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Automated Control System for the Assembly of a Composite Punching Tool

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Abstract—An automated system for simulation and control of the assembly of a composite hole-punching tool is developed. It consists of an information system used in preparations for assembly, with decision-making support on the basis of precedents; and modules for simulation and correction of the assembly process.

Keywords: punching tool, composite tool, automated system, modeling, control, technological process, broaching, shaping

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In tool production, it is important to reduce production costs by using smaller quantities of expensive alloy steel. In some cases, composite tools are expedient: tool steel is used for the cutting components, while structural components are made from less expensive carbon steel. In Fig. 1a, we compare one-piece and composite hole-punching tools, as well as their working life and relative cost.

The production of a composite punching tool by broaching is a complex multistage process. For practical purposes, automated production systems are required [1]. Thus, we need to develop an automated system for simulation and control of tool assembly.

In Fig. 1b, we show the structure of an automated system for the simulation and control of tool assembly. It consists of an information system used in preparations for assembly, with decision-making support on the basis of precedents; and modules for simulation and correction of the assembly process.

The initial data for the proposed system are a CAD model of the final composite tool and information regarding the tool materials employed. From the initial data, the information system searches for a relevant precedent in an archive consisting of CAD models of the complex workpiece and the rod section of existing tools; decisions made regarding the selection and design of the equipment required; and the control commands employed. In the absence of a precisely matching precedent, either a new precedent is created or the closest existing precedent is selected and subsequently adapted. In either case, we use the module for simulation of the process of composite-tool assembly.

In that module, the geometric parameters of the complex workpiece and rod section of the tool are mathematically simulated on the basis of mathematical models taking account of the displacement of the metal, the formation of an annular gap, and the shrinkage cavity in broaching.

The introduction of the tool's rod section (henceforth, the rod) in a cylindrical workpiece (open broaching) is simulated by means of Deform-2D software so as to develop mathematical models of shaping and design algorithms for the complex workpiece and the rod.

In the Deform-2D simulation, we employ virtual velocities and virtual work and also the finite-element method. On that basis, we may write the following system of initial equations in digital form:

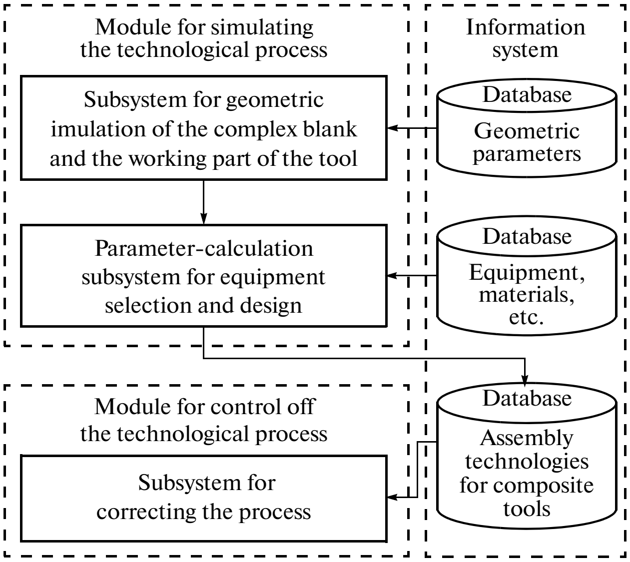

Fig. 1. Comparison of one-piece and composite tools for hole punching and structure of the automated system for simulation and control of composite-tool assembly.

(a) the equilibrium equation $\sigma_{ij,j} = 0$, where $\sigma_{ij,j}$ are the components of the stress tensor;

(b) the equation of motion $\sigma_{ij,j} + \rho dv_i/dt = 0$, where ρ is the density and v_i are the components of the velocity vector;

(c) the flux equation $s_{ij} = \dot{\varepsilon}_{ij} 2\bar{\sigma}/3\dot{\bar{\varepsilon}}_{ij}$, where s_{ij} is the stress-tensor deviator; $\bar{\sigma}, \dot{\bar{\varepsilon}}$ are the effective stresses and strain rates, respectively;

(d) the incompressibility condition $v_{i,i} = 0$.

The shaping of the workpiece in open broaching (broach diameter $d_b = 0.3–0.7D_0$) may be understood on the basis of simulation and literature analysis [2–4].

When $d_b < 0.3D_0$, the deformation of the workpiece is local, since broaching begins to resemble broach insertion in a half-space. When $d_b = 0.7D_0–D_0$, we observe only slight insertion of the broach in the blank. That rules out the production of a permanent joint.

Before broaching, the workpiece is of height H_0 and diameter D_0 (Fig. 2a, contour *1*). Broaching results in upsetting of the workpiece; its new height is H_f. The workpiece becomes barrel-shaped (diameter D_{ba}; Fig. 2a, contour *2*).

The size of the annular gap in broaching may be characterized as $\theta_g = V_g/V_{int} \times 100\%$, where V_g is the volume of the annular gap, mm^3; and V_{int} is the volume of the cylindrical broach introduced, mm^3. The contour of the upper end surface is rotated by φ, forming the shrinkage cavity.

The figures 1, 2, ..., n in Fig. 2a denote the initial positions of equidistant points on the lateral surface (n is the total number of points). The figures 1*, 2*, ..., n* denote the final positions of the points after broaching. The motion from the initial position is characterized by the vector $\vec{s}_i(\Delta r_i, \Delta h_i)$, where Δr_i and Δh_i are, respectively, the radial and axial displacements of point i. Hence, on the basis of those displacements of the points from the required shaping contour, we may obtain the contour of the complex workpiece at points 1**, 2**, ..., n** (Fig. 2b).

However, this method does not permit compensation of the shrinkage cavity formed at the upper end of the workpiece. Therefore, the intended contour of the complex workpiece must be corrected by an angle φ in the direction of shrinkage-cavity formation. To this end, we pass secant plane AA through the point with coordinates ($d_b/2$; H_0) at an angle φ to the end surface (Fig. 2b).

In Fig. 2a, we show the contours of the complex workpiece before (to the left) and after (to the right) broaching; after broaching, it is represented by a cylinder of diameter D_{ba} and height H_f. We now consider different relative dimensions of the workpiece and rod: broach diameter $d_b/D_0 = 0.3–0.7$; workpiece height $H_0/D_0 = 0.5–1.5$ (at large H_0/D_0, it is difficult to ensure stability of the punch); base angle of punch $\alpha = 45°–90°$. The depth of punch introduction is $0.8H_0$. (Greater depth leads to the formation of a removable flap and is used mainly to punch holes through workpieces.)

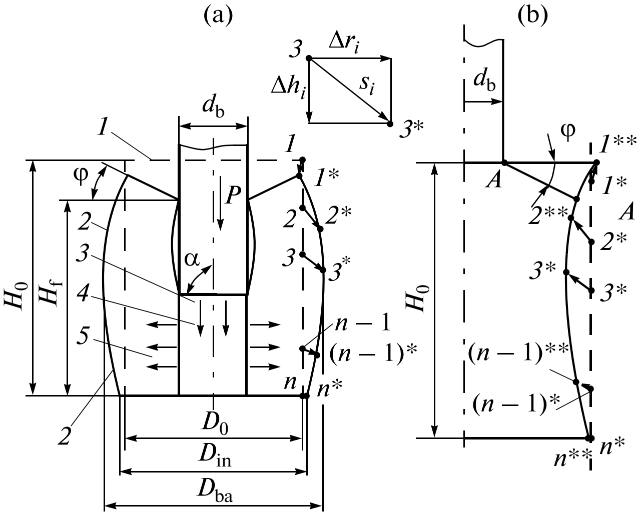

Fig. 2. Analysis of the shaping of a cylindrical workpiece in open broaching (a) and design of the generatrix of a complex workpiece (b).

As a result of modeling, the final shaping dimensions of the workpiece Δr_i, Δh_i, D_{ba}, D_{in}, H_f, φ, θ_g may be expressed as a function of the relative rod diameter d_b/D_0, the relative workpiece height H_0/D_0, and the punch's base angle α

$$\left.\begin{aligned} \Delta r_i &= f_1(d_b/D_0;\ H_0/D_0;\ \alpha); \\ \Delta h_i &= f_2(d_b/D_0;\ H_0/D_0;\ \alpha); \\ D_{ba} &= f_3(d_b/D_0;\ H_0/D_0;\ \alpha); \\ H_f &= f_4(d_b/D_0;\ H_0/D_0;\ \alpha); \\ \varphi &= f_5(d_b/D_0;\ H_0/D_0;\ \alpha); \\ \theta_g &= f_6(d_b/D_0;\ H_0/D_0;\ \alpha). \end{aligned}\right\}$$

An algorithm is developed for the geometric design of the complex workpiece and rod and for determination of the required tool displacements according to the drawing of the composite tool (Fig. 3).

In the first stage, the initial data are introduced in the form of a CAD model of the composite hole punch for which the workpiece is being designed. Then we solve the system of equations

$$\left.\begin{aligned} D_{ba} &= f_3(d_b/D_0;\ H_0/D_0;\ \alpha); \\ H_f &= f_4(d_b/D_0;\ H_0/D_0;\ \alpha); \\ \theta_g &= f_6(d_b/D_0;\ H_0/D_0;\ \alpha). \end{aligned}\right\}$$

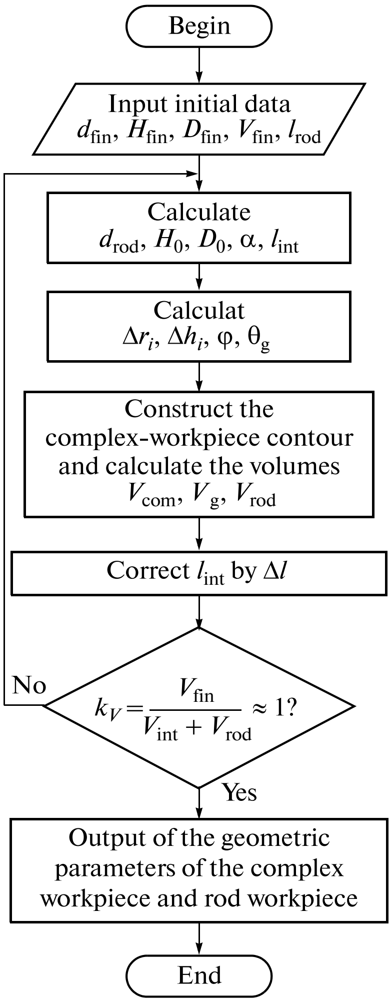

Fig. 3. Geometric design algorithm for the complex workpiece and rod in the production of a composite tool: l_{rod}, rod length of the final composite punch, mm; $d_{\text{rod}} = d_{\text{b}}$, diameter of the designed rod, mm; V_{fin}, volume of the final composite tool, mm^3. The other notation is explained in the text.

Next, the dimensions D_0 and H_0 of cylindrical workpiece *3*, the annular gap θ_{g}, the rod's taper angle α, and the length l_{int} of the inserted part of the rod are calculated (Fig. 4).

The contour of this cylindrical workpiece *2* after broaching must be inscribed in the contour of the final composite tool *1*. In other words, the following condition must be satisfied

$$\left.\begin{aligned} d_{\text{b}} &= d_{\text{fin}}; \\ H_{\text{f}} &= k_V H_{\text{fin}}; \\ D_{\text{ba}} &= D_{\text{fin}}, \end{aligned}\right\} \tag{1}$$

where H_{fin} and D_{fin} are the housing height and diameter; d_{fin} is the rod diameter of the final composite tool; H_{f} and D_{ba} are the dimensions of the cylindrical workpiece after broaching (contour *2*); k_V is a correction factor introduced to ensure constancy of the volume. (In the first calculation cycle, $k_V = 1$). Since there are many such contours (four unknowns in three equations), we select the contour with the maximum possible annular gap $\theta_{\text{g}} = \theta_{\text{gmax}}$.

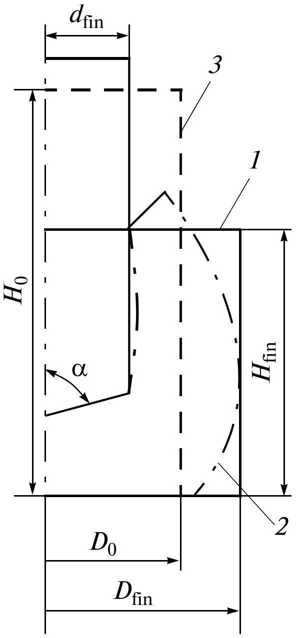

Fig. 4. Design of the complex workpiece.

After determining the dimensions of the cylindrical workpiece, the radial and axial displacements Δr_i and Δh_i of points on its lateral surface are calculated, as well as the shrinkage angle φ of the upper end surface, by substituting the values of D_0, H_0, and α obtained in the previous stage into the following equations:

$$\Delta r_i = f_1(d_{\text{b}}/D_0;\ H_0/D_0;\ \alpha);$$

$$\Delta h_i = f_2(d_{\text{b}}/D_0;\ H_0/D_0;\ \alpha);$$

$$\varphi = f_5(d_{\text{b}}/D_0;\ H_0/D_0;\ \alpha).$$

The results are used to plot the contour of the convex workpiece (Fig. 2b). To fill the annular gap with the rod as a result of upsetting in the course of assembly, the rod must be elongated by Δl: $\Delta l = \theta_{\text{g}} l_{\text{int}}/100$, where l_{int} is the length of the rod introduced in the workpiece.

In the final stage, the constant-volume condition is verified by calculating the actual value of the correction coefficient

$$k_{V\text{act}} = V_{\text{fin}}/(V_{\text{com}} + V_{\text{rod}}) \approx 1, \tag{2}$$

where V_{fin} is the volume of the final composite tool, mm^3; V_{com} is the volume of the complex workpiece, mm^3; and $V_{\text{rod}} = (\pi d_{\text{rod}}/4)(l_{\text{int}} + \Delta l)$ is the volume of the rod that is introduced (taking account of the annular gap), mm^3.

If $k_V \approx 1$ (within the limits of precise hot bulk stamping: ± 0.01), the calculation stops and the result is recorded. If $k_V \neq 1$, the calculations is repeated with the value $k_V = k_{V\text{act}}$ in Eq. (1). The calculation continues until Eq. (2) is satisfied.

The geometric parameters of the complex workpiece and the rod are presented in the form of CAD models.

The module for simulation of the technological process also includes a subsystem for calculation of the process parameters so as to permit selection and design of the necessary equipment. This subsystem simulates the assembly forces and temperature. It selects (from the database of equipment and materials) the press, the inductor, the method of workpiece and rod manufacture (depending on the production program), and so on. The assembly equipment is designed and simulated; and control programs for the machining of the workpieces themselves or the stamping system for workpiece production are formulated.

The module for control of the technological process ensures correct assembly of the composite tool by correcting the following parameters.

(1) At rod introduction, the insertion depth.

(2) In the heating stage, the loss of rod strength. It is maintained at the specified level by the adjustment of the temperature sensor (after the first stage) so as to signal when the temperature corresponds to plasticization of the inserted rod section, with allowance for the maximum deforming force recorded in the first stage and the specified properties of the material.

(3) In preliminary assembly: the annular gap, which is filled so as to ensure tight physical contact of the adjacent surfaces, on the basis of analysis of the recorded force on the rod.

(4) In final assembly, the shape and the surface pressure. The shape is calibrated, with final filling of the matrix cavity; and the pressure on the adjacent surfaces is created in omnidirectional compression, on the basis of analysis of the recorded force on the rod.

This process-control module may be integrated into the automated system used in preparations for the production of forgings by pressure treatment, in the case of components with a large difference in diameter or bimetallic components. It is also useful for the restoration of worn surfaces by the plastic displacement of metal volumes.

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