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Investigation of the Accuracy of the Height Dimensions of Forgings for Cold Volumetric Stamping Processes by the Computational and Analytical Method

Sergei Matveev

M1-CF "Machine-building Technologies", Kaluga Branch of the Bauman Moscow State Technical University, Kaluga, Russia

Email address:
s.matveev@alarmtrade.ru

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Abstract: In mechanical engineering, product quality indicators are inextricably linked with the accuracy of machining parts. The dimensions, shape and location of the surfaces obtained during processing determine the actual gaps and tightnesses in the joints of machine parts, and consequently, the technical parameters that affect the quality, reliability and economic performance of production and operation. Very often in practice, the achievable accuracy of processing, including cold volumetric stamping (HOS), is judged by the accuracy tables contained in special reference literature. Such tables contain indicative data on achievable accuracy for various technological operations, obtained by systematization of direct long-term observations in production conditions. However, the peculiarities of individual operations do not allow us to give a conclusion about the accuracy of stamping by analogy with other operations, since there is no comprehensive similarity between them. In particular, the sizes and shape of the initial blanks differ, mechanical the properties of their material, the friction conditions in the die cavity, the characteristics of the press used and other technological factors. Thus, taking into account the listed circumstances, in each specific case it is necessary to calculate the accuracy of processing, which should have the ultimate goal not only to obtain a numerical result, but first of all to disclose the mechanisms of accuracy control. The calculation of the processing accuracy should be carried out taking into account the methods of obtaining dimensions and methods of setting up the technological system. The article is devoted to the computational and analytical method for calculating the forging accuracy based on the application of the theory of parametric sensitivity.

Keywords: Parametric Sensitivity, Accuracy, Cold Volumetric Stamping, Forging

1. Introduction

The objective of the study is to use a computational and analytical method to determine the qualitative indicators of forgings, which is based on the provisions of the theory of parametric sensitivity. Thanks to modern approaches, it is possible to predict the desired accuracy of forgings without preliminary adjustments in production processes. The methods of implementation consist in theoretical approaches and empirical relationships of the processes occurring during stamping. However, not all methods are able to take into account a large number of factors arising in the initial workpieces, during commissioning, type of equipment, process. The basis of one of the approaches was laid by E. N. Lanskoy the essence and purpose of this approach is the computational and analytical study of the output parameter, taking into account the relationship of the initial factors.

To analyze and calculate the accuracy of technological processes, it is preferable to use such methods where the maximum number of factors affecting accuracy is taken into account, taking into account their mutual influence. One of these methods is a method based on the application of the basic provisions of the theory of parametric sensitivity. The theory of sensitivity is based on the representation of a technological system in the form of a closed system and provides for a comprehensive, taking into account all the relationships, study of the object in question as a whole from the standpoint of system analysis. Signs of a systematic approach are manifested in the following [1, 2]:

1) If a technological system is represented as a system, for example, a press-stamp-forging, then a set of elements can be distinguished in it, each of which, under certain conditions, can be considered as a separate independent system.

2) The necessary completeness of the elements included in the system of the object under study (the closeness of the system) is determined by the strength of the connection between these elements, which should be more than 2 orders of magnitude greater than the strength of the connection of the same elements with others not included in this system.

3) The system must have new properties that are not inherent in any of its elements. This means that by dividing the technological system into parts and studying them separately, it is impossible to know all its properties. The latter statement is a very important circumstance, which implies an analysis of the accuracy of the technological operation in inseparable connection with the characteristics of the equipment used and, conversely, the stamping accuracy achieved on presses with different types of drive depends on the characteristics of the forgings being stamped and the features of the technological operation.

All this sets the goal of investigating the accuracy of forgings for Cold Volumetric Stamping (CVS) operations by the computational and analytical method. Thanks to the analytical and experimental-static base created by foreign [4, 6-11] and domestic scientists, it is possible to fully investigate the processes of CVS, there are a number of functional dependencies for determining the height dimensions of forgings, in particular, the basic provisions of the theory of parametric sensitivity (TPS) are used [12-17].

2. Materials and Methods

The parametric sensitivity of the technological system "press - stamp - forging" is understood as its property to change its output characteristics, for example, deviations in the height of forgings from the parameters (errors) of the initial workpiece and the technological process. The main problem of the theory of sensitivity of systems is the development of effective methods for quantifying the effect of errors in the initial parameters on the output characteristic – the error of the height of forgings. In the theory of sensitivity, a quantitative indicator of parametric sensitivity is widely used in the form of a partial derivative of the output characteristic for the corresponding parameter setting the error. Such an indicator in the theory of sensitivity is called the sensitivity function, and in the theory of the accuracy of technological processes and the theory of dimensional circuits – the coefficient of influence or the gear ratio. Thus, it is assumed that the mathematical model that determines the dependence of the output characteristic (parameter) on the input parameters is an analytical differentiable function of the form [2]:

$$y = \left(x_1, \ldots, x_n\right), \tag{1}$$

where y – is the output parameter of the system; $x_1, \ldots, x_n$ – are the primary parameters; n – is the number of primary parameters. For ideal conditions in the absence of disturbances in the form of errors, respectively, we have:

$$y_0 = \left(x_{10}, \ldots, x_{n0}\right). \tag{2}$$

In real conditions, the values of the parameters differ from the ideal (nominal) values by some amount $\Delta x_i = (x_i - x_0)$. When calculating, it is assumed that the deviations of the parameters are small ($\Delta x_i << x_i$) and mutually independent. The products of errors are neglected. The function $y = (x_1, \ldots, x_n)$ in the vicinity of the nominal values of the parameters is decomposed into a Taylor series. Limiting ourselves only to the terms of the expansion in the first degree, we obtain a ratio for calculating the absolute error Δy of the output parameter y:

$$\Delta y = \sum_{i=1}^{n} \frac{\partial \varphi}{\partial x_i} \Delta x_i . \tag{3}$$

This expression is called the equation of the absolute error of the output parameter in the most general form. Values $\frac{\partial \varphi}{\partial x_i}$ – are absolute sensitivity coefficients (influence coefficients) showing how the value of Δy reacts to the deviation of Δx_i.

The main feature of the described analytical method for calculating sensitivity coefficients is that the dependence between the input and output parameters, the so-called transformative function is known in explicit or implicit analytical form. If the initial model is an analytical function, then, depending on the form of its representation, analytical differentiation methods, sensitivity tables of transfer operators or frequency polynomials can be used to calculate sensitivity coefficients [2, 12–17].

The main advantage of computational and analytical methods is that they not only allow calculations for particular specific cases, but also give an idea of the regularities of the influence of certain parameters and their errors on the deviations of the output parameter in general. Thus, prerequisites are created for the possibility of controlling the accuracy of processing.

3. Research Results

3.1. Theoretical Parts

The presented method has been tested at the M1-CF Department "Machine-Building Technologies" of the Kaluga branch of the Bauman Moscow State Technical University for the accuracy of CVS operations. When evaluating any technological process (both mechanical processing and CVS) by the criterion of achievable accuracy, it is necessary to determine the dependence of the main parameter characterizing the accuracy of the process on the primary errors. This dependence can be determined on the basis of the theory of parametric sensitivity, which allows us to identify the influence of primary errors on the accuracy of the output parameter.

Let's consider the main provisions of the theory of parametric sensitivity.

An important condition for the possibility of applying the theory of parametric sensitivity is the need to fulfill a number of conditions:

1) the function describing the technological process must be continuous and differentiable in the vicinity of the point y_0;

2) the errors of the primary parameters should be significantly less than the parameters themselves $(\Delta x_i << x_i)$.

Let 's imagine the technological process in the form of the following model:

$$y = \ (x_1, x_2, \ldots, x_n), \tag{4}$$

where y – is the output parameter of the system; x_1, x_2, …, x_n – are the primary parameters; n –is the number of primary parameters.

Then you can write

$$y + \Delta y = \ (x_1 + \Delta x_1, x_2 + \Delta x_2, \ldots, x_n + \Delta x_n). \tag{5}$$

Decompose equation (5) into a Taylor series at the point

$$x_0 = (x_{i0}, \ldots, x_{n0}),$$

where x_{i0} - is the average value of the i-th primary parameter.

Then we get

$$y + \Delta y = \ (x_{i0}, \ldots, x_{n0}) + \sum_{i=1}^{n} \frac{\partial \varphi}{\partial x_i} \Delta x_i + \frac{1}{2} \sum_{i=1}^{n} \frac{\partial \varphi^2}{\partial x_i^2} (\Delta x_i)^2 + \ldots \tag{6}$$

Subtracting equation (4) from equation (6) and discarding the terms of the 2nd and higher order, we obtain

$$\Delta y = \sum_{i=1}^{n} \frac{\partial \varphi}{\partial x_i} \Delta x_i. \tag{7}$$

This expression is called the absolute error equation of the output parameter. In the above equation Δx_i there are absolute errors of the primary parameters, $i=1,\ldots, n$.

The values $\frac{\partial \varphi}{\partial x_i}$ are called absolute sensitivity coefficients, they show how the value Δy reacts to the values of deviations Δx_i. Dividing (7) by (5), we obtain the equation of the relative error of the output parameter

$$\frac{\Delta y}{y} = \sum_{i=1}^{n} \frac{\partial \varphi}{\partial x_i} \ \frac{\Delta x_i}{x_i} \ \frac{x_i}{x_i} = \sum_{i=1}^{n} K_i \ \frac{\Delta x_i}{x_i}. \tag{8}$$

Relationship

$$K_i = \left[\frac{\partial \varphi \cdot x_i}{\partial x_i \cdot \varphi} \right]_0 \tag{9}$$

they are called the relative sensitivity coefficient (SC) or the influence coefficient. It characterizes the degree of influence of the relative error of the primary parameter on the relative error of the output parameter.

With a given type of model and the selected nominal values of the primary parameters, the sensitivity coefficients are deterministic values, i.e. they are fixed numbers. The sensitivity coefficient can be either positive or negative, either greater than one or less than one.

The expression K_i that allows you to determine its value is obtained from the analysis of functions describing the process. When performing stamping operations, such a function will be the equality of the force developed by the press and the strength of the forging resistance to deformation. The strength of the forging resistance to deformation can be determined by well-known analytical formulas for almost all CVS operations. The force developed by the press depends on its type and, first of all, on the nature of the connections existing in the technological system, press-stamp-forging [3-5].

For a crank press, such a connection is a coordinate one, and for a hydraulic one – a power one. Thus, for a crank press, the function describing the deformation process can be represented as:

$$C(x_1 - H) = P(x_1, \ldots, x_i, \ldots, x_n), \tag{10}$$

where C - is the rigidity of the press-stamp system, x_1– is the forging height, H – is the die height, $P(x_1, \ldots, x_i, \ldots, x_n)$ – is the strength of the forging resistance to deformation, as a function of the parameters $x_1, \ldots, x_i, \ldots, x_n$, which include the geometric parameters of the forging, the mechanical characteristics of its material and others.

For a hydraulic press, the function looks like this:

$$P_G = P(x_1, \ldots, x_i, \ldots, x_n), \tag{11}$$

where P_G – is the force of the hydraulic press.

Unlike crank and hydraulic presses for screw presses, the function describing the deformation process looks like the equality of the energy accumulated by the moving part of the press and the work aimed at deforming the forging:

$$E = E_C + E_f + A,$$

where E - is the energy accumulated by the moving part of the press; E_C – is the energy spent on elastic deformation of the system; E_f – is the energy spent on overcoming friction forces; A – is the work aimed at deforming the forging.

Given that $E_C = \frac{(P(x_1, \ldots, x_i, \ldots, x_n))^2}{2C}$, $E_f = k_f(A + E_C)$, we obtain the final dependence describing the process of forging deformation on a screw press:

$$E = \left(1 + k_f\right) \cdot \left(A(x_1, \dots, x_i, \dots, x_n) + \frac{\left(P(x_1, \dots, x_i, \dots, x_n)\right)^2}{2C}\right), \quad (12)$$

where k_f – is a coefficient that takes into account friction losses; $A(x_1, \dots, x_i, \dots, x_n)$ – is the work spent on deformation of the forging; $P(x_1, \dots, x_i, \dots, x_n)$ – is the forging resistance force as a function of the parameters $x_1, \dots, x_i, \dots, x_n$.

Using the dependencies (10, 11, 12) and supplementing them with the condition of volume constancy, since the operations of precipitation and closed stamping are performed with the preservation of the entire volume in the die cavity, according to the well-known method [2] we obtain mathematical dependencies that allow us to determine the values of the sensitivity coefficients for various types of presses.

For crank press:

$$K_i = \frac{\frac{\partial P}{\partial x_i} \cdot x_i}{C - \frac{\partial P}{\partial x_1} + \frac{\partial P}{\partial x_2} \cdot \frac{\partial V}{\partial x_1} \cdot \frac{1}{\frac{\partial V}{\partial x_2}}} \cdot \frac{x_i}{x_1}, \quad (13)$$

For hydraulic press:

$$K_i = \frac{\frac{\partial P}{\partial x_i}}{-\frac{\partial P}{\partial x_1} + \frac{\partial P}{\partial x_2} \cdot \frac{\partial V}{\partial x_1} \cdot \frac{1}{\frac{\partial V}{\partial x_2}}} \cdot \frac{x_i}{x_1} \quad (14)$$

For screw press:

$$K_i = \frac{C\frac{\partial A}{\partial x_i} + P\frac{\partial P}{\partial x_i}}{\left(C\frac{\partial A}{\partial x_2} + P\frac{\partial P}{\partial x_2}\right) \cdot \frac{\partial V}{\partial x_1} \cdot \frac{1}{\frac{\partial V}{\partial x_2}} - \left(C\frac{\partial A}{\partial x_1} + P\frac{\partial P}{\partial x_1}\right)} \cdot \frac{x_i}{x_1} \quad (15)$$

where C – the rigidity of the press-stamp system; P– the nominal strength of the forging resistance to deformation; x_1 – the height size of the forging; x_2 – the size of the forging associated with the size of x_1 by the condition of constancy of volume; x_i – the forging parameter affecting the accuracy of forging; And A – the work of plastic deformation of the forging.

3.2. Calculation Part

On the basis of this technique, dependences were obtained for calculating the SC for precipitation operations performed on a crank [1, 2, 15], hydraulic [15] and screw press [12, 13, 14]. In particular, functions are obtained for determining $K\sigma$ and K_V, characterizing the effect of errors associated with changes in the mechanical properties of the forging material ($\delta\sigma_s$) and changes in the volume of the initial workpieces (δV), respectively, during precipitation.

On the crank

$$K_V = \frac{\frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{d}{2h}\right)}{C + \frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{5d}{6h}\right)}, \quad (16)$$

$$K_\sigma = \frac{\frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{d}{3h}\right)}{C + \frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{5d}{6h}\right)} \quad (17)$$

hydraulic

$$K_V = \frac{\frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{d}{2h}\right)}{\frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{5d}{6h}\right)} \quad (18)$$

$$K_\sigma = \frac{\frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{d}{3h}\right)}{\frac{\pi d^2}{4h} \cdot \sigma_S \cdot \left(1 + \mu\frac{5d}{6h}\right)} \quad (19)$$

screw

$$K_V = \frac{C\left(\frac{\varepsilon}{1-\varepsilon} + \frac{\mu}{2}\frac{d}{h} \cdot \ln\frac{1}{1-\varepsilon}\right) + \frac{P}{h}\left(1 + \frac{\mu}{2}\frac{d}{h}\right)}{C\left(\frac{1}{1-\varepsilon} + \frac{\mu}{6}\frac{d}{h}\left(2 + 3 \cdot \ln\frac{1}{1-\varepsilon}\right)\right) + \frac{P}{h}\left(1 + \frac{5\mu}{6}\frac{d}{h}\right)} \quad (20)$$

$$K_\sigma = \frac{C\left(\frac{\varepsilon}{1-\varepsilon} + \frac{\mu}{3}\frac{d}{h} \cdot \ln\frac{1}{1-\varepsilon}\right) + \frac{P}{h}\left(1 + \frac{\mu}{3}\frac{d}{h}\right)}{C\left(\frac{1}{1-\varepsilon} + \frac{\mu}{6}\frac{d}{h}\left(2 + 3 \cdot \ln\frac{1}{1-\varepsilon}\right)\right) + \frac{P}{h}\left(1 + \frac{5\mu}{6}\frac{d}{h}\right)} \quad (21)$$

Analyzing the obtained formulas for calculating the SC, it can be seen that their value for crank and screw presses depends on their rigidity (C) and the rigidity of forgings. Taking into account the fact that the rigidity of the forging is the rate of change of the force along the displacement of the deforming surface, it can be defined as a partial derivative of the resistance force of the forging from its height ($C_{forging} = \frac{\partial P}{\partial h}$) [17].

For precipitation

$$C_{forging} = \frac{\partial P}{\partial h} = \left(\frac{\pi d^2}{4}\sigma_s\left(1 + \mu\frac{d}{3h}\right)\right)'_h = -\frac{\pi d^2}{4h}\sigma_s \cdot \frac{\mu}{3} \cdot 2 \cdot \frac{d}{h}.$$

From where it can be seen, the rigidity of the forging during precipitation depends on the ratio of its dimensions *d/h*, the yield stress of the material and the magnitude of the coefficient of contact friction. If forgings are made of the same material and under the same conditions of contact friction, then the rigidity of the forgings will be determined by the ratio of their dimensions *d/h*. When draining on a hydraulic press, the value of the SC, and hence the accuracy of the height dimensions, depends on the rigidity of the forging.

Figure 1 shows the graphical dependences of $K\sigma$, on the ratio *d/h*, which characterizes the rigidity of the forging, for the operation of the draft of steel 45 (σ_s*=828 MPa* ε*=0.34, d=25 mm,* μ *=0.1*), calculated for crank, hydraulic, screw press according to the formulas (16, 17, 18, 19, 20, 21) [17].

The analysis of the obtained graphs in Figure 1 shows a fundamentally different effect of *d/h* (forging stiffness) on the magnitude of the coefficients $K\sigma$, K_V for a hydraulic press compared with crank and screw presses. If for a hydraulic press with an increase in the rigidity of the forging, the value of the coefficients decreases, then for the crank and screw increases. This indicates a decrease in the influence of the initial errors ($\delta\sigma_s$, δV) on the accuracy of the forging height when draining on a hydraulic press with an increase in the rigidity of the forging, and when draining on crank and screw presses, this influence increases [17].

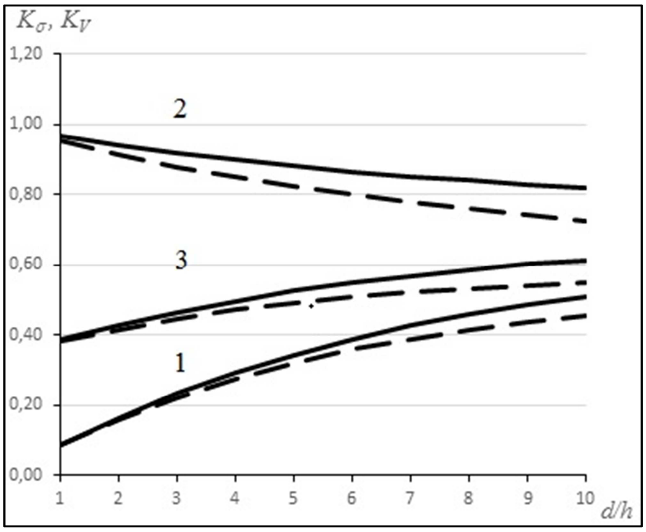

Figure 1. *Dependence of the coefficients KV, Kσ on the ratio d/h for crank (1), hydraulic (2) and screw press (3). (-K_V, -K_σ).*

4. Conclusion

1) The theoretical studies carried out on the accuracy of the height dimensions of forgings for various CVS operations performed on different types of presses, using the TPS method, allows us to assess the effect of the initial errors of the workpiece (δV, $\delta\sigma_s$) on the accuracy of the height dimensions of forgings.
2) When performing the precipitation operation, the error of the volume of the initial workpieces has a greater effect on the accuracy of the height (the K_V coefficient is greater than the $K\sigma$ coefficient), and for all types of presses. The effect of the initial errors on the accuracy of the forgings height depends significantly on their rigidity, one of the characteristics of which is the d/h ratio. For hydraulic presses, with an increase in the rigidity of forgings, this effect decreases, for crank and screw presses, it increases. With low rigidity of forgings (*d/h = 1.0*), the accuracy of the height at the draft on the hydraulic press differs significantly from the accuracy at the draft on the crank and screw presses (for the hydraulic press K_V = 0.969, for the crank K_V= 0.086, for the screw K_V= 0.387). With a high rigidity of forgings (*d/h =10.0*), the accuracy becomes comparable (for a hydraulic press K_V = 0.818, for a crank press K_V= 0.510, for a screw press K_V=0.614).
3) In order to reduce the error of the height dimensions of forgings, when designing the technological processes of CVS, the above method allows us to assess the effect of the initial errors of the workpieces on the accuracy of the height dimensions of forgings, to determine the feasibility of using forging equipment for a specific operation. This technique has been tested at the enterprises of the Kaluga region of Public Corporation KZAE, Kaluga Electrotechnical Plant KWT.

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