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Methodology of Specification of Parameters of Strengthening of Elements of Bearing Surfaces of Aircraft

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***Abstract*— The methodology of choosing the parameters of strengthening the structural elements of the bearing surfaces of aircraft is presented in the article. Using mathematical methods of deformable solids, a mathematical model of processing elements of aircraft is built, which will be much more resistant to external mechanical impact. To give the surface water-repellent and anti-icing properties, surface treatment with highly concentrated energy flows can be used, followed by its strengthening. Such technologies include laser irradiation, plasma flux, electron beam, light beam, and ion flux.**

The proposed model is based on the problem of determining the technological parameters of the impact of concentrated energy flow on the surface of the part in order to determine with high accuracy the area of hardening and forecasting of zones of plastic deformation. The precision of determining these parameters is justified by taking into account the problem of dependence of physical and mechanical characteristics of the material on temperature - thermal sensitivity of the material. As these technologies involve significant changes in temperature values, taking into account temperature dependences is an important factor. The proposed methodology of determining the parameters is an actual task and is based on the solution of nonlinear problems, as well as allows you to create more accurate models of physical processes and provides reliability.

Keywords — concentrated energy flow, strengthening, stresses, temperature, deformation, reliability, thermal sensitivity.

I. INTRODUCTION

Today, concentrated energy flows are widely used in the treatment of surfaces of various materials and have proven themselves in most fields of mechanical engineering, including aircraft [1-5]. Hardening of parts with the use of concentrated energy flows was formed for industrial applications to replace traditional methods of thermal, thermomechanical and chemical treatments, which are more expensive and time consuming. The advantages of such treatment include [6]: control and regulation of heat flux, suitable for both metals and non-metals; high efficiency (up to 98%); process automation.

II. CURRENT STATE

Concentrated energy flow is a source of heat that increases the supply of thermal energy to the body surface, and the volume of metal acts as a heat sink at high cooling rates. High-power concentrated energy flow treatment is promising for surface modification of structural elements. The surfaces strengthened by such methodology acquire unique characteristics. Surface hardening by concentrated energy flow is a process of improving the mechanical properties of individual parts of the surface of detail, which has proven itself well in most branches of mechanical engineering, in particular in aircraft construction. Surface hardening is used to change the characteristics of materials such as corrosion resistance and hardness. Due to high-speed heating it is possible to obtain a fine structure with a high density of dislocations, higher values of hardness, strength and viscosity compared to other types of hardening treatments. Of all the modern methods of strengthening, hardening with a concentrated flow of energy is the most economical. As an example, the wear resistance characteristics of surfaces after modification increase up to 7 times [7,8]. To reduce the time of research into the relationships of parameters and properties of processing, it is necessary to develop mathematical models that would specify the processing processes: structural and phase transformations, heat transfer, stress, etc. Mathematical models for thermal and thermoelastic processes were proposed in the last century [9]. The problem statement contains: a kinetic equation that simulates the interaction of concentrated energy flows with the body surface, the energy conservation equation and the equation of state.

Given that the thermal and mechanical characteristics of the material of structural elements are dependent on temperature, the mathematical models that take this into account more accurately describe their thermal and thermoelastic state. This dependence is especially noticeable at high temperatures [1,10]. The methodology of constructing the solution of problems of thermal conductivity and thermoelasticity in linear formulation cannot be used in solving problems that take into account the temperature dependences of the characteristics. Mathematical models taking into account the temperature dependence of the characteristics of the body material are nonlinear problems of mathematical physics. Such problems do not have precise analytical solutions and require special methods for solving them.

The basis for calculating the strength of structural elements is the exact determination of their mechanical and physical characteristics. Much attention is paid to the study of temperature field and stress distributions in machine parts, including aircraft. The aviation industry is characterized by increased requirements for construction materials, and in some cases is the main customer and consumer of new materials and technologies [11,12]. Today, new methods of additive production are available in the aviation industry for metal parts: electron beam melting (EBM), selective laser melting (SLM), direct laser deposition (DLD). Creation on the surface of the structural elements of aircraft water-repellent and anti-icing layers is carried out using electronic or laser irradiation [13]. In general, this problem can be solved by determining the optimal parameters of heat treatment, which do not depend on the initial phase composition of the material and can provide a uniform surface structure and the desired properties.

Thus, the relevance of this study is the need to streamline and expand scientific knowledge in the field of energy flows, establish the nature of the impact of processing parameters on changes in microstructure and mechanical properties, strengthening zones, which will develop technology for hardening high-alloy tool steels to increase their durability [14,15].

III. THE METHODOLOGY OF DETERMINATION OF PARAMETERS OF CONCENTRATED ENERGY FLOW PROCESSING

The creation of models of heat treatment of aircraft structural elements that describe their behavior in the process of external mechanical and physical influences and which are accompanied by significant deformation and internal heat fluxes are directly related to the creation of new and improvement of existing surface technologies. For such technologies, heat treatment using concentrated energy flows of significant power is important.

The theoretical basis for determining the optimal modes of such processing, in order to ensure the expected strength of the surface areas of details and elements of constructions, is the study of finite deformation processes and thermodynamic descriptions of material behavior under different modes of thermal exposure.

The paper presents the solution of the thermoelasticity problem for a cylindrical body whose physical and mechanical characteristics are functions of temperature. The body is under the influence of a ring of concentrated heat flow on the side surface. The solution of problems is built in two phases. The first is the function of the temperature field distribution in the cylinder depending on the coordinates and time. It is taken into account that the thermophysical characteristics of the material are temperature-dependent values. In the second phase, taking into account the already known temperature distribution, the solution of the elasticity problem is built. This takes into account the dependence of physical and mechanical characteristics of the material on temperature.

A. Formation of a mathematical model of the action of energy flow on the surface of details

To determine the nonstationary temperature field we write a nonlinear problem of thermal conductivity, which consists of equations and conditions

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda(t)\frac{\partial t}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\phi}\left(\lambda(t)\frac{\partial t}{\partial\phi}\right)+\frac{\partial}{\partial z}\left(\lambda(t)\frac{\partial t}{\partial z}\right)=c(t)\frac{\partial t}{\partial\tau}$$

$$\lambda(t)\left.\frac{\partial t}{\partial r}\right|_{r=b}=\gamma(t)\,q(\phi,z,\tau),\quad t\big|_{\tau=0}=t_0 \tag{1}$$

where $\lambda(t)$, $c(t)$, $\gamma(t)$ thermophysical characteristics. Value $q(\phi, z, \tau)$ is called the heat flux density and includes parameters and physical characteristics that describe the concentrated heat flux.

Determine the distribution of the temperature field in the body using the Kirchhoff variable [1]

$$\upsilon=\frac{1}{\lambda_0}\int_{t_0}^{t}\lambda(\xi)d\xi \tag{2}$$

The solution is in the form of a piecewise homogeneous function

$$t=\lambda_0\left\{\upsilon+t_0S_+(\upsilon-\upsilon_0)+\frac{1}{\lambda_0}\sum_{j=1}^{N}(\lambda_j-\lambda_{j-1})t_jS_+(\upsilon-\upsilon_j)\right\}\times$$
$$\times\left\{\frac{1}{\lambda_0}S_+(\upsilon-\upsilon_0)+\sum_{j=1}^{N}\left(\frac{1}{\lambda_j}-\frac{1}{\lambda_{j-1}}\right)S_+(\upsilon-\upsilon_j)\right\} \tag{3}$$

here $S_+(\upsilon)$ is the Heaviside step function.

Therefore, the model of thermal conductivity according to the written scheme is reduced to a linear problem with respect to the Kirchhoff variable ϑ and systems of equations to determine time points τ, at which the temperature at the characteristic point takes reference values.

B. Determination of the stress state created by the flow of energy

The next step in the model is to solve the elasticity problem taking into account the already known temperature distribution. This takes into account the dependence of physical and mechanical characteristics of the material on temperature. The corresponding problem of thermoelasticity is to determine the components of the stress tensor and the vector of deformation, as well as the component of the vector of displacements [1,10]. We get the following system of equations:

$$\left(\Delta-\frac{1}{r^2}\right)u_r+\frac{1}{1-2\nu}\frac{\partial e}{\partial r}-\frac{2}{r^2}\frac{\partial u_\phi}{\partial\phi}=$$
$$=2\frac{1+\nu}{1-2\nu}\frac{\partial}{\partial r}\Phi(t)-\frac{1}{G^2}\left[\frac{\partial G}{\partial r}\sigma_{rr}+\frac{1}{r}\frac{\partial G}{\partial\phi}\sigma_{r\phi}+\frac{\partial G}{\partial z}\sigma_{rz}\right],$$

$$\left(\Delta-\frac{1}{r^2}\right)u_\phi+\frac{1}{1-2\nu}\frac{1}{r}\frac{\partial e}{\partial\phi}+\frac{2}{r^2}\frac{\partial u_r}{\partial\phi}=$$
$$=\frac{2}{r}\frac{1+\nu}{1-2\nu}\frac{\partial}{\partial\phi}\Phi(t)-\frac{1}{G^2}\left[\frac{\partial G}{\partial r}\sigma_{r\phi}+\frac{1}{r}\frac{\partial G}{\partial\phi}\sigma_{\phi\phi}+\frac{\partial G}{\partial z}\sigma_{\phi z}\right], \tag{4}$$

$$\Delta u_z+\frac{1}{1-2\nu}\frac{\partial e}{\partial z}=$$
$$=2\frac{1+\nu}{1-2\nu}\frac{\partial}{\partial z}\Phi(t)-\frac{1}{G^2}\left[\frac{\partial G}{\partial r}\sigma_{rz}+\frac{1}{r}\frac{\partial G}{\partial\phi}\sigma_{\phi z}+\frac{\partial G}{\partial z}\sigma_{zz}\right].$$

here Δ is Laplace operator.

This model takes into account that the temperature coefficient of linear expansion is also a function of temperature

$$\Phi(t)=\int_{t_0}^{t}\alpha_t(\xi)d\xi. \quad (5)$$

The written system of equations, as well as the boundary conditions represent the boundary value problem of mathematical physics, which is used to determine the elastic state of a cylindrical body. This takes into account the dependence of the characteristics of the material on temperature. To solve this boundary value problem, we will use the perturbation method, as well as the method of successive approximations. Assume that shear module G is defined as a function of temperature as follows:

$$G(t)=G_0\cdot\exp\left(-\varepsilon\frac{t-t^*}{t^*}\right) \quad (6)$$

Using the smallness of the fixed parameter ε, we present displacements and stresses using asymptotic series

$$(u_\alpha,\sigma_{\alpha\beta})=\sum_{n=0}^{\infty}\varepsilon^n(u_\alpha^{(n)},\sigma_{\alpha\beta}^{(n)}),\quad (\alpha,\beta=r,\varphi,z). \quad (7)$$

Therefore, the initial task for determining the stress state is reduced to a recurrent sequence of boundary value problems:

attached to n = 0

$$\left(\Delta-\frac{1}{r^2}\right)u_r^{(0)}+\frac{1}{1-2\nu}\frac{\partial e^{(0)}}{\partial r}-\frac{2}{r^2}\frac{\partial u_\phi^{(0)}}{\partial\phi}=2\frac{1+\nu}{1-2\nu}\frac{\partial}{\partial r}\Phi(t),$$

$$\left(\Delta-\frac{1}{r^2}\right)u_\phi^{(0)}+\frac{1}{1-2\nu}\frac{\partial e^{(0)}}{\partial\phi}+\frac{2}{r^2}\frac{\partial u_r^{(0)}}{\partial\phi}=\frac{2}{r}\frac{1+\nu}{1-2\nu}\frac{\partial}{\partial\phi}\Phi(t),$$

$$\Delta u_z^{(0)}+\frac{1}{1-2\nu}\frac{\partial e^{(0)}}{\partial z}=2\frac{1+\nu}{1-2\nu}\frac{\partial}{\partial z}\Phi(t),$$

attached to n > 1

$$\left(\Delta-\frac{1}{r^2}\right)u_r^{(n)}+\frac{1}{1-2\nu}\frac{\partial e^{(n)}}{\partial r}-\frac{2}{r^2}\frac{\partial u_\phi^{(n)}}{\partial\phi}=F_r^{(n)},$$

$$\left(\Delta-\frac{1}{r^2}\right)u_\phi^{(n)}+\frac{1}{1-2\nu}\frac{1}{r}\frac{\partial e^{(n)}}{\partial\phi}+\frac{2}{r^2}\frac{\partial u_r^{(n)}}{\partial\phi}=F_\phi^{(n)},$$

$$\Delta u_z^{(n)}+\frac{1}{1-2\nu}\frac{\partial e^{(n)}}{\partial z}=F_z^{(n)}$$

as well as the condition of absence of power load on the surface.

The modern mathematical apparatus of operational calculation, the use of Bessel functions, and the Dini and Fourier-Bessel series were used to construct the solution of the corresponding problems of mathematical physics.

C. Determining relations of stresses.

As a result of solving the thermoelasticity problem, a sequence is obtained that determines the components of the stress tensor. The main components are as follows:

$$\sigma_{rr}^{(n)}=2G\left(\frac{\partial u_r^{(n)}}{\partial r}+\frac{\nu}{1-2\nu}e^{(n)}-\delta_{n0}\frac{1+\nu}{1-\nu}\Phi(t)\right), \quad (8)$$

$$\sigma_{\phi\phi}^{(n)}=2G\left(\frac{1}{r}\frac{\partial u_\phi^{(n)}}{\partial\phi}+\frac{1}{r}u_r^{(n)}+\frac{\nu}{1-2\nu}e^{(n)}-\delta_{n0}\frac{1+\nu}{1-\nu}\Phi(t)\right),$$

$$\sigma_{zz}^{(n)}=2G\left(\frac{\partial u_z^{(n)}}{\partial z}+\frac{\nu}{1-2\nu}e^{(n)}-\delta_{n0}\frac{1+\nu}{1-\nu}\Phi(t)\right).$$

Thus, the thermoelasticity problem can be rewritten as a recurrent sequence.

IV. Application of the Developed Methodology

Based on the above solution of the problem of thermal conductivity and the problem of determining the elastic state for a cylinder heated by a ring concentrated energy flow, numerous studies of nonstationary temperature field and quasi-static temperature stresses have been performed.

Calculations were performed for a cylinder with a radius of not more than 10 mm, the thermophysical and mechanical characteristics of the material of which correspond to tool steels.

According to [1], the coefficient of heat absorption capacity of the material γ(t) varies according to the law

$$\gamma(t)=0,3+4\cdot10^{-3}\frac{t}{t^*},\quad t^*=\text{const}. \quad (9)$$

Cylinder heating parameters, namely power density q_0 and energy flux concentration factor k selected as a constant value, but in the course of numerical research, these values can be changed and their optimal values sought.

Graphs 1 and 2 show the temperature distributions for the time component $\tau=6$ msec. depending on the axial coordinate z on the surface of the body and depth $\delta=b-r$ when $z=0$ accordingly.

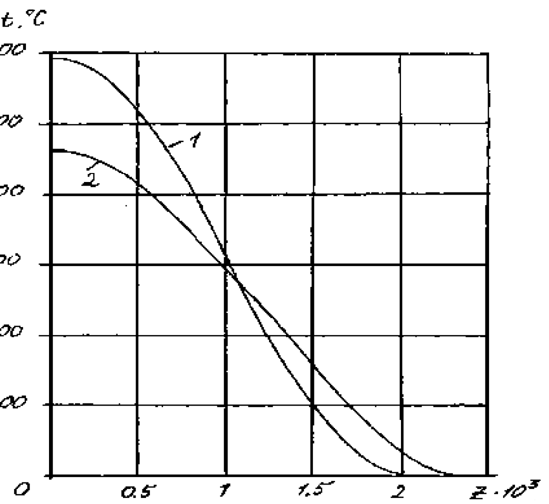

Fig. 1. The temperature distribution along the axial coordinate.

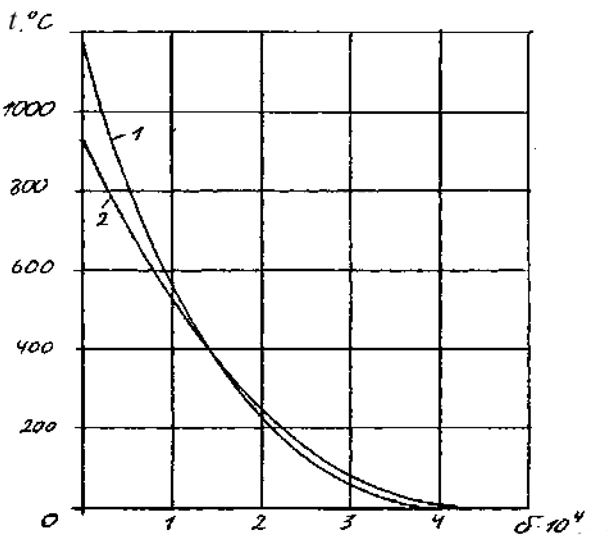

Fig. 2. The temperature distribution by depth.

Line 1 in the presented graphs corresponds to the solution taking into account the temperature dependence of the values of the coefficients of thermal conductivity and heat absorption capacity of the body material, and line 2 - the solution at the average values in the considered range of changes in temperature characteristics.

As can be seen from the graphs on the surface, the discrepancy between the temperature calculated taking into account the thermal sensitivity of the material and the corresponding averages is 23%.

The next object of study is the components of the stress tensor. Exceeding the value of the components of the stress tensor of the allow values can lead to plastic deformation and destruction of structural elements. The changing of the parameters of concentrated heat flux is important to determine the stress distribution in the body.

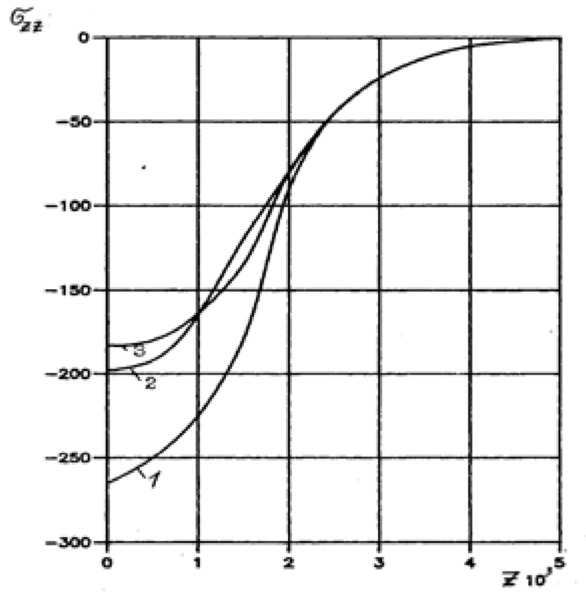

Fig. 3. The stress distribution along the axial coordinate

In fig. 3. the distributions of the components of the stress tensor along the axial coordinate on the body surface are given. Line 1 corresponds to the problem with temperature-dependent on material characteristics.

From comparison of the received data it is visible that the stresses calculated taking into account dependence on temperature of characteristics of material, in size much higher than those found at the corresponding average values. In this case, the maximum value of stresses achieved on the surface of the cylinder at, taking into account the thermal sensitivity of the material by 32% exceeds the corresponding, which is calculated at average values. The determining factor is the temperature dependence on the coefficient of heat absorption capacity of the material, which follows from the comparison of lines 2 and 3. The difference in the maximum values is 9%. Similar research have been performed for other components of the stress tensor.

Using software created for research makes it possible to optimize the effect of concentrated energy flow on the surface. This allow you to choose the value of power density q_0 and the energy flux concentration factor k so as to obtain the best result of heat treatment of the bearing surfaces of aircraft.

CONCLUSIONS

1. The mathematical model of influence of the concentrated flow of heat on a lateral surface of elements of designs of a cylindrical form is constructed. The dependence of the temperature change on the thermophysical and mechanical characteristics of the material is taken into account, which leads to the clarification of the results.
2. Studies of the distribution of a nonstationary temperature field, as well as the stress state in a cylindrical body created by a change in temperature. A comparative analysis of the results taking into account the influence of the dependences of the thermophysical and mechanical characteristics of the material on temperature with the results obtained in the linear model is presented.
3. It is established that the values of temperature, which is determined taking into account the dependence of thermophysical characteristics of the material on temperature, exceed similar values, calculated without taking into account. A comparative analysis of the dependence of the temperature field distribution on the diameter is performed.
4. It is established that the influence of the degree of deformation of structural parts and their mechanical characteristics significantly depends on the temperature, and hence from the parameters of the concentrated flow of energy to their surface.
5. The results of research can be used to determine the strength limits, areas of nonelastic deformations in the body, as well as to predict areas of thermal influence and destruction.
6. The presented methodology of determining the temperature distribution, stress state and mechanical properties at different parameters of the concentrated energy flow can be used in the technology of strengthening the bearing surface. This will increase the accuracy of assessing the operational reliability of structural elements, as well as to reduce their metal consumption.

7. Using the created software it is possible to optimize the action of concentrated energy flow on the surface and get the best result of heat treatment of the bearing surfaces of aircraft.

8. The scientific novelty is the proposed mathematical model of influence of concentrated energy flow on the body surface, taking into account to the thermal sensitivity of the characteristics of the material. This model can be used to determine and specification the parameters of concentrated energy flow.

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