IRRADIATION SYSTEMS WHICH ADAPT TO THE SHAPE OF THE HEATED OBJECT

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The concept of technical systems designed for adaptive thermal irradiation of objects whose shape and position in space are variable is presented.

Thermal irradiation is today one of the most promising technologies, employed in different fields of endeavor, ranging from heat treatment in machine building to heat therapy in medicine. The equipment employed for this purpose is also very diverse, ranging from the simplest infrared heaters for domestic use to systems containing tens and unique systems containing hundreds of computer-controlled sources of radiation for thermal testing of space vehicles.

In order to improve this technology new means of converting and controlling the propagation of radiation, especially means which enable equipment of this type to adjust or adapt to different and not predetermined operating conditions, must be introducd. This is the trend at the present stage of scientific—technological progress. Examples are adaptive optics [1, 2], robot technology [3, 4], and other fields.

One direction of development of irradiation technology is the development of systems that can adapt to the shape of the object being irradiated and can deliver to the surface of the object radiation with prescribed parameters (irradiance, distribution over the surface, etc.) without a priori information about the shape of the surface. These are either objects whose geometry can change or interchangeable objects having different shapes.

Such systems are important primarily in medicine for thermal irradiation of some region (burns, growth of new skin, etc.), in general having an arbitrary shape and position, of the patient's body. Here adaptation is necessary when tracking different body motions during medical treatment and when the system is switched from one patient to another. This fundamentally new technology makes it possible to introduce into medical practice new methods of heat therapy, in which heat can be applied to specifically selected locations on the body, and, as a result, to reduce the treatment times sharply.

The concept of adaptive irradiation is based on a series of principles, such as the following:

adaptation in the wide sense [4], i.e., the adaptive system contains sensors which make it possible to obtain information about the working zone of the system — the zone of action — and/or the properties of separate objects, and this information is used to solve different problems associated with the formation of the controlling signals (adaptation in the narrow sense [4] — adaptive algorithms are employed for processing information about these state of the zone and/or the state of objects);

a prescribed field of irradiance is formed on the object with the help of a limited set of controllable sources of directed thermal radiation — the irradiation system;

these sources are controlled with the help of a three-dimensional mathematical model of the irradiation system and the object;

a mathematical model of the irradiated object is constructed with the help of sensors while the system is in operation.

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Hence, one can see the main difference between this system and the systems employed in adaptive optics: adaptive optics is based on the classical theory of automatic control [1], where the temporal aspect of the control process is accentuated, whereas adaptive irradiation is based on more general principles of adaptive robot technology, where the spatial aspect is important [4], and this makes the problem of describing the interation of the system and the object and organizing the control processes much more difficult.

Figure 1 shows a diagram of a system for performing adaptive irradiation with heat. The system contains the following:

a subsystem of sources of directed thermal radiation;

a system for control and communication with the operator;

a system for determining, with the help of technical-vision sensors, the shape of the object being irradiated.

We shall describe the properties and basic functions of each subsystem.

The sources of the directed radiation differ from other sources by their narrow directional pattern (phase function). This makes it possible to form quite accurately a prescribed irradiation field on the object being irradiated. The sources consist of laser beams, miniprojectors — halogen lamps with mirror reflectors of the type NARROW BEAM (Iwasaki, Japan; General Electric, USA; Osram, Federal Republic of Germany), and other sources, most often with special deflectors, which form the directional pattern [5]. A second feature of the radiation sources employed here is that the position and orientation of the directional pattern in space and the energy parameters of the sources can be controlled.

The subsystem which determines the shape of the object being irradiated employs location detectors — sensors which are used for performing remote measurements of the shape of the surface of the object or a part of the object; it is best to use laser location detectors here.

In the control subsystem a three-dimensional mathematical model of the object being irradiated is constructed from the results of location measurements and the optimal parameters (position, orientation, intensity, etc.) of the sources of directed thermal radiation are calculated on the basis of this model for the instantaneous values of the geometric parameters of the object.

The control subsystem is based on a microprocessor or a computer and is incorporated in the communication subsystem for on-line information transfer between the system and the operator (doctor in medical applications) and between the system and other equipment.

The algorithm governing the operation of the adaptive irradiation system can be represented as follows.

After the object is positioned in the working zone of the system the geometric parameters of the surface of the object are measured with the help of the technical-vision subsystem and a three-dimensional mathematical model of the object is constructed in the control subsystem on the basis of these measurements. In the case when only a part of the surface is to be irradiated this region is separated with the help of markers, for example, corner reflectors, etc., measurements are made, and a model of only the separated region is constructed. Next, the parameters of the irradiation field which must be formed on the surface of the object and maintained throughout the irradiation process are set.

The parameters of the radiation sources are calculated in the control subsystem, according to the model, for instantaneous values of the geometric parameters of the object for which a prescribed irradiance field will be produced on the surface of the object. Sources of radiation are chosen with the help of the control subsystem in accordance with the computed parameters.

Measurements are performed regularly and they determine whether or not the shape and position of the object have changed. If they have changed, then a new corresponding model is constructed, the new parameters are determined, and the radiation source subsystem is adjusted to them; if the position and shape of the object have not changed, then a new model is not constructed and the system operates in the mode determined from the preceding measurements.

Thus, the system makes it possible to follow the change in the position and shape of the object being irradiated, for example, as the object turns in the working zone or one object

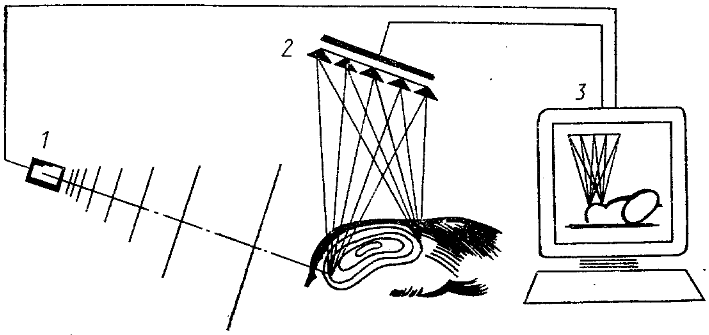

Fig. 1. Diagram of the irradiation system which adapts to the shape of the object being heated: 1) technical-vision subsystem; 2) subsystem of sources of directed radiation; 3) subsystem for control and communication with the operator.

is replaced with another object, i.e., the system adapts to an a priori unknown shape of the surface of the object.

The adaptational possibilities of such an irradiation system are determined primarily by the algorithms and software employed in the control subsystems. They are associated primarily with the solution of the following applied problems.

1. Mathematical modeling of the surfaces of complicated three-dimensional forms – irradiated objects, irradiance fields on the objects, deflectors, for example, mirror reflectors of the sources of directed radiation, directional patterns. Here it is necessary to employ methods of computational geometry, with whose help, in particular, the surface of the irradiated object is reconstructed at prescribed points which are determined by the location measurements. In computer-aided development of systems with sources of directed radiation one such method is modeling of surfaces with the help of splines [5].

2. Mathematical modeling of the process of radiation transfer from the sources to the objects being irradiated, including solution of the conjugate problems (in the same example of medical applications – the control subsystem contains a mathematical model of the body's temperature regulation system), problems of optimizing the parameters of the sources of directed radiation and their components, choice of position and orientation of the sources, and a number of other problems.

The latter problems – the optimization of the position and orientation of the sources of directed radiation – are important in a number of related fields of radiation technology: light and solar technology, optical and thermal technology, etc. This is essentially one type of inverse problem, when a cause, in the general case the number, intensity, directional pattern, and position of the sources and other parameters of the irradiation system with the corresponding boundary conditions, must be determined from a prescribed effect (irradiance field on the object).

In contrast to the inverse problems of creating the source of directional radiation itself, in which the required parameters of deflectors–reflectors, lenses, focusers, and other devices for controlling the direction of radiation must be found, problems of the type studied here belong to the class of problems in which the optimal spatial arrangement of the sources relative to the object being irradiated is determined – configuration synthesis problems. Particular formulations of problems of this type in radiation heat exchange are given, for example, in [6, 7]; general approaches are presented in [8, 9].

Following [9], we give a comprehensive formulation of the main problem of configurational synthesis of systems with sources of directed radiation. In the process of configuring the system it is necessary to determine the geometric characteristics of the system (form, dimensions, location of the system components, etc.), the mutual arrangement and orientation of the radiation sources and the objects being irradiated (in statics or dynamics – depending on the formulation of the problem). In so doing, a number of restrictions (on the intensity and location of the radiation sources, the resulting irradiance field, dimensions, etc.) must be satisfied and an extremal value must be given to some target function.

In the general case the irradiation system consists of a bounded region $\Omega \in R^3$, containing discrete sources of directed radiation with carriers $S_i (i = 1, 2, \ldots, m)$. The radiation field generated in the system by the sources and the surrounding medium is in the general case described by the boundary-value problem

$$Au = F, \; B_j u = f_j \; (j = 1, 2, \ldots, n),$$

where A is a prescribed operator; the function u(x, y, z, t) characterizes the space–time distribution of the field; $B_j (j = 1, 2, \ldots, n)$ are given operators, characterizing the boundary conditions, the initial conditions, and the conditions of matching at the interfaces between the media; $f_j (j = 1, 2, \ldots, n)$ are prescribed functions; the function F characterizes the spatiotemporal distribution of the sources in the system and has the following form for continuously operating sources:

$$F = \begin{cases} F_i(x, y, z, t), & \text{if } (x, y, z) \in S_i, \\ 0, & \text{if } (x, y, z) \notin \bigcup\limits_{i=1}^{m} S_i. \end{cases}$$

The control $F \in \theta_1, \; \theta_1 \neq 0$ is the region of admissible controls F. The region θ_1 is determined by the constraints on the control F; these constraints could be the condition that the finite functions belong to some space of functions, restrictions on the range of the maximum values of the finite functions, etc.

In order for the formulation to be informative, the system must be synthesized taking into account the geometric characteristics of the system as a whole. Such information is contained in the vector of geometric information g, in particular, in the parameter ν, which includes the varible components of the information [9]. The information contains the size characteristics of the carriers of the sources and the radiation system as a whole, the source location parameters, etc. The information ν is present in the function characterizing the state of the system, and for this reason it is a second type of control. Let $\nu \in \theta_2$, where $\theta_2 \neq 0$ is the region of admissible ν; it is determined by the restrictions on the range of the components of the vector ν. Such restrictions are that the source carriers must not intersect with one another and they must belong to the region Ω and the carriers must not intersect with the forbidden regions in Ω.

Let the geometric information $g \in G$ induce a point set T in the space R^t, and let the information $g^* \in G^*$ induce a point set T* in the metric space R^k. A mapping P of the form $g^* = Pg$ is called the problem of configurational synthesis. Then the optimization problem of configurational synthesis of radiation systems can be formulated as follows:

Determine controls $F \in \theta_1$ and $\nu \in \theta_2$ and the corresponding mapping T*, induced by the geometic information

$$g^* = P[g(\nu)],$$

so that the functional $\varkappa(F, \nu)$ in the region of admissible controls $D \subset X$ takes an extremal value, i.e.,

$$\varkappa(\omega^*) = \operatorname*{extr}_{\omega \in D} \varkappa(\omega) = \operatorname*{extr}_{(F, \nu) \in D} \varkappa(F, \nu).$$

This problem apparently must be solved both at the stage of system design and during system operation. Hence, the software used to solve the configuration problem must operate in real-time.

This problem is one of the key problems in the development of the theoretical foundations of adaptive irradiation — a new scientific direction in heat exchange by radiation, and the solution of this problem is urgent.

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CALCULATION OF RESIDUAL STRESSES INDUCED DURING LASER QUENCH-HARDENING OF STEEL

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We present a theoretical and numerical analysis of the quasi-stationary uncoupled problem of thermoelastic—plasticity with the goal of estimating the amount of residual stress in steel after laser quench-hardening.

During laser quench-hardening of steels, temperature and concentration gradients and also structural phase transformations lead to the inception and development of temperature-, concentration- and phase-stresses, respectively, in the hardened layer of the metal. These are in turn imposed on the initial structure of the material, which in general is deformed. As a result, during heating the conditions for microscopic plastic deformation are created [1]. By changing the activation energy of the processes, this deformation significantly influences the kinetics of laser austenizing, carbide decay, and the diffusion of carbon and alloying elements out of the carbides in the matrix, and finally leads to a shift of the instrumental start of the (α—γ) phase change. Residual stresses are formed in the surface layer during rapid cooling. The mechanical properties of the laser quench-hardened layer depend to a significant degree on these residual stresses.

At present, analysis of the thermoelastic behavior of a solid body during laser heating has been widely developed [2-4], based on the simultaneous solution of the uncoupled problems of thermal conductivity and thermoelasticity. Fewer works are devoted to the theoretical investigation of phase stresses and plastic deformation during laser heating [1]. However, due to the difficulty of high-temperature γ-phase diagnostics, comparison with experiment for laser heating is problematic. On the other hand, there are well-known works on laser cooling [5-7], where the residual stresses in the hardened layer have been determined using x-radiography. The stresses were determined in this layer as a functon of depth in the zone of laser influence (ZLI) and as a function of the spot of laser action (LA) on the surface. There are only a few attempts to theoretically analyze the residual stresses during laser cooling [8, 9]. For example, in [8] only the martensite phase (γ—α) residual stresses after LA are analyzed, and in [3] thermal stresses calculated for the heating stage in a stationary approximation are called residual stresses. Moreover in both cases [3, 8], residual stress calculation was done within the framework of elasticity theory, which is physically unfounded. The most complete approach is in [9], where a method developed earlier for computing residual thermal stresses in welded joints is carried over to laser heat-treating of steel. This method takes the theory of plastic deformation into account. Thus the development of a theoretical and numerical method of computing stresses is a topical problem in laser production technology. Its solution will permit more exact prediction of the mechanical characteristics of the layer modified by laser radiation (LR).

The model of laser quench-hardening developed by us earlier [1, 10] creates a physically clear picture of the thermal, kinetic, and diffusion processes in time and space during heating. We examine the interconnection of these processes and their influence on the development and redistribution of stresses during LA. Let an axisymmetric beam flux with Gaussian intensity distribution in the laser beam cross section fall on the surface of the steel.

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