Thermal processes in the electromechanical mandrel of holes in steel billets

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Abstract. The article presents findings on the distribution of temperature fields during Electromechanical mandreling (EMM) of holes in the surface of the workpiece and the tool. The design temperatures significantly exceed the phase transformation temperatures, but the melting of structural components in the surface layer of the workpiece does not occur due to high cooling rates. It is not possible to fix the maximum process temperatures experimentally due to their short duration of action.

Introduction

The level of quality and durability of both individual parts and assembly units as a whole is determined by the quality of the source material and the perfection and efficiency of the technological systems used in the manufacture of component parts.

The energy capacity of technological systems and the efficiency of energy use in them are constantly increasing with the development of production [1].

Electro-mechanical processing (EMP) refers to finishing and strengthening technologies, while the surface of the workpiece is subjected to simultaneous heating with phase transformations and force action on the surface in the austenitic state. The resulting white layer on the surface does not have a characteristic crystal structure, has a high hardness and high enough impact strength. These properties white layer under EMP acquires under the influence of ultra-fast heating, pressure and rapid cooling [2–6].

The surface quality required by the operating conditions is achieved by the correct assignment of the technological modes of EMP, their optimization. However, the purpose of technological modes for averaged (fixed) values of temperatures at various points along the section of the workpiece, significantly differ from the real ones and do not allow that to get a surface of the specified quality. Therefore, the task of modeling thermal processes in EMP is extremely important.

The use of EMP processes for processing small-diameter holes (PSD) is very relevant, since the use of known hardening technologies is problematic [7–11].

Materials and methods

For ESD of holes with a diameter of less than 40 mm, a mandrel is used as a tool, and the heat source would be bandwise (Fig. 1) [12, 13].
The solution to finding the temperature field when heated by a band-type high-temperature source \( q \) moving along the surface of the workpiece hole at the speed of \( v \) is found on the basis of the differential equation of thermal conductivity

\[
c_i(T_i) \rho_i(T_i) \frac{\partial T_i(\vec{r}, t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda_i(T_i) \frac{\partial T_i(\vec{r}, t)}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda_i(T_i) \frac{\partial T_i(\vec{r}, t)}{\partial z} \right), \quad \vec{r} \in V_i, i = I, II,
\]

where \( V_i \) — spatial regions of an axisymmetric cylindrical structure; \( \vec{r} = (r, \phi, z) \), \( 0 \leq \phi \leq 2\pi \); \( \lambda_i, c_i, \rho_i \) — coefficients of thermal conductivity, specific heat capacity and density of structural elements.

Initial condition:

\[
T_i(\vec{r}, 0) = T_c,
\]

where: \( T_c \) — initial temperature equal to the ambient temperature 300 K.

The complexity of thermal phenomena that occur when a high-temperature moving band source is exposed to the surface of a metal material in the EMM process is caused by the interaction of a large number of factors on which they depend. These factors include: heat release as a result of electrophysical effects (Joule heat release, Peltier, Thomson, Seebeck effects, electrolytic phenomena), heat released during tool friction on the surface of the workpiece, heat released as a result of deformation of the metal surface layer, heat exchange between the tool and the surface layer, heat release as a result of phase transformations, heat transfer from the source to the workpiece, and heat exchange with the environment.

The solution of this problem was carried out by the most common finite element method in the theory of thermal conductivity.

When choosing a modeling method, should take into account not only the effectiveness of the mathematical calculation procedure itself, but also the ability of the software product itself to ensure the proper level of adequacy.

For convenience and clarity, the simulation was carried out in two stages.

At the first stage, thermal processes were modeled with a band-band high-temperature source without taking into account tool movement (quasi-static model) in the COMSOL Multiphysics V5 mathematical modeling environment.

In the second stage, simulation was carried out with the movement of the tool relative to the surface (quasidynamic model) using environment mathematical modeling ANSYS 14.5.

The use of two environments of mathematical modeling allowed a more accurate way to assess convergence of the results.

To form the boundary conditions of the modeled process, the calculation schemes are presented (Fig. 2).
Fig. 2. Calculation schemes: a — for boundary conditions on the external surfaces of the structure; b — for thermal effects from a moving source

For the center 1 of the axisymmetric structure I (figure 2 a), the following conditions apply:

\[
\left. \frac{\partial T_i(r,t)}{\partial r} \right|_{r=0} = 0, \quad T_i(r,t) \bigg|_{r=0} \neq \infty.
\]

Boundary conditions on the external surfaces of the structure:

5, 4 \quad \lambda_i \frac{\partial T_i(r,t)}{\partial n} + \alpha_{\text{en}} (T_i(r,t) - T_e) = 0,

12 \quad \lambda_{II} \frac{\partial T_{II}(r,t)}{\partial n} + \alpha_{\text{en}} (T_{II}(r,t) - T_e) = 0,

2, 3 \quad \lambda_i \frac{\partial T_i(r,t)}{\partial n} + \alpha_{\text{ec}} (T_i(r,t) - T_e) = 0,

6, 7, 8, 9 \quad \lambda_{II} \frac{\partial T_{II}(r,t)}{\partial n} + \alpha_{\text{ec}} (T_{II}(r,t) - T_e) = 0,

where \( \frac{\partial}{\partial n} \) — derivative in the direction of the external normal to the corresponding surface, \( \alpha_{\text{en}} \), \( \alpha_{\text{en}} \), \( \alpha_{\text{ec}} \), \( \alpha_{\text{ec}} \), \( \alpha_{\text{ec}} \), \( \alpha_{\text{ec}} \), \( \alpha_{\text{ec}} \) — coefficients of natural (\( \alpha_{\text{ec}} \)) and forced (\( \alpha_{\text{en}} \)) heat exchange with the environment, W/(m² K).

In the zone of contact between the tool and the part with different thermophysical parameters, the heat flux density is continuous, that is

\[
-n_i (\lambda_i \nabla T_i) - n_{II} (\lambda_{II} \nabla T_{II}) = q(\vec{r}),
\]

where the function \( q(\vec{r}) \) is modeled by the normal distribution function in the following form

\[
q(\vec{r}) = (2,056 \cdot 10^7) e^{-4.938 z^2}.
\]

The resulting system of equations allows us to calculate the temperature field in a metal alloy for any time.
The models were built using real dimensions. When creating a finite element model, special attention was paid to splitting the area where there is a direct contact interaction between the tool and the hole surface to be processed, this is expressed in the need to significantly reduce the size of the grid elements in the area of contact between the tool and the part.

A two-dimensional idealization of the object in question was used to construct the geometric model. At the same time, the number of finite elements was about 3500.

**Research Results and Discussion**

As an example, consider the process of electro-mechanical mandreling (EMMP) of a sample hole made of steel 403 S 17 with a carbide mandrel made of VK8 in the following processing modes: current $I = 5000$ A, $I = 5200$ A, $I = 5400$ A; tension $i = 0.1$ mm.

In the study of heat processes was analyzed the time required to reach the maximum temperature on the surface of the workpiece as the source of electric current and the temperature change into the contacting objects under quasi-static model (EMM).
Figure 4 shows the dynamics of temperature changes in the body of the workpiece and tool of the sample and tool depending on the time of action of the heat source. Based on the results of calculations, it was found that the maximum temperature on the surface of the workpiece is reached in about one second and at a current strength of $I = 5400$ A is $1214$ °C. The temperature change in the tool and the workpiece depending on the time of action of the heat source is shown in figure 5.

The study of the temperature along the line of contact of the tool with the surface of the workpiece revealed that its maximum value is reached at the point of contact of the lower part of the spherical surface of the mandrel with the sample (figure 6). This is due to the high contact pressures at this site, which ensures the best contact.

As a result of calculations, it was found that with an increase in the current strength in the range from 5000 A to 5400 A, there is an increase in the surface temperature from 921 °C to 1214 °C (Fig. 8).

As can be seen from figures 7 and 8, the temperature values decrease sharply in the depth of the surface layer.

Figure 9 shows the results of calculation and measurement of temperature changes in the depth of the workpiece under the same conditions. The discrepancy of 4% can be explained by the fact that the simulation did not take into account possible current losses during its passage from the source (transformer) to the tool and workpiece, since current losses depend on a number of factors, it is almost impossible to adequately consider them in the simulation.
Conclusion
The results of solving the thermal problem are: visualization of the distribution of temperature fields, numerical values of heating-cooling rates depending on the modes of the studied EMM processes by a band-band high-temperature source.

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