Experimental verification of the adequacy of a theoretical model of draft accuracy performed on a hydraulic press

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Abstract. The technique of obtaining a theoretical model of draft accuracy performed on a hydraulic press is considered. Using the basic principles of the theory of parametric sensitivity, a theoretical model was obtained to calculate the expected error in the height dimensions of the forgings. Applying the obtained model, the error in forging height was calculated, caused by the error in setting up the hydraulic press. The results of experimental studies to determine the influence of the error of setting up a hydraulic press on the accuracy of the height of the forgings are presented. A comparative analysis of theoretical calculations with experimental results is performed. Based on a comparative analysis, it was concluded that the obtained theoretical model is adequate.

One of the most important tasks in the design of technological processes is predicting the accuracy provided when performing a particular technological operation. Cold forming operations (CFO) are no exception. One of the most common CFO operations is sediment. Precipitation accuracy in most cases refers to the accuracy of the height dimensions of the upsetting forgings, since the accuracy of the diametric dimensions is related to the condition of constant volume with the height dimensions of the forgings.

The error $\Delta h$ is influenced by a significant number of factors related to both the errors of the initial blanks and the features of operations on various types of forging equipment.

We will consider the influence of the error of setting up a hydraulic press on the accuracy of the height dimensions of the forgings during upsetting.

The magnitude of the error in the height of the forgings can be determined on the basis of experimental studies, as well as using theoretical dependencies. Experimental relate to quite expensive methods, although they give more accurate results. Theoretical studies allow us to determine the approximate values of deviations from the nominal dimensions of the forgings, however, at the initial stage of the design of technological processes, their use is more appropriate.

Since theoretical dependences give approximate values, the question of their adequacy arises.

A theoretical model of the accuracy of the draft performed on a hydraulic press can be obtained using the basic principles of the theory of parametric sensitivity [1,2]. According to this theory, the forging height error can be represented by equation (1) in which $\Delta h_{x_i}$ is the error in the forging height caused by the $x_i$ factor; $A_{x_i}$ is the conversion coefficient or the sensitivity function of the output parameter ($\Delta h_{x_i}$) to changes in the input ($x_i$).
Using the mathematical apparatus of the theory of parametric sensitivity, we determine the
dependence describing the sensitivity function of the error in the forging height $\Delta h_p$ to the error in setting
up the hydraulic press $\Delta P$.

When stamping on a hydraulic press with emphasis on forging, when the force on the slider is
constant, the final position of the movable part of the stamp, and hence the size of the forging height $h$,
is determined only by the equality of the force on the slider of the press, with a set pressure limit and
the strength of the forging resistance. In this case, the connection implemented in the technological
system is called power one, and it is written in the form of the equality presented in equation (2) in
which $P_r$ is the force on the slider of the hydraulic press; $P(x_1, x_2, ..., x_i, ..., x_n)$ is the resistance force of
the forging deformation; $x_1, x_2, ..., x_i, ..., x_n$ are forging parameters affecting the strength of the resistance;
$x_1$ и $x_2$ are the geometric parameters $h$ and $d$, respectively.

$$P_r - P(x_1, x_2, ..., x_i, ..., x_n) = 0$$

An analysis of the accuracy of the technological system should take into account the peculiarities of
the deformation of the plastic element that arise as a result of the implementation of various CFO
operations, and significantly affect the force mode of deformation. From this point of view, two options
are possible: deformation of the initial workpiece while maintaining its entire volume between the
deforming surfaces, or deformation with the displacement of part of the volume from the open cavity.
In the first case, the geometrical parameters of the forging ($x_1$ и $x_2$) are related to the condition that the
entire volume of the workpiece is preserved between the deforming surfaces of the stamp, which means
that they depend on the volume error of the original workpiece. In the second, they do not depend on
errors in the volume of the workpiece, and this must be taken into account in the analysis. Draft refers
to the first option, when the entire volume of the initial billet is stored between deforming planes, which
means the dependence of the geometrical parameters of the forging $x_1$ and $x_2$ on the volumetric error of
the initial billet, therefore, equation (2) needs to be supplemented by the condition of constant volume
of equation (3).

$$V(x_1, x_2) = 0$$

Assuming functions (2) and (3) to be continuous and differentiable, and after passing to small finite
increments ($dx_i \approx \Delta x_i$), we obtain the following system of linear equations (4):

$$\begin{align*}
\frac{\partial P}{\partial x_1} \Delta x_1 + \frac{\partial P}{\partial x_2} \Delta x_2 + \ldots + \frac{\partial P}{\partial x_i} \Delta x_i + \ldots &= \Delta P \\
\frac{\partial V}{\partial x_1} \Delta x_1 + \frac{\partial V}{\partial x_2} \Delta x_2 + \ldots &= 0
\end{align*}$$

The solution to system (4) is determined by the Cramer formula: $\Delta x_i = \frac{D_{xi}}{D}$. The determinants $D$ and
$D_{x_1}$ in the presence of only one error $\Delta P$ will have the following form:

$$D = \begin{vmatrix}
\frac{\partial P}{\partial x_1} & \frac{\partial P}{\partial x_2} \\
\frac{\partial V}{\partial x_1} & \frac{\partial V}{\partial x_2}
\end{vmatrix} = \frac{\partial P}{\partial x_1} \frac{\partial V}{\partial x_2} - \frac{\partial P}{\partial x_2} \frac{\partial V}{\partial x_1} \neq 0$$

$$\Delta h_x = A_x \cdot \Delta x_i$$ (1)
\[
D_{x_1} = \begin{bmatrix}
\Delta P \\
0
\end{bmatrix}
\begin{bmatrix}
\frac{\partial P}{\partial x_2} \\
\frac{\partial V}{\partial x_2}
\end{bmatrix} = \Delta P \cdot \frac{\partial V}{\partial x_2} 
\]

(6)

Dividing equation (6) by equation (5) and performing the transformations, we obtain a formula for determining the forging height error stamped with the condition that its volume is constant in the die cavity on the hydraulic press and caused only by the error of setting up the hydraulic press (\(\Delta P\)):

\[
\Delta x_1 p = \frac{1}{\partial V / \partial x_1} \frac{\partial P}{\partial x_2} \cdot \Delta P 
\]

(7)

We will reduce the obtained equation (7) to the form (1), then the equation describing the sensitivity function of the forging height error \(\Delta h_p\) to the error of setting up the hydraulic press (\(\Delta P\)) will look like:

\[
A_p = \frac{1}{\partial V / \partial x_1} \frac{\partial P}{\partial x_2} 
\]

(8)

We represent the resistance force of the forgings to deformation in the form of the Siebel formula [3]:

\[
P = \sigma_S \frac{\pi d^2}{4} \cdot (1 + \frac{d}{3h}) 
\]

(9)

The condition for the constancy of the volume will be in the form:

\[
V = \frac{\pi d^2}{4} h 
\]

(10)

Having determined the partial derivatives of equations (9), (10) and substituting into equation (8), we obtain the final formula for determining the coefficient of conversion of the error of setting up the hydraulic press (\(\Delta P\)) into the error of the forging height \(\Delta h_p\) when upsetting operations on a hydraulic press:

\[
A_p = -\frac{h}{\sigma_S \frac{\pi d^2}{4} \left(1 + \frac{\frac{d}{3h}}{\left(\frac{d}{h}\right)}\right)} 
\]

(11)

where \(h\) and \(d\) are the height and diameter of the forgings, \(\sigma_S\) is the yield stress of the forgings material at the corresponding degree of deformation, \(\mu\) is the contact friction coefficient.

The «→» sign in the obtained dependence indicates that with increasing force on the slider (error \(\Delta P\) positive), the forging height decreases (\(\Delta h_p\) negative) and vice versa.

It should be noted that the error \(\Delta h\) to a large extent depends on the stiffness of the forging, which is determined by the geometrical parameters of the forging at the final moment of deformation (\(d/h\) ratio). Therefore, it is advisable to consider the influence of the adjustment error (\(\Delta P\)) depending on the rigidity of the forging (\(d/h\)).

Effect of adjustment error (\(\Delta P\)) depends on the rigidity of the forging (\(d/h\)).

Using equation (1) and equation (11), we will determine the errors \(\Delta h_p\) for forgings with different \(d/h\) ratios. The calculation results for steel forgings 45 (\(\sigma_S=985\text{MPa}\)) with a diameter of \(d=16\text{mm}\) with an error in setting up a hydraulic press \(\Delta P=15\) are shown in the graph in figure 1 (curve 1). Errors \(\Delta h_p\) are given in absolute form without regard to the sign.

To verify the adequacy of the theoretical model, a series of one-factor experiments was performed. Forgings made of steel 45 were deposited on a hydraulic press. The press was adjusted for forgings with nominal dimensions \(d=16\text{mm}\) and \(h=8\text{mm}\) (\(d/h = 2\)); \(d=16\) and \(h=4\text{mm}\) (\(d/h = 4\)); \(d=16\) and \(h=2\text{mm}\)
(d/h = 8), deposited with a degree of deformation $\varepsilon=0.35$ without lubrication ($\mu=0.1$) [4]. Next, the adjustment error was introduced by increasing the press force $\Delta P=15$ kN by a corresponding change in the pressure of the working fluid in the hydraulic system. Then the initial blanks were upset with increased force. The experiments were performed with three repetitions. The results are presented in figure 1 (curve 2).

It follows from the analysis of equation (11), that the value of the conversion coefficient $A_p$ depends both on the d/h ratio and on the physicomechanical properties of the forging material $\sigma_S$. Therefore, calculations were performed and experiments were carried out for forgings made of aluminum alloy AD31 ($\sigma_S=150$ MPa) with the same adjustment error $\Delta P=15$ kN. The results of calculations and performed experiments are presented in figure 2.

Comparing the obtained theoretical and experimental dependences for steel 45 and alloy AD31, it is clear that they are almost the same. With an increase in the rigidity of the forgings, determined by the d/h ratio, the influence of the adjustment error ($\Delta P$) on the accuracy of the height dimensions of the forgings ($\Delta h_p$) decreases. This is true for both theoretical and experimental dependence, which confirms the adequacy of the theoretical model. However, one should note the difference in the values of the error obtained by the calculated and experimental method. This difference is explained by the fact that the calculation method did not take into account factors that inevitably appear during cold forming operations. One of these factors is the hardening of the forging material associated with the degree of deformation. In the calculation method, the degree of deformation was assumed to be nominal, and the value $\sigma_S$ was also taken corresponding to this degree of deformation. During the experiment, a change in the force on the slider causes a change in the degree of deformation and, as a result, an error $\Delta \sigma_S$,
occurs, which in turn causes a change in the height of the forging, that is, an additional error appears due to the change in $\sigma_S$. Moreover, it should be noted that this error is positive, in contrast to the error caused by the change in force on the slider. In the calculation and analytical model, this factor was not taken into account. If this factor is taken into account, then the values of the errors obtained by the calculation and experimental methods become comparable. It is also seen from the analysis of the obtained dependences presented in figure 1 and 2 that with an increase in the stiffness of the forgings, determined by the $d/h$ ratio, the difference between the theoretical and experimental values of the errors becomes minimal. This means that for hard forgings, the influence of $\Delta \sigma_S$ on the height error becomes less significant. Moreover, this is true both for steel forgings and forgings from AD31 alloy, which also confirms the adequacy of the theoretical model.

It is advisable to use the resulting calculation model in the initial design of the technological process in order to determine the nature of the influence of the studied factors on the accuracy of the height parameters of the forgings and to predict achievable accuracy.

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