces at a constant mass of the structure and its rigidity.
- Determination of the parameters of technological operations according to the obtained dependencies (1) and (2), allowing to ensure the specified durability and not get into the low-cycle fatigue zone.

4. Conclusions

1. It has been proposed to introduce for a CHFP designed for a given durability, another type of limit state ALS4 - the occurrence of specific degradation processes in the material of the frame during operational thermal cycling.

2. A design methodology was developed to provide the durability of the base parts of the crank punching machines specified by the technical specification, while preserving the standardized technical documentation rigidity of the machine, based on the parameters of the main technological operations performed on the crank punching machine. For hot upsetting of billet on CHFP with a force of 20 MN, the following parameter range was considered - diameter after hot upsetting from 250 mm to 1250 mm, height after hot upsetting from 100 to 500 mm, σs - deformation resistance from 1 to 25.3 MPa. It is shown that it is only possible to increase the technological force on this press up to 1.5 times without
entering the low-cycle fatigue zone. For a crank punching machines KD2130 as the variable parameters of the technological cutting/punching operations were taken — the area of the cut (varied in the interval from 50 to 6700 mm²) and the shear resistance (from 300 to 590 MPa). It is shown that the maximum increase in force is 3 times.

3. The optimal constructive concentrators of the frames of the KD2130 press and the CHFP with a nominal force of 20 MN were determined according to the fatigue strength criterion. It is shown that under cyclic loading even a slight decrease in static stresses (by 7 MPa relative to the existing version of the frame) allows to increase the number of cycles to failure by 20%. The dependence of the ratio of the technological force of a crank punching machine to the weight of the frame for presses KD2130 and CHFP with a nominal force of 20 MN is compared. In the existing version for CHFP the ratio of the nominal force to mass is 0.28 kN/kg and for press KD2130 -0.13 kN/kg.

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