FEM simulation of C45 steel and Cu-ETP billet shaping at hot upsetting between convex conical dies

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Abstract. On the basis of finite element analysis (FEA), geometric differences in the shaping during hot upsetting of cylindrical billets with a height-to-diameter ratio of 1.0 and 2.0 made of C45 (1.0503) steel and copper (Cu-ETP) between pointed convex conical dies with a cone slant angle of 12.5°, 15.0° and 17.5° are considered. The stroke velocity of the upper die is 0.5 m/s; process temperature (t) and accepted surface friction coefficient (μ): for steel – t = 1100 °C, μ = 0.32, for copper – t = 850 °C, μ = 0.34. An equation is obtained for the relation between values of reduction in height ratio and engineering strain on height of workpiece during upsetting between conical dies, taking into account the initial billet dimensions and unevenness of forming due to the geometry of tool. The presence of qualitative and quantitative differences in shaping along the height of upset steel and copper billets was revealed, i.e. influence on unevenness of forming the rheological properties of materials under process conditions. It is advisable to use the results obtained to design and improve of technological processes of open die and closed die forging with preforming of billets.

1. Introduction

The application in metal-forming the upsetting of billets or ingots between convex dies usually pursues several goals: reducing of shrinkage and porosity defects, void closing in the axial zone of the ingot [1–3], providing a technologically advanced form of a semi-finished product (preform) for optimization of forming at subsequent stages of open die or closed die forging [4–6]. The pressure on the tool at finishing forming is reduced, and increasing the tool life of which is always relevant and requires the use of additional hardening processes [7]. Herewith, descaling after heating of the workpiece occurs, which excludes its pressing into the forging body, reduces the likelihood of defect formation and improves the acceptance indices of shop products [1, 3, 8–10]. At the same time, among the processes of upsetting with convex working tool, the preforming of workpieces by pointed convex conical dies is the least studied [8].

Upsetting between convex conical dies under certain their shape characteristics and conditions of surface friction leads to a decrease in the uneven deformation of the workpiece, which is used in methods for determining the coefficient of friction when choosing an effective lubricant [11, 12]. It is known that surface friction coefficients for cases of plastic upsetting of heated workpieces of steel and copper between dies made of tool steel are μ = 0.32 and μ = 0.34 respectively [11, 12]. Usually, at
the open die forging and pre-stages of closed die forging technological lubricants are not used, and the effect of friction conditions on the contact of dies and workpieces with a height $H_0$ to diameter $D_0$ ratio more than 1.0 is insignificant [1, 8, 12]. Therefore, a change of the upper die inclination affects the workpiece shaping not only at the face zones, but also on the forming of the lateral surface of the upsetted preform. The ongoing processes of material volume displacement when the upper conical die is wedge in to the billet face are accompanied by severe plastic deformation of the surface layer, which is the object of separate studies [13, 14].

To identify the conditions for obtaining the most technologically advanced form for preformed workpiece and to ensure the optimal shaping at further stages, it is necessary to establish the patterns of workpiece forming at the upsetting under study. Information in this area is fragmentary (for example, there is limited information about the shaping at the initial stage of the penetration of conical rotating die into the end face of the workpiece during orbital forging [15–17]), which unreasonably narrows the application of workpieces upsetting by conical dies as a preforming. The use of a conical tool reduces the workpiece unevenness of deformation in rotary forming methods [15–17], requiring the operation of complex kinematic units of equipment with several degrees of freedom and complex gears of special profile [18, 19], which complicates the technology.

Also, the effect on the shaping of the workpieces material (steel and copper) properties under certain thermo-mechanical and physical-geometric conditions of forming is not reliably known, which is objectively due to the difference in patterns of materials strain hardening [8, 10, 20]. Analytical methods are used to research of workpiece forming allow to take into account the properties of the material and moving from shape indices to the analysis of the stress-strain state in different zones [21, 22]. The most common numerical method is finite element analysis (FEA), which allow to research the shaping, stress-strain state, force modes, accuracy of equipment and assemblies [23, 24], and the rheological model of the material can be included in the calculations [25]. It should be noted that the hot press forming process is applicable for low and medium carbon steels and copper [4, 8, 9, 27–30]. The influence on the preform shape of the differences between the strain hardening models of hot steel C45 and copper Cu-ETP under certain thermo-mechanical conditions is obvious. Comparison of the corresponding work hardening curves for the flow stress $\sigma_s$ given in the sources [8, 26–30] confirms this; however, this effect is practically not taken into account when studying the upsetting processes.

The aim of the work is to reveal the differences in the shaping of solid cross-section cylindrical billets made of C45 steel (1.0503 EN 10083-2) and Cu-ETP copper (EN 1652) during hot upsetting between conical convex pointed dies.

2. Materials, method and assumptions

The most powerful means of researching metalforming processes are computer-aided FEA tools, one of which (QFORM) was used to solve the set goal. The visualization of the forming in QForm occurs simultaneously with the calculation, which allows to immediately interpret the obtained results and make the necessary changes to the research process. QForm provides automatic generation of computational models (splitting into finite elements) and, accordingly, high calculation accuracy. When implementing finite element method (FEM), the forming during upsetting is divided into a number of successive and time-identical stages, depending on the movement of the upper die. The final criterion is the smallest change in the strain rate field within the stage. The values of stresses, strains and displacements are calculated step by step, taking into account the totality of kinematic, dynamic and temperature boundary conditions passing from stage to stage. The final values of the accumulated shear strain, obtained at each stage, are used as initial values when calculating at the next stage. Accordingly, the method of FEM for upsetting included: creation of a conformal mapping of the flow area on the canonical region; finding the fields of strain and stress rates; calculation of the accumulated strains and assessment of residual material plasticity.

The upsetting of billets by convex conical dies with a slant angle at the base of the cone (Fig. 1) $\alpha = 12.5^\circ; 15^\circ; 17.5^\circ$ was simulated. The initial diameter of the billet $D_0 = 25$ mm, and the height --
$H_0 = 25$ mm and $H_0 = 50$ mm, i.e. ratio $H_0/D_0 = 1.0$ and $H_0/D_0 = 2.0$ respectively. Splitting the solid-state computer model of the billet into a mesh of finite elements with the determination of their types was provided by means of FAM tools, while fulfilling the condition of impermeability of the finite elements of the working dies model to the finite elements of the billet model. Billet materials: (i) C45 steel (forming temperature $t = 1100^\circ$C) and (ii) Cu-ETP copper (forming temperature $t = 850^\circ$C). The taken temperature environment was to isothermal. In accordance with the review, the surface friction coefficients during billet upsetting are taken for steel $\mu = 0.32$ and copper $\mu = 0.34$.

As a technological process parameter characterizing the reduction in height ratio of billets during upsetting, $\varepsilon_h = \Delta h / H_0$ was taken, where $\Delta h = (H_0 - h_1)$ is the upsetting stroke, mm, and $h_1$ is the distance between opposite points of the upper and lower conical dies after deformation, mm, see Fig. 1(a). Forming at steady state of upsetting only is for practical importance, i.e. for $\varepsilon_h \geq 0.25 \ldots 0.3$. The maximum reducing ratio was limited to $\varepsilon_h = 0.5$.

![Figure 1. Upsetting steady state of the billets by conical dies: upper half of the workpiece (symmetry along the horizontal axis) (a); models of the billets upset up to $\varepsilon_h = 0.5$ (Cu-ETP, $t = 850^\circ$C) with $H_0/D_0 = 1.0$ (b) and $H_0/D_0 = 2.0$ (c) respectively at $\alpha = 17.5^\circ$; 1 – workpiece with sizes $h_1, h_2, r_1, r_2$ after upsetting; 2 – upper cone upsetting dies; $V_{cn}$ – metal volume GBC, displaced by the cone (increases along the upsetting due to an increase in the values $r_{cn}$ and $h_{cn}$); $V_{bs}$ – metal volume KMNE, displaced with respect to the vertical axis; $e_i$ – equivalent strain (scale).](image)

The stroke velocity of the upper die $v = 0.5$ m/s was considered, which corresponds to the displacement velocity of the sliders of mechanical presses and provides a strain rate of the workpiece of about $\xi = 5 \ldots 10$ s$^{-1}$. The changes in the properties of the workpiece materials during forming under the given conditions were taken into account by choosing models of their strain hardening from the data list of the used package for finite element modeling (FEM) as functions $\sigma_y = f(e_i, \xi, t)$.

In the process of simulation, the values of displaced volumes (displaced mass) were determined as $V_{dsv} = V_{cn2} + V_{bs2}$, where $V_{cn2} = 2 \cdot V_{cn}$ and $V_{bs2} = 2 \cdot V_{bs}$ are doubled volumes according to Fig. 1 referring to the entire workpiece. Accordingly, the true engineering strain $e_k$ in the vertical direction was found as $e_k = V_{dsv} / V_{wp}$, where $V_{wp} = \pi D_0^2 H_0 / 4$ is the volume of the billet. The maximum difference in computer calculation of displaced volumes for steel and copper billets did not exceed 0.8%. This error is negligible and is associated with differences in finite element mesh generation for materials with different properties. Thus, the graphs of the relation between the technological parameter $e_k$ and the values $e_k$ (Fig. 2) for steel and copper billets will not differ.

3. Results and discussion

Considering that the nature of the dependences shown in Fig. 2, is close to linear, then based on the simulation results, a planning matrix for a full factorial experiment design ($2^3$) was compiled taking
into account the interaction of influencing factors \( (H_0/D_0, \varepsilon_h \text{ and } \alpha) \). The variable factors and their levels, as well as the simulation plan \( (2^3) \), are given in Table 1.

![Figure 2](image-url)  
**Figure 2.** The relation between the reduction in height ratio of billets \( \varepsilon_h \) and the true engineering strain \( \varepsilon_h \), calculated through displaced volumes for upsetting of billets \( (H_0/D_0=1.0 \text{ and } H_0/D_0=2.0) \) by convex conical dies with \( \alpha=12.5^\circ, 15^\circ, 17.5^\circ \).

| Variable factors, their levels and simulation plan. | No. | \( H_0/D_0 \) (x1) | \( \varepsilon_h \) (x2) | \( \alpha^\circ \) (x3) | \( e_h \) (y) |
|---|---|---|---|---|---|
| Basic level | 1 | 1.0 | 0.3 | 12.5 | 0.164 |
| | 2 | 2.0 | 0.3 | 12.5 | 0.233 |
| | 3 | 1.0 | 0.3 | 17.5 | 0.142 |
| | 4 | 2.0 | 0.3 | 17.5 | 0.202 |
| Variation interval | 5 | 1.0 | 0.5 | 12.5 | 0.377 |
| | 6 | 2.0 | 0.5 | 12.5 | 0.444 |
| Top level | 7 | 1.0 | 0.5 | 17.5 | 0.319 |
| | 8 | 2.0 | 0.5 | 17.5 | 0.408 |
| Lower level | 9 | 1.0 | 0.3 | 12.5 | 0.164 |

The processing of the plan made possible to obtain the regression equation:

\[
e_h = 0.287 + 0.035X_1 + 0.098X_2 - 0.017X_3 + 0.004X_1X_2 - 0.006X_2X_3 + 0.005X_1X_2X_3
\]

where \( X_1 = (H_0/D_0 - 1.5)/0.5, \ X_2 = (\varepsilon_h - 0.4)/0.1 \) and \( X_3 = (\alpha - 15^\circ)/2.5^\circ \) are coded values of specified influencing factors.

As the main indices of the billet shaping during hot upsetting between conical dies, the following ratios were chosen: \( h_2/H_0, d_1/D_0 \) and \( d_2/d_1 \). As functions of their dependences on influencing factors for steel and copper billets are plotted (Fig. 3–5). Obviously, \( d_2/d_1 = r_2/r_1 \). At the same time, the material flow of the workpiece to lateral surface is forming the double barrel profile with the presence of \( r_1 \) and \( r_2 \) values occurs when upsetting relatively high billets with \( H_0/D_0 = 2.0 \) ratio. When forming a lateral profile in the shape of a single barrel, which is typical for billets with \( H_0/D_0 = 1.0 \) ratio, it was assumed that \( r_1 = r_2 \), see Fig. 1(a), where \( r_2 \) is the radius of the contact circle of the workpiece with the convex conical dies.

Graph \( h_2/H_0 = f(\varepsilon_h; \alpha; H_0/D_0) \), drawn in Fig. 3, shows the change in the vertical dimension of the workpiece depending on the reduction in height ratio \( \varepsilon_h \), the slant angle at the base of the cone \( \alpha \) of the upsetting dies and \( H_0/D_0 \) ratio of the initial billet. The obtained dependences of the change in the height dimension on the conditions of upsetting by conical dies of steel and copper billets are qualitatively identical, and the quantitative differences are insignificant (no more than 2%). This is due to the insignificant difference in the surface friction coefficients, the difference in the generated finite
element mesh, and allows using the same graph for different materials. Consequently, the influence of the rheological properties of materials on the shaping on vertical of billets during upsetting by convex conical dies can be neglected.

Graph $d_i / D_0 = f(\varepsilon_0; \alpha; H_0 / D_0)$, drawn in Fig. 4, shows that an increase in $H_0 / D_0$ ratio increases the relative diameter after upsetting in the middle of the height of the workpiece at the same reductions, which is relate with a larger metal volume involved in plastic forming. The obtained dependences of the change in the relative median diameter are characterized by its rising with an increase in the reduction in height ratio and a decrease with an increase in the slant angle at the base of the cone. These dependences for steel and copper billets are qualitatively identical, and the quantitative differences are very insignificant (up to 1%). This is explained in the same way as in the previous case and allows using the same graph for different materials also. Consequently, the influence of the rheological properties of materials on the change in the relative median diameter of the workpiece during upsetting by conical dies is insignificant.

Figure 3. Dependency graph $h_2 / H_0 = f(\varepsilon_0; \alpha; H_0 / D_0)$ for steel and copper billets while upsetting by convex conical dies.

Figure 4. Dependency graph $d_i / D_0 = f(\varepsilon_0; \alpha; H_0 / D_0)$ for steel and copper billets while upsetting by convex conical dies.

Figure 5. Dependency graph $d_2 / d_1 = f(\varepsilon_0; \alpha; H_0 / D_0)$ for steel (a) and copper (b) billets while upsetting by convex conical dies.

Graph $d_2 / d_1 = f(\varepsilon_0; \alpha; H_0 / D_0)$, drawn in Fig. 5, describes the change in the unevenness of workpiece deformation along the height. In general, for billets with $H_0 / D_0 = 1.0$ ratio, values $d_2 / d_1$ are less than 1.0, and for billets with $H_0 / D_0 = 2.0$, values $d_2 / d_1$ are greater than 1.0. At the same time, for copper workpiece, the presence of maxima is observed on the graphs related to the upsetting of higher billets. The obtained dependences of the change in the value of the ratio of the front end ($d_2$) diameter to the median diameter ($d_1$) for steel and copper billets have qualitative and quantitative differences. This testifies to the significant influence of the rheological properties of materials on the change in the unevenness of the workpiece deformation along the height during upsetting by convex conical dies, which cannot be neglected in the design of forging processes.
4. Conclusions
An equation is obtained for the relation between the upsetting reduction ratio (adjustment index) and engineering strain on height of a cylindrical workpiece during upsetting between conical dies, taking into account initial billet dimensions and upsetting dies geometry (cone slant angle to the base). The patterns of the workpiece shaping during upsetting with conical dies have been established, which make it possible to determine the dimensions of upsetted preform, depending on its initial height-to-diameter ratio, reduction in height ratio and taper of convex cone dies. It was revealed that the unevenness of deformation along the height of the upsetted preforms is significantly influenced by the rheological properties of the billet material. It is advisable to use the results obtained to improve the technological processes of open die and closed die forging on the basis of preforming of workpiece by upsetting with profiled dies.

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