The energy-power parameters of the semi-enclosed heading of the rod-shaped hardware

O S Zhelezkov1, M V Kharchenko1,*, E M Martynov2 and E V Suvorova1

1Nosov Magnitogorsk State Technical University, Magnitogorsk, Russia
2Stary Oskol Technological Institute named after A.A. Ugarov (branch) NUST MISIS, Stary Oskol, Russia

*kharchenko.mv@bk.ru

Abstract. The paper presents a mathematical model developed on the basis of the variational method and the calculations of the energy-power parameters of the semi-enclosed heading of the rod-shaped hardware. The results of the calculations are illustrated in the form of a chart, which can be used to determine the deformation forces in relation to the ratio of sizes of the bolt heads to be formed.

When producing bolts and screws with multi-faceted heads on multiple-point presses, mainly the technologies of heading are used, technologies are used, including head landing in one or two steps operations with its subsequent trimming to a polyhedron [1-3]. It should be noted, that after heading but before cropping the head has a clear barrel shape. It happens because during the final punching the side surface of the head is formed by a free flow, while in the place where the metal contacts with the punch and the die, significant friction forces are in motion. Besides, a misadjustment or an uneven metal flow in radial directions often results in the bar axis offset. That is why, when cropping facets, the off scouring amounts to 5-8% of the head mass. To diminish the barreling and misalignment and, as a consequence, to reduce the metal consumption in the manufacture of bolts it is efficient to use semi-enclosed heading.

In case of the semi-enclosed heading, the final punching of the head occurs in a special hollow in the working end of the die. The diameter of the hollow is equal to the minimum allowable diameter of the circle of the described six-sided polyhedron. The part of the head adjacent to the bar is formed in the hollow of the die, while the end part of the head is formed by a free flow. The clearance between the die and the punch is necessary to prevent the breakdown of the tool if the metal overfills the working cavity of the die.

During the semi-enclosed heading (in comparison with the free forging) the deformation forces slightly increase, mainly in dependence on the clearance between the punch and the die. That is why, the task of determining the energy power parameters of the semi-enclosed heading process is of significant practical importance. It allows getting true information about the deformation forces, and thus, making a correct choice of forging equipment as well as developing an efficient design of the tool.
The aim of the study is the development of a mathematical model and the calculation of energy power parameters of the semi-enclosed heading of the rod-shaped hardware and, afterwards, the application of the results to the low-waste technologies.

The analysis of the known methods of determining the plastic working forces [4] shows that the variational method [5], in particular the discrete variational method [6,7], is suitable to define the energy power parameters of the semi-enclosed heading. The main idea of the method is the contingent division of the deformation process into two stages. In the initial stage the deformation forces have a final value, and the inhomogeneity of deformation appearing in the deformable body can be determined experimentally or analytically. In the final stage of punching the deformation is insignificant and it allows using strain relations of the deformation theory of plasticity. The rheology of properties of the metal being punched [8] is presented as a model of rigid-plastic environment with non-linear age-hardening. The hardening curve is described through the exponential dependence, proposed by G.A. Smirnov-Alyaev [9].

\[
\sigma_s = M - Ce^{-ei} - Be^{-Nei},
\]

where \( e_i \) is a hot forming ratio; \( M, C, B, N \) are the parameters, determined according to the compression and tensile tests.

The final stage of the semi-enclosed heading, when the metal fills the working cavity of the die and is forced out into the clearance between the die and the punch (fig. 1) is also under consideration. Die 1 has a cylindrical hollow with a radius \( R \) in the working end. The working surface of punch 2 is formed by two parallel planes with a conical transition surface, where the head facet is formed.

![Figure 1. The scheme of the metal flow at the final stage of the semi-enclosed heading](image)

The whole final deformed volume is divided into rigid and plastic regions. In the cylindrical system of axes \((r, z, \varphi)\) the boundary between the regions looks like a parabolic surface.

\[
h_r = h + a h (1 - \frac{r^2}{R^2}),
\]

where \( a \) is a varying parameter.

The whole plastic region is divided into 3 areas. At the borders of the plastic areas the displacement functions should meet the following conditions:

\[
U_{r|z=0} = 0; \ U_{z|x=0} = 0; \ U_{r|z=h_r} = U_{r|x=h_r} = -\Delta h; \ U_{z|x=h} = -\Delta h; \ U_{r|z=R} = U_{r|x=R}
\]
In equation 3 the indices marked by roman numerals point to the belonging of the functions to the corresponding plastic areas. If the index is not marked, the condition belongs to all the plastic areas.

According to the applied Rietz method, the function of radial motions for plastic areas I and II are set in the following form

\[ U_r^{I-II} = \frac{3\Delta h}{4h} r (1 - \frac{z^2}{R^2}) \quad (4) \]

The chosen function \( U_r \) meets the boundary conditions (3) and is close to the actual metal flow.

The function of vertical motions \( U_z^{I-II} \) is determined by using the condition of incompressibility. The components of the deformation tensor \( \varepsilon_r, \varepsilon_\varphi, \gamma_zr \) and the deformation intensity at the final stage of punching are determined with an application of Cauchy differential relationship for the case of axisymmetric deformation.

\[ \varepsilon_i = \frac{2\sqrt{3}}{3} \left( \varepsilon_r^2 + \varepsilon_r \varepsilon_\varphi + \varepsilon_\varphi^2 + \frac{1}{4} \gamma_zr^2 \right) \quad (5) \]

The radial motion function for the plastic area III is set in the form

\[ U_r^{III} = a_1 r (R - 1) + \left[ \frac{3\Delta h}{4h} - \frac{3}{2} a_1 (\frac{C}{R} - 1) \right] (1 - \frac{z^2}{R^2}) r \quad (6) \]

The vertical motion function \( U_z^{III} \) is determined regarding the condition of incompressibility. The components of the deformation tensor \( \varepsilon_r, \varepsilon_\varphi, \gamma_zr \) and the deformation intensity \( \varepsilon_i \) for the plastic area III at the final stage of punching are also determined.

The work of the internal forces for the plastic areas I, II и III at the final stage of semi-enclosed heading are defined like

\[ A_{b1} = \int_0^{2\pi} \int_0^R \int_{-h}^{hr} W r d\varphi dr dz ; A_{b2} = \int_0^{2\pi} \int_{R_1}^R \int_{-h}^{hr} W r d\varphi dr dz ; A_{b3} = \int_0^{2\pi} \int_R^{R_2} \int_{-h}^{hr} W r d\varphi dr dz \quad (7) \]

In equation 7 \( W \) is the per-unit work of the internal forces, which is determined according to the formula

\[ W = [Me_i - Ce^{-e_{i0}}(1 - e^{-e_i}) - \frac{B}{h} e^{-Ne_{i0}}(1 - e^{-Ne_i})], \quad (8) \]

where \( e_i \) is the deformation degree at the initial stage of punching, which is determined by the method of hardness measurement [9]; \( M, C, B, N \) are the parameters of the hardening curve [3], determined in relation to the compression and tensile tests.

The work of the friction forces on the surface of the contact of the metal and the tool is determined according to 8:

\[ A_{t1} = 2 \int_0^{2\pi} \int_R^{R_2} U_{|F_1} \tau r d\varphi dr \quad A_{T2} = \int_0^{2\pi} \int U_{|F_3} \tau r d\varphi dr \quad A_{T3} = \int_0^{2\pi} \int \tau U_{|F_3} r d\varphi dr \quad (9) \]

In equation 8 \( \tau = \psi \tau_s \), where \( \tau_s \) is the yield point in shear that is determined by the method [4].

The total deformation work at the final stage of punching is determined as a sum of works of both the internal force \( A_{b1}, A_{b2}, A_{b3} \) and the friction force \( A_{T1}, A_{T2}, A_{T3} \). The search for the minimum of the total deformation work \( A^{\text{min}} \) is carried out by the numerical methods with the use of a specially developed program. The received values of the minimum total deformation work \( A^{\text{min}} \) allow determining the forging forces \( P \) and the per-unit forces \( p = \frac{P}{F_0} \), where \( F_0 = \pi R_0^2 \). The calculations are presented in the form of a chart, which allows determining per-unit forces \( p \) of semi-enclosed cold heading with regard to the relevant sizes of heads for such grades of steel as (steel 10, 20, 35 and 40Cr) which are widely used in the manufacturing of the rod-shaped hardware (fig.2).
Figure 2. The nomogram for determining the forging forces $P$ and the per-unit forces

Conclusion
The result of the study is the development of a mathematical model and the calculations of energy power parameters of the semi-enclosed heading of rod-shaped hardware, which are carried out with the use of the discrete variational method. The final results of the calculations are presented in the form of a chart, which can be used to determine the deformation forces regarding the ratio of sizes of the heads for the grades of steel widely used in the manufacturing of the rod-shaped hardware. The results of the study are used in the development of some low-waste technologies of producing bolts with hexagon heads (GOST 7798-70) on multiple-point automatic apparatus at OJSC “MMK-Metiz” (Magnitogorsk). The application of the developed technologies provides savings of metal by $2 \div 4\%$.

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