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Investigation of changes in temperature of pressing tool during laser processing

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Abstract. The article is devoted to improving the wear resistance of forging tools, in particular punches for punching holes and cutting stamp dies. Low tool life leads to an increase in the cost of finished products, an increase in labor and material costs for replacing worn tools and adjusting them, a decrease in the productivity of pressing equipment and an increase in the number of defective products. A method is presented for theoretical research of solving the problem of calculating the temperature field of a stamp die tool during laser processing. A differential equation was compiled for a numerical solution of the problem. The authors proposed the modes of laser heat treatment of a punch for punching holes and a stamp die tool made of high-hardness steel. Field tests conducted in industrial conditions showed that the proposed laser heat treatment modes made it possible to increase resistance of the punch intended for punching holes by 2 – 3 times and the resistance of the stamp dies by 2.2 – 2.8 times.

Keywords: press forging, temperature field, punch, stamp die, laser

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Исследование изменения температуры прессового инструмента при обработке лазером

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Аннотация. Работа посвящена повышению износостойкости кузнечно-прессового инструмента, в частности пуансонов для пробивки отверстий и вырубных штампов. Низкая стойкость инструмента приводит к повышению стоимости готовых изделий, увеличению трудовых и материальных затрат на замену изношенного инструмента и его наладку, снижению производительности прессового оборудования и повышению количества бракованной продукции. Представлена методика теоретического исследования для решения задачи по расчету температурного поля штампового инструмента при лазерной обработке. Составлено дифференциальное уравнение для численного решения поставленной задачи. Предложены режимы лазерной термообработки пуансона для пробивки отверстий и штампового инструмента из стали повышенной твердости. Натурные испытания, проведенные в промышленных условиях, показали, что рекомендованные режимы лазерной термообработки позволили повысить стойкость пуансона, предназначенного для пробивки отверстий, в 2 – 3 раза, а стойкость вырубных штампов в 2,2 – 2,8 раз.

Ключевые слова: кузнечно-прессовое производство, поле температур, пуансон, штамп, лазер

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Introduction

One of the most widely used methods of cold metal working (CMW) by pressure is cold stamping [1 – 3], which allows for the production of high-precision parts in a wide range. Cold forming dies are used as tools for this process [4 – 6]. In recent years, the development of new domestic technologies aimed at improving the quality of manufactured products and reducing their cost has become highly relevant. This task can be efficiently solved by improving equipment and tools, including CMW [9; 10].

Formulation of the problem

One of the main reasons of the failure of stamping tools is the wear of their working surfaces. To improve the durability of cold metal working (CMW) tools, thermal, thermochemical, and thermomechanical treatments are applied [11 – 13]. These methods significantly increase the hardness of the tool's working surfaces and enhance the strength of the base metal from which the tool is made. Laser treatment is an effective method for improving the quality of CMW tools by processing their working surfaces. Laser treatment is characterized by a short exposure time to the treated surfaces and completely eliminates deformation. Only a thin surface layer of the processed part is heated when exposed to laser [14 – 16]. Numerous studies have shown that the thermal processes occurring during laser heating are similar to the results of heating metals by other methods. This allows for the application of classical equations of heat conduction theory to solve theoretical problems of laser processing, taking into account the specifics of laser heat treatment.

This work presents a solution to the problem of calculating the temperature field of a stamping tool when hardening its working surface using laser radiation.

Method of theoretical study of temperature field distribution during laser hardening

As it is known, the result of hardening tool steels [17; 18] significantly depends on distribution of the temperature field that forms during this process [19; 20]. To strengthen the surface layers, it is necessary to heat the working surface of the stamp above the austenitic transformation temperature T_a, after which it is rapidly cooled to a temperature below the pearlitic transformation temperature T_p. If a high-density laser beam is used for heat treatment, the surface layers of the tool will be heated to a temperature depending on the duration of the laser radiation and its power. After laser heating, the surface of the stamp quickly cools down due to the transfer of heat from the heated surface to the other distant areas of the tool. Moreover, temperature of the heated areas depends on their distance from the stamp surface. The depth of the hardened layer can be estimated by studying the characteristics of the resulting temperature field [21; 22].

Let us provide a mathematical description of the temperature field for a cylindrical cutting punch (Fig. 1).

The change in temperature T over time t can be calculated by numerically solving a two-dimensional differential equation, which in a cylindrical coordinate system is given by [23 – 25]

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right).$$

Here, $T(r, z, t)$ is the temperature at an arbitrary point of the cutting punch at any given time t, characterized by cylindrical coordinates r and z; a is the thermal conductivity coefficient of the material of the cutting punch; q is the power density of the external heat source (laser radiation) [26 – 28].

Let us define initial and boundary conditions:

– at the initial moment of deformation of the workpiece, the temperature of the cutting punch is assumed to be uniform throughout the entire volume, i.e.

$$T_0 = T(z, r, 0) = \text{const};$$

– on the free surfaces of the punch, heat exchange of convective and radiant types occurs with the environment

$$\frac{\partial T}{\partial t} = \alpha\left(T_{\text{surf}} - T_{\text{env}}\right) + \varepsilon\sigma\left[\left(T_{\text{surf}} - 273\right)^4 - \left(T_{\text{env}} - 273\right)^4\right];$$

– radiant heat exchange occurs on the end (irradiated) surface of the punch

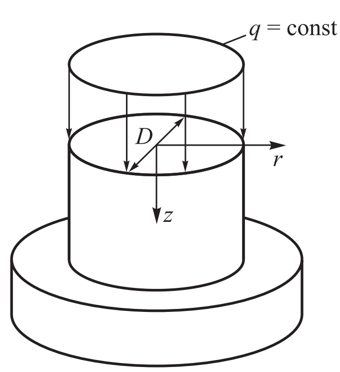

Fig. 1. Calculation scheme for temperature field of a cylindrical punch of diameter D

Рис. 1. Схема к расчету температурного поля цилиндрического пуансона диаметром D

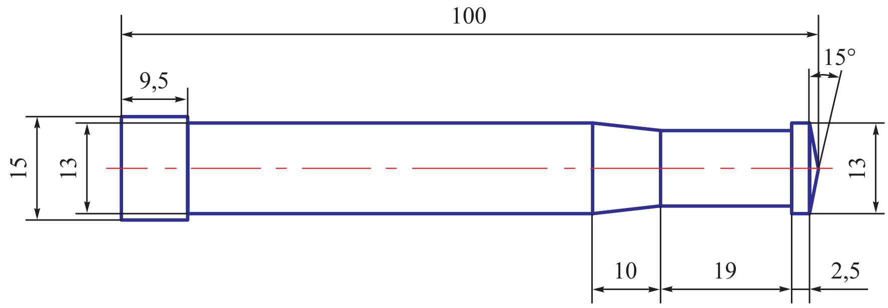

Fig. 2. Hole punch

Рис. 2. Пуансон для пробивки отверстий

$$\frac{\partial T}{\partial t} = q + \varepsilon\sigma\left[\left(T_{surf} - 273\right)^4 - \left(T_{env} - 273\right)^4\right],$$

where α is the convective heat transfer coefficient; T_{surf} and T_{env} are the temperatures of punch surface and the environment, respectively; ε is the degree of emissivity of the punch surface; σ is the emissivity of an absolutely solid body.

Experimental results

According to the methodology described above, theoretical and experimental studies were conducted on a punch (Fig. 2) made of high-hardness chromium tool steel Kh12M[1] [29; 30] with a working surface diameter $D = 13$ mm.

Based on the analysis of the preliminary experiment results with samples made of Kh12M steel, which are consistent with known data from scientific and technical literature, the following thermal-physical parameters were used in further research:

– thermal conductivity coefficient $\lambda = 0.028$ W/(mm·°C);

– temperature conductivity coefficient $a = 7.78$ mm²/s;

– quenching temperature $T_q = 1000$ °C;

– melting temperature $T_m = 1280$ °C.

Fig. 3 shows the results of calculating the temperature field in axial and radial directions with λ = const (solid lines) and $\lambda = f(T)$ (dashed lines) at a laser power of $P = 0.97$ kW, laser beam movement speed $v = 12$ mm/s, and laser spot diameter $d_{sp} = 4$ mm. Analysis of the obtained graphs shows that the difference in the punch temperature obtained with constant and variable λ values is insignificant. Therefore, when conducting engineering calculations, the average value of the thermal conductivity coefficient can be used.

[1] Characteristics of Kh12M material / Grade Guide of steels and alloys. Available at URL: http://www.splav-kharkov.com (accessed 23.08.2023).

Analysis of the results

The analysis of the obtained research results served as the basis for conducting a full-scale experiment. Two experimental batches of punches and dies made of Kh12M steel were manufactured for various stamping operations. The first batch underwent traditional bulk thermal treatment, while the second batch received additional strengthening treatment using a CO_2 laser. Based on the data obtained, the following parameters of laser irradiation were recommended for efficient strengthening of the working surface of the stamping tool: with a laser spot diameter of $d_{sp} = 4$ mm, laser power $P = 0.95–0.99$ kW, and laser beam movement speed $v = 11–13$ mm/s.

Pilot tests have shown that the durability of stamping tools significantly increases after laser heat treatment. For example, the working lifespan of punching punches after traditional thermal processing is 10 – 12 h, while after additional strengthening laser treatment, the durability increased to 20 – 36 h, that is, doubled or tripled. Pilot tests of a sample batch of blanking dies, consisting of 20 pieces, demonstrated that the application of addi-

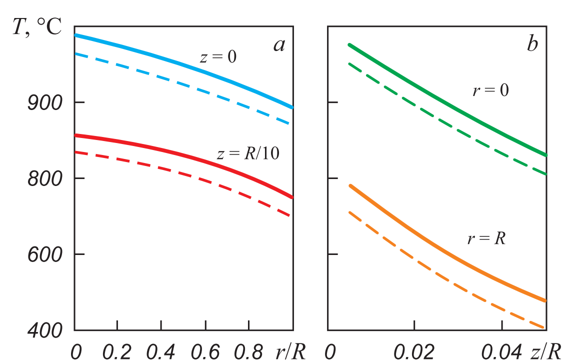

Fig. 3. Graphs of the punch temperature change in axial (*a*) and radial (*b*) directions at λ = const (solid lines) and λ = *f*(*T*) (dashed lines)

Рис. 3. Графики изменения температуры пуансона в осевом (*a*) и радиальном (*b*) направлении при λ = const (сплошные линии) и λ = *f*(*T*) (штриховые линии) tional strengthening treatment with a CO_2 laser allows for a 2.2 – 2.8 times increase in their operational durability. The technical and economic efficiency of using laser strengthening is determined not only by saving on expensive tool steel but also by reducing labor costs due to aligning the replacement period of stamping tools with the schedule of preventive and repair works.

Conclusions

A methodology for theoretical analysis of the temperature field of a cylindrical punch formed during laser processing is proposed. The methodology is based on the numerical solution of a two-dimensional differential equation in cylindrical coordinates. As a result of the theoretical analysis, laser heat treatment modes have been proposed for stamping tools of various purposes made of Kh12M tool steel. Studies conducted in industrial conditions have shown that laser heat treatment carried out according to the proposed modes has allowed an increase in the operational durability of punches for hole punching by 2 – 3 times, and cutting dies by 2.2 – 2.8 times.

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N. A. Chichenev – development of method for calculating the temperature field of a cylindrical body.
S. M. Gorbatyuk – analysis and generalization of the obtained modeling results.
K. N. Solomonov – formation of the article concept, setting the research goals and objectives, writing the text.
S. A. Snitko – technical justification of research tasks, justification of process parameters.
O. N. Chicheneva – graphic design of the obtained results.

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