

High power optics

Abstract

The advent of the laser has placed stringent requirements on the fabrication, performance and quality of optical elements employed within systems for most practical applications. Their high power performance is generally governed by three distinct steps, firstly the absorption of incident optical radiation (governed primarily by various absorption mechanisms); secondly, followed by a temperature increase and response governed primarily by thermal properties and finally the elements thermo-optical and thermomechanical response, e.g., distortion, stress birefringent fracture, etc. All of which needs to be understood in the design of efficient, compact, reliable and useful for many applications high power systems, under a variety of operating conditions, pulsed, continuous wave, rep-rated or burst mode of varying duty cycles which is the most important for the wide spectrum of applications.

Volume I Issue 3 - 2018

Apollonov VV

Prokhorov GPI RAS Vavilov, Russia

Correspondence: Apollonov VV, Prokhorov GPI RAS Vavilov str.38, Moscow, 119991, Russia, Email vapollo@kapella.gpi.ru

Received: February 27, 2018 | **Published:** May 11 2018

Introduction

On the basis of the theory we developed in the early 1970s, a broad range of phenomena is considered in the paper for an optical surface of a solid body that is exposed to radiation arbitrarily varying in time and producing temperature gradients, thermoelastic stresses and thermal deformations on the surface layer. The examination is based on the relations between the quantities characterising the thermal stress state in any non-stationary regimes of energy input into a solid, which are similar to Duhamel's integral formula from the theory of heat conduction. A peculiar feature of the analysis of the thermal stress state in this case consists in the fact that this relation comprises time as a parameter, which in turn is a consequence of incoherence of the quasi-stationary problem of thermoelasticity. This phenomenon is particularly important for the optics of high power level, high-pulse repetition rate lasers, which are being actively developed. In the review, we have recently published in Laser Physics Journal,¹ the thermal stress state of a solid is analysed. In this state, time is treated as an independent variable used in differentiation. Such an approach greatly reduces the possibility of the method. The review published contains data on the use of capillary porous structures made of various materials with different degrees of the surface development. Moreover, such structures can be efficiently employed to increase the heat exchange at a temperature below the boiling point of the coolant. In the paper we discuss the dependences of the limiting laser intensities on the duration of a pulse or a pulse train, corresponding to the three stages of the state of the reflecting surface and leading to unacceptable elastic deformations of the surface, to the plastic yield of the material accompanied by the formation of residual stresses and to the melting of the surface layer. We also analyse the problem of heat exchange in the surface layer with a liquid metal coolant pumped through it. The theoretical estimates are compared with the experimental data. Review represents the issues related to the technology of fabrication of power optics elements based on materials with a porous structure, of lightweight highly stable large optics based on highly porous materials, multi-layer honeycomb structures and silicon carbide, as well as problems of application of physical and technical fundamentals of power optics in modern high-end technology.

The second part of the review is devoted to the problem of high power high repetition rate lasers pulse periodic laser systems, which in the nearest time will find a lot of applications in the field of

space ecology, long range energy transfer, heavy machinery, space engineering, nuclear technologies and many others. Our paper has considered in details a new approach to the problem of a laser jet engine creation, which is based on the resonance merging of shock waves generated by an optical pulsating discharge, produced by such a lasers. To obtain an optical pulsating discharge, we suggested the usage of high-power pulse-periodic laser radiation, which can be generated by wide aperture carbon dioxide, chemical and mono-module disk type solid-state laser systems. Future developments of the disk laser technology as the most effective and scalable to the level of many hundreds of kW as well are under consideration in the paper.

The history of high power optics is inextricably associated with the creation of a single-mode CO_2 laser ($P = 1.2\text{ kW}$), operating in the master oscillator–power amplifier regime and employing the principle of a quasi-optical transmission line, at the Laboratory of Oscillations of the P.N. Lebedev Physics Institute headed at the time by AM Prokhorov. Its creator was A.I. Barchukov, who worked with a team of young scientists on the problem of scaling of single-mode electric-discharge laser systems.^{2–5} Due to the research conducted on such a laser system, we managed to study many physical phenomena occurring when high intensity radiation interacts with matter, including with the elements of the optical path of laser systems, which subsequently greatly facilitated creation of high-power lasers. Then, in the early 1970s, we paid attention to a phenomenon that was to limit undoubtedly the further growth of the power generated by lasers being developed.⁶ More than twenty years of fundamental and applied research devoted to the study of this phenomenon and to the solution of problems associated with it allow a conclusion that its essence consists in the following. An optical surface of a highly reflecting power optics element (POE) or any element of an optical path does not fully reflect radiation falling on it. A small portion of energy (fractions of a percent, depending on the wavelength) is absorbed by this reflecting element and turns into heat. As the output power increases, even a small amount of it is sufficient to induce thermal stresses in a POE. Thermal stresses distort the geometry of the reflecting surface, affecting thereby, for example, the possibility of long-distance delivery of radiation and its concentration in a small volume. The discovered effect of thermal deformations of a POE required a theoretical study of the problem that had not been solved in such a setting ever before. Very useful was the experience in solving the problems of thermoelasticity, gained by the theoretical department headed at that time at by B.L. Indenbom

at the Institute of Crystallography, USSR Academy of Sciences. Minimisation of the thermoelastic response of the optical surface of the POE exposed to intense laser radiation is one of the key problems of power optics. Improving the efficiency of laser systems, increasing the output power and imposing stricter requirements to the directivity of generated radiation fluxes are inextricably linked with the need to design and create a POE with elastic distortions $\lambda/10 \div \lambda/20$ (λ is the wavelength) at specific radiation loads up to several tens of $\text{kW} \cdot \text{cm}^{-2}$.⁷⁻¹⁰

Interest in high power optics and its physical, technical and technological solutions is unabated to this day. An almost simultaneous creation of first lasers in the USA and the USSR gave birth to annual symposia on Optical Materials for High-Power Lasers (Boulder, USA) and Nonresonant Laser-Matter Interaction (Leningrad, USSR). Regular meetings of scientists and engineers, as well as proceedings of the symposia have had a significant impact on the development of research in the field of high power optics in many countries.¹¹⁻¹³

The data presented in this review allow one to reconsider important aspects of temperature gradients, thermoelastic stresses and thermal deformations in POEs, resulting from the exposure of their surfaces to high-power laser radiation. In this case, use is made of the relations between the quantities characterising the thermal stress state in any nonstationary regimes of energy input into a solid, which are similar to Duhamel's integral formula from the theory of heat conduction. A peculiar feature of the analysis of the thermal stress state in this case consists in the fact that these relations comprise time t not as an independent variable, which is used in the differentiation (as, for example, in review¹⁴) but as a parameter, which is a consequence of incoherence of the quasi-stationary problem of thermoelasticity presented below. Thus, by using the theory we developed in the early 1970s, we consider in this review a wide range of phenomena related to the thermal stress state of a solid-body surface exposed to radiation arbitrarily varying in time.¹⁵⁻²¹ This consideration is particularly important for the optics of high-power, high-pulse repetition rate laser systems that are being actively developed. In review¹⁴ we analysed important for the development of high power optics problems of using capillary-porous structures with different degrees of development for the enhancement of heat transfer surface with water temperatures below the boiling point. The review published¹⁴ contains data (important for the development of high power optics) on the use of capillary porous structures with a different degree of the surface development, which can be efficiently employed to increase the heat exchange at a temperature below the boiling point of the coolant. The evaporation-condensation mechanism of heat transfer in the POE on the basis of porous structures and the idea of lowering the boiling temperature under reduced pressure of the coolant in cellular materials, developed by us at the same time,^{14,21} are not considered in this review.

Static POEs based on monolithic materials

Consider the most important aspects of the problem of static POE fabrication, namely, the conditions needed to achieve high optical efficiency thresholds for a mirror surface. Note that in our first studies⁴⁻⁹ we obtained only stationary expression for the limiting intensities, leading to the optical destruction of POEs, and the stability parameters of optical surfaces based on them.

Thermal stress state of a body exposed to laser radiation

Temperature field

We considered a strongly absorbing isotropic body, which at the initial moment of time has a fixed temperature. The body surface with the absorption coefficient A is exposed to an axisymmetric radiation flux of arbitrary temporal shape. It is assumed that the intensity distribution in the laser beam cross section obeys the Gaussian law: $I(\vec{r}) = I_0 \exp(-K_0 r^2)$, where $K_0 = 2/r_0^2$. Energy absorption takes place directly on the irradiated surface. Physically, this means that the skin-layer depth τ is smaller than the depth of the temperature field penetration in the body under consideration during the characteristic times τ of changes in the radiation intensity, i.e., $\delta \ll \sqrt{a^2 \tau}$, where a^2 is the thermal diffusivity of the material.

The problem of determining the temperature field was considered in the linear formulation: it was assumed that all thermal and mechanical characteristics of the materials are independent of temperature and energy loss by radiation and convection was neglected. Provided that the characteristic size of the beam is $r_0 < L$, where L is the characteristic size of the irradiated body, and the energy input time is $t < L^2/a^2$, in solving this problem one can use the half-space model. The heating of the sample material is described in this case by the heat conduction equation²²

$$\frac{\partial T}{\partial t} = a^2 \Delta T \quad (1)$$

at the following initial and boundary conditions:

$$\begin{aligned} \left. \frac{\partial T}{\partial z} \right|_{z=0} &= -\frac{I_0 A}{\lambda} f(t) \exp(-K_0 r^2), \\ T(r, z, 0) &= 0, \\ \lim_{r, z \rightarrow \infty} T &< M, \end{aligned} \quad (2)$$

where M is the finite quantity; $f(t)$ is the time function of the laser beam intensity normalised to I_0 ; λ is the absorption coefficient of laser radiation on a metal surface; λ is the thermal conductivity of the body material; and T is the temperature.

Using the method of successive integral Hankel and Laplace transforms, we obtain the solution to (1)

$$\begin{aligned} T(r, z, t) &= T^* \frac{I_0 A}{2\lambda \sqrt{K_0}}, \\ T^* &= \frac{1}{2\pi i \sqrt{K_0}} \int_{\sigma-j\infty}^{\sigma+j\infty} dp \psi(p) \exp(pt) \times \\ &\times \int_0^\infty \xi \frac{\exp(-\xi^2/4K_0)}{\gamma} \exp(-yz) J_0(\xi r) d\xi, \end{aligned} \quad (3)$$

where p and ξ are the parameters of Laplace and Hankel transforms; $\gamma^2 = p/a^2 + \xi^2$; $\psi(p)$ is the image of the Laplace transform of $f(t)$; and J_0 is the zero-order Bessel function.

This expression allows us to describe the thermal state of a solid body heated by laser radiation, whose intensity varies with time in an arbitrary manner.

Thermoelastic stresses

The thermoelastic behaviour of the body is analysed by using the system of equations:^{22,23}

$$\mu \nabla^2 \vec{u} + (\lambda' + \mu) \text{grad div } \vec{u} - (3\lambda' + 2\mu) \alpha_T \nabla T + \vec{F} - \rho \ddot{\vec{u}} = 0, \quad (4)$$

$$\nabla^2 T - \frac{1}{a^2} \frac{\partial T}{\partial t} + \frac{W}{\lambda} - \frac{(3\lambda' + 2\mu) \alpha_T T}{\lambda} \text{div } \vec{u} = 0,$$

where λ' and μ are the Lamé coefficients;²⁴ $\vec{u}$ is the deformation vector; ρ is the density of the material; $\vec{F}$ is the external force; W_0 is the coefficient of thermal expansion; and W_0 is the density of volume heat sources.

In considering the deformation of an elastic metal half-space whose surface is exposed to pulsed laser radiation, when the inequalities

$$|\rho \ddot{\vec{u}}| \ll (3\lambda' + 2\mu) \alpha_T |\nabla T|, \quad (5)$$

$$\nabla^2 T \sim \frac{1}{a^2} \frac{\partial T}{\partial t} \gg \frac{(3\lambda' + 2\mu) \alpha_T T}{\lambda} \text{div } \vec{u}$$

are fulfilled, we can pass to the system of equations of the quasi-stationary thermoelasticity theory:

$$\mu \nabla^2 \vec{u} + (\lambda' + \mu) \text{grad div } \vec{u} - (3\lambda' + 2\mu) \alpha_T \nabla T = 0, \quad (6)$$

$$\nabla^2 T - \frac{1}{a^2} \frac{\partial T}{\partial t} = 0.$$

In this case, from the first inequality we obtain the duration of a single pulse

$$\tau \gg \max \left(\frac{\rho a^2}{\lambda'}, \frac{\rho a^2}{\mu} \right) \sim 10^{-6} \div 10^{-8} \text{ s}, \quad (7a)$$

and from the second –

$$\tau^{3/2} \ll \frac{\rho^2 c^2 \sqrt{a^2}}{\mu \alpha_T I_0 A} \quad (7b)$$

We represented the stress tensor components in the general form:²¹

$$\sigma_{zz}^{\wedge} = 2GD \int_0^{\infty} \xi^2 J_0(\xi r) \phi(\xi) \left[e^{-\gamma z} - e^{-\xi z} (1 + z(\xi - \gamma)) \right] d\xi, \quad (8)$$

$$\sigma_{rr}^{\wedge} = 2GD \int_0^{\infty} \phi(\xi) \left\{ J_0(\xi r) \left[\xi(\xi z - 2)(\xi - \gamma) e^{-\xi z} + \xi^2 e^{-\xi z} - \gamma^2 e^{-\gamma z} \right] + \frac{J_1(\xi r)}{r} \left[\xi e^{-\gamma z} - ((\xi - \gamma)(\xi z - 2(1 - \nu)) + \xi) e^{-\xi z} \right] \right\} d\xi,$$

$$\sigma_{rz}^{\wedge} = 2GD \int_0^{\infty} \xi \phi(\xi) J_1(\xi r) \left[\gamma (e^{-\gamma z} - e^{-\xi z}) - \xi z (\xi - \gamma) e^{-\xi z} \right] d\xi,$$

$$\sigma_{\phi\phi}^{\wedge} = 2GD \int_0^{\infty} \phi(\xi) \left\{ J_0(\xi r) \left[(\xi^2 - \gamma^2) e^{-\gamma z} - 2\nu \xi (\xi - \gamma) e^{-\xi z} \right] + \frac{J_1(\xi r)}{r} \left[((\xi - \gamma)(\xi z - 2(1 - \nu)) + \xi) e^{-\xi z} - \xi e^{-\gamma z} \right] \right\} d\xi,$$

where J_1 is the shear modulus; J_1 is the first-order Bessel function;

$$D = \frac{\alpha_T (1 + \nu) I_0 A a^2}{2 (1 - \nu) K_0 \lambda_p} \psi(p); \quad \phi(\xi) = \frac{\xi}{\gamma} \exp(-\xi^2 / 4K_0);$$

and ν is Poisson's ratio. Analysis of the expression reveals the nature of the time changes at any point in the half-space.

Thermal deformations

The stress state occurring in a solid body is accompanied by its deformation, its largest amplitude being achieved on the irradiated surface. The expression for the normal displacement of the surface, corresponding to a given temperature distribution, has the form:

$$W(r, z, t) = W^* \frac{(1 + \nu) \alpha_T I_0 A}{\lambda K_0}, \quad (9)$$

$$W^* = \frac{F_0}{2\pi i_0} \int_0^{\infty} dv \int_{\sigma-i\infty}^{\sigma+i\infty} dp \frac{\psi(p/t)}{p} \exp(p - \nu) \times$$

$$\times J_0 \left(\sqrt{\nu} \delta r \right) \frac{\sqrt{\nu} - \sqrt{\nu + p/F_0}}{\sqrt{\nu + p/F_0}}, \quad (10)$$

where $F_0 = 4K_0 a^2 \tau$. The resulting expression allows us to trace the changes in the surface shape during irradiation.

Thus, this consideration has made it possible to describe fully the characteristics of temperature fields, thermoelastic stresses and thermal deformations occurring in solids whose surface is exposed to high-power laser radiation varying with time in an arbitrary manner. In addition, the following relations are fulfilled between the quantities characterising the thermal stress state in the continuous-wave and any other nonstationary regime of energy input into the solid:^{22,24}

$$T^{\text{tr}} = \int_0^t f(t - \tau) \frac{\partial T^{\text{st}}}{\partial \tau} d\tau,$$

$$\sigma_{ik}^{\text{tr}} = \int_0^t f(t - \tau) \frac{\partial \sigma_{ik}^{\text{st}}}{\partial \tau} d\tau, \quad (11)$$

$$W^{\text{tr}} = \int_0^t f(t - \tau) \frac{\partial W^{\text{st}}}{\partial \tau} d\tau.$$

These relations are similar to Duhamel's integral formula from the theory of heat conduction. It should be noted that the local deformation of the POE surface is the determining factor of the laser impact and the bending deformation component of the POE as a whole can be reduced to zero due to the large thickness of its effectively cooled base. Later, both components of the POE deformation were examined in the book of L.S. Tsесnek et al.²⁵

Continuous-wave irradiation

Temperature field

If the time of laser irradiation satisfies the inequality $r_0^2/a^2 \leq t \leq L^2/a^2$, a steady-state temperature field can be established in the sample material. The main property of the process of its establishment is described by the expression²¹

$$T^* = \frac{2}{\sqrt{\pi}} \arctg(\sqrt{F_0}). \quad (12)$$

It follows from (12) that for instants of times t , at which $F_0 \geq 4$, the current temperature is 10% less than the steady-state value. We therefore assume that, starting at time t , at which $F_0 > 4$, a stationary thermal state is established in the sample material (Figure 1).

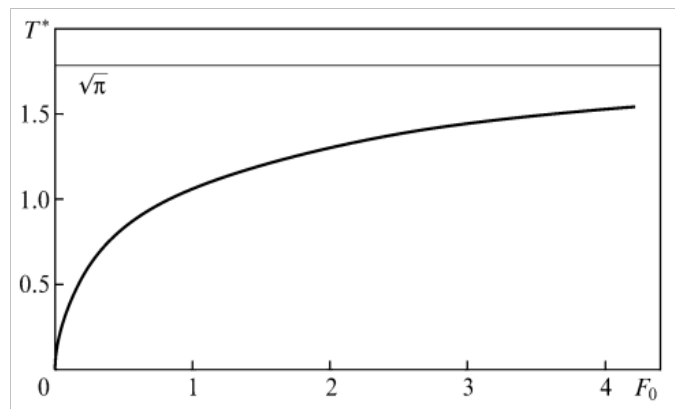


Figure 1 Time dependence of the sample surface temperature at the centre of the region (number F_0) exposed to cw radiation.

The expression for the temperature field in the half-space has the form²¹

$$T^* = \int_0^\infty J_0(\sqrt{v}\delta_r) \exp[-\sqrt{v}(\delta_z + \sqrt{v})] \frac{dv}{\sqrt{v}}, \quad (13)$$

where $\delta_z = 2\sqrt{K_0}z$ and $\delta_r = 2\sqrt{K_0}r$. From this expression we obtain the locality of the temperature field, the characteristic values of which decrease with increasing distance from the centre of the surface irradiation region and inside the material (Figures 2–4).

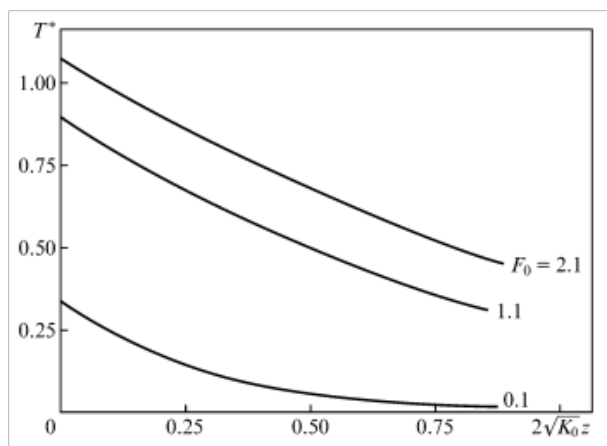


Figure 2 Temperature field distributions on the z axis.

Thermoelastic stresses

In the steady-state regime ($p \rightarrow 0$), nonzero are only the components of the tensor of thermal stresses $\sigma_{\phi\phi}^*$ and σ_{rr}^* .²¹

$$\sigma_{rr}^* = 2(1-\nu) \int_0^\infty \exp[-\sqrt{v}(\sqrt{v} + \delta_z)] \left[J_1(\sqrt{v}\delta_r) / \sqrt{v}\delta_r - J_0(\sqrt{v}\delta_r) \right] \frac{dv}{\sqrt{v}}, \quad (14)$$

$$\sigma_{\phi\phi}^* = 2(1-\nu) \int_0^\infty \exp[-\sqrt{v}(\sqrt{v} + \delta_z)] \left[-J_1(\sqrt{v}\delta_r) / (v\delta_r) \right] dv,$$

where

$$\sigma_{ik}^* = \frac{\lambda\sqrt{K_0}(1-\nu)}{I_0AG\alpha_T(1+\nu)} \sigma_{ik}(\vec{r}).$$

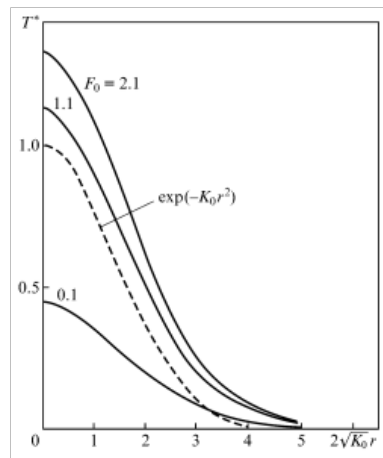


Figure 3 Temperature field distributions on the sample surface.

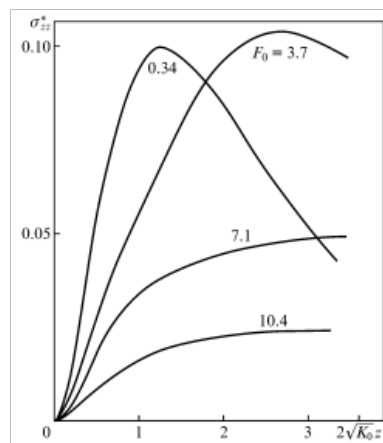


Figure 4 Dependence of the axial stress σ_{zz} on the exposure time of laser irradiation.

The maximum values of these components are achieved in the centre of the irradiated region (Figure 5) on the surface of the half-space, where the stationary field of thermoelastic stresses have the form (Figure 6) (Figure 7)

$$\sigma_{rr}^* = \frac{\sqrt{\pi}(1-\nu)}{2} {}_1F_1\left(\frac{1}{2}; 2; -\delta_r^2/4\right),$$

$$\sigma_{\phi\phi}^* = \frac{\sqrt{\pi}(1-\nu)}{2} \left[{}_1F_1\left(\frac{1}{2}; 2; -\delta_r^2/4\right) - {}_1F_1\left(\frac{1}{2}; 1; -\delta_r^2/4\right) \right]. \quad (15)$$

The main property in establishing a steady state for σ_{rr} and $\sigma_{\phi\phi}$ are characterised by the dependence shown in Figure 8:

$$\sigma_{ii}^*(\delta_r = \delta_z = 0) = \frac{1+\nu}{\sqrt{\pi}} \left[F_0 \left(\arctan \frac{1}{\sqrt{F_0}} - \frac{1}{\sqrt{F_0}} \right) - \frac{1-\nu}{1+\nu} \arctan \sqrt{F_0} \right]. \quad (16)$$

This expression completely describes the characteristics of the stressed state arising in a solid when its surface is irradiated by cw laser radiation.

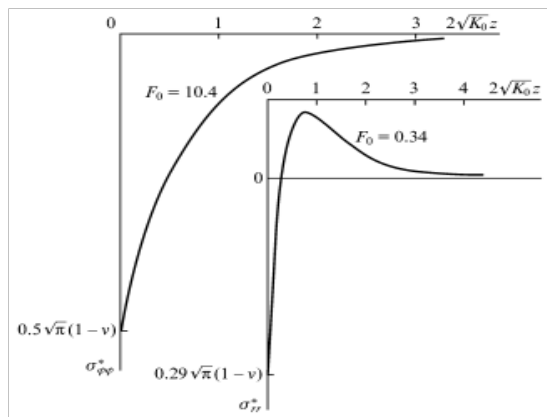


Figure 5 Distribution of the peripheral ($\sigma_{\phi\phi}$) and radial (σ_{rr}) tensor components on the z axis for different exposure times of laser irradiation.

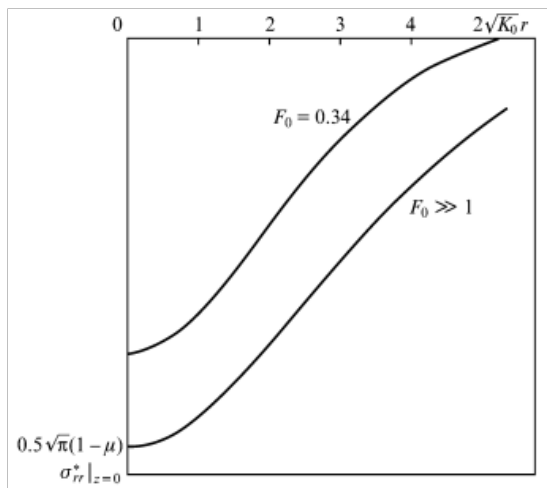


Figure 6 Stress field σ_{rr} on the surface of the half-space.

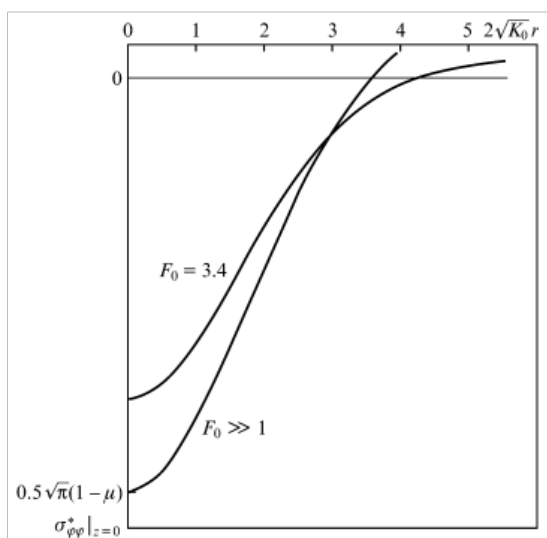


Figure 7 Stress field $\sigma_{\phi\phi}$ on the surface of the half-space.

Thermal deformation of the surface

The expression for the displacement W^* of the reflective surface in the half-space model has the form:²¹

$$W^* = -\frac{1}{2} \left\{ F_0 \exp\left(-\delta_r^2/4\right) - \left[\frac{4\sqrt{F_0}}{1+F_0} - 2 \ln(\sqrt{F_0} + \sqrt{F_0+1}) \right] {}_1F_1\left(\frac{3}{2}; 1; -\frac{\delta_r^2}{4}\right) \right\}. \quad (17)$$

Deformation surface profiles for different exposure times are shown in Figure 9.

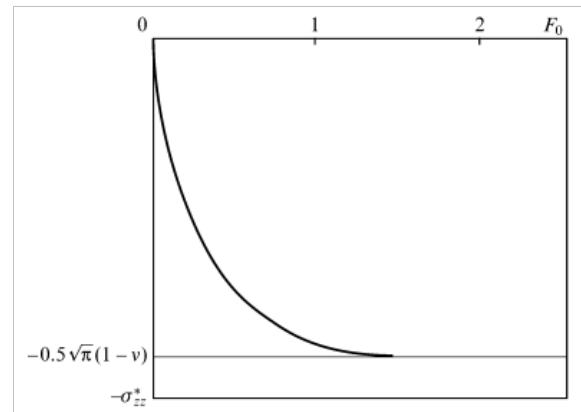


Figure 8 Establishment of a stationary strain state on the surface, in the centre of the irradiated region.

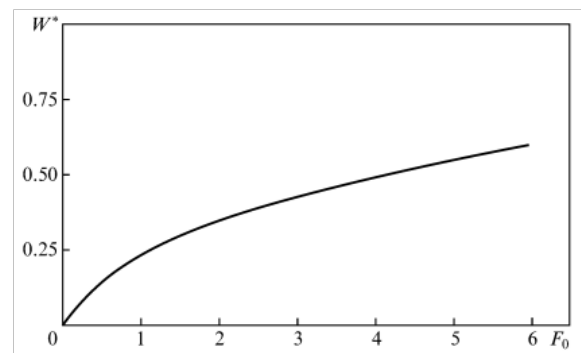


Figure 9 Establishment of a quasi-stationary deformation state on the surface, in the centre of the irradiated region.

Pulsed irradiation

Temperature field

In the case of short irradiation times, the depth of the temperature field penetration into the material is proportional to $\sqrt{a^2 t} \ll r_0$; therefore, the radial heat spreading can be ignored, and the temperature distribution over the surface repeats the laser beam intensity distribution profile:²⁶

$$T^* = \frac{2}{\sqrt{\pi}} \left[\Theta(t^*) \operatorname{arctg}\left(\sqrt{F_0 t^*}\right) - \Theta(t^*-1) \operatorname{arctg}\left(\sqrt{F_0(t^*-1)}\right) \right] \exp(-K_0 r^2), \quad (18)$$

where $\Theta(t^*)$ is the Heaviside function; $t^* = t/\tau$; and τ is the pulse duration.

Thermoelastic stresses

Thermoelastic stresses arising in a solid irradiated by laser light play an important role in the destruction of the optical surface of the POE. Under pulsed irradiation ($F_0 \ll 1$) the expressions for the stress tensor components are given by (15), because in this case the propagation of heat in a solid is of quasi-one-dimensional character and the radial heat spreading can be neglected. The depth of penetration of thermal stresses in the material is $\sqrt{a^2 \tau} \ll r_0$, which follows from the form of σ_{ik} on the z axis:

$$\sigma_{rr}^*(\delta_r = 0) = -\frac{2}{\sqrt{\pi}} \sqrt{F_0} \left[\exp(-\delta_z^2/4F_0) - \frac{\sqrt{\pi} \delta_z}{2F_0} \operatorname{erfc}\left(\frac{\delta_z}{2\sqrt{F_0}}\right) \right] \approx -\frac{8F_0^{3/2}}{\sqrt{\pi} \delta_z^2} \exp\left(-\frac{\delta_z^2}{4F_0}\right), \quad (19)$$

where $\frac{\delta_z}{2\sqrt{F_0}} \gg 1$.

The maximum values of the components σ_{rr}^* and $\sigma_{\phi\phi}^*$ are achieved on the surface,

$$\sigma_{rr}^* = \sigma_{\phi\phi}^* = -2\sqrt{\frac{F_0}{\pi}} \exp\left(-\frac{\delta_r^2}{4}\right), \quad (20)$$

i.e., the distribution of the components σ_{rr}^* and $\sigma_{\phi\phi}^*$ on the surface repeat the laser beam intensity distribution. The components σ_{rr}^* and $\sigma_{\phi\phi}^*$ on the surface $z=0$ are equal, and the expression for σ_{ii}^* ($\delta_r, \delta_z=0$) has the form:

$$\sigma_{ii}^* = -\frac{2}{\sqrt{\pi}} \left[\Theta(t^*) \sqrt{F_0 t^*} - \Theta(t^*-1) \sqrt{F_0(t^*-1)} \right]. \quad (21)$$

In the case of small irradiation times

$$\sigma_{zz}^* = 2\delta_z F_0 t^* \int_0^\infty V^3 \exp(-V^2 - V\delta_z) dV, \\ \sigma_{rz}^* = -\frac{\delta_r}{2} \exp(-\delta_r^2/4) \left[F_0 t^* \operatorname{erf}\left(\frac{\delta_z}{2\sqrt{F_0 t^*}}\right) + \frac{\sqrt{F_0 t^*}}{\pi} \delta_z \exp\left(-\frac{\delta_z^2}{4F_0 t^*}\right) \right], \quad (22)$$

where V is a transform variable. The difference in signs of the components means that in the case of thermal deformation of the sample by laser radiation, for σ_{zz} tension of a material is realised, whereas for σ_{rz} – compression. The maximum value of σ_{zz} is achieved on the z axis; in this case, $\delta_z^{\max} \approx \sqrt{12}$, i.e., $z_0^{\max} \approx 0.66r_0$, and $\sigma_{zz}^{\max} \approx 1.9F_0$. The component σ_{rz}^* reaches its maximum value at point $r_0^{\max} = \frac{r_0}{2}$ and $z_0^{\max} \approx 2\sqrt{a^2 \tau}$:

$$\sigma_{rz}^{\max} \approx -0.5F_0. \quad (23)$$

A distinctive feature of the behaviour of the σ_{zz}^* component is that if the inequality $F_0 \ll 1$ is fulfilled, the position of its maximum on the z axis is determined by the spatial characteristics of the laser beam rather than the irradiation time. The maximum of this component is achieved by the end of the laser pulse. This feature is explained by the fact that at $F_0 t^* \ll 1$ the region of thermoelastic perturbations lies on the sample surface and localizes in the irradiation region, because heat due to heat conduction has no time to spread over the sample material. In the opposite case, i.e., at $F_0 t^* > 1$, the point of this component maximum is determined from the condition $(\delta_z^2/4F_0 t^*)=1$.

Thermal deformations

The expression for the thermal deformation of the reflecting surface irradiated by a rectangular laser pulse, whose duration satisfies the condition $F_0 \ll 1$, has the form:²¹

$$W^* = \frac{F_0}{2} \exp(-K_0 r^2) \left[\Theta(t^*) t^* - \Theta(t^*-1)(t^*-1) \right]. \quad (24)$$

The distribution of thermal deformations of the reflecting surface repeats the laser beam intensity distribution (Figure 10), which we used in our method of the dynamic control of the intensity distribution of laser radiation.²⁷

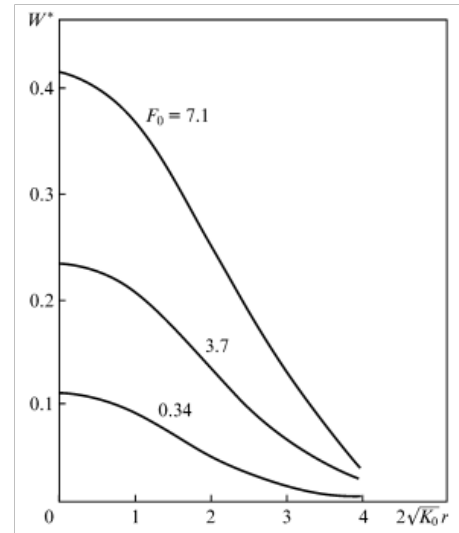


Figure 10 Deformation surface profiles for different exposure times.

Repetitively pulsed irradiation

Thermal deformations of a solid body exposed to repetitively pulsed laser radiation were analysed by using the previously derived relations that are similar to Duhamel's integral formulas. The energy flow was treated as a train of rectangular pulses having a duration τ , period T_0 (repetition rate $\nu_0 = 1/T_0$) and off-duty ratio SQ $V = \tau/T_0$.

It was assumed that $F_0 = 4K_0 a^2 T_0 < 1$. The thermal stresses and deformations of the temperature field are expressed in terms of the integrals (typical of the cw regime) that are similar to Duhamel's integrals:²⁸

$$F^{PP} = \int_0^t f(t-\tau) \frac{\partial F^{cw}}{\partial \tau} d\tau. \quad (25)$$

At the initial instants of time, i.e., when $F_0 t^* < 1$, repetitively pulsed irradiation is similar to pulsed irradiation. The geometric meaning of (25) is characterised by the area of the integrals in Figure 11. (For the temperature and the components $\sigma_{\phi\phi}$ and σ_{rr} , the value of $\frac{\partial F^{cw}}{\partial \tau}$ tend to infinity as $1/\sqrt{t}$ at $t \rightarrow 0$ and to zero at $t \rightarrow \infty$, for deformation $\frac{\partial F^{cw}}{\partial \tau}$ tends to const at $t \rightarrow 0$ and to zero at $t \rightarrow \infty$.) In the case of long irradiation times, i.e., when $F_0 t^* > 1$, the temperature and thermal stresses reach their quasi-steady states, i.e., a constant component of these values becomes similar to that in the cw regime of energy input with a reduced intensity I_0 SQV. In this case, against the background of this component, along with changes in the laser beam intensity, there will be the characteristic peaks of temperature and stress, which are similar to peaks during pulsed irradiation. A separate 'pulse' of thermal deformations of the reflecting surface exists against the background of a 'stationary component' tending to infinity.

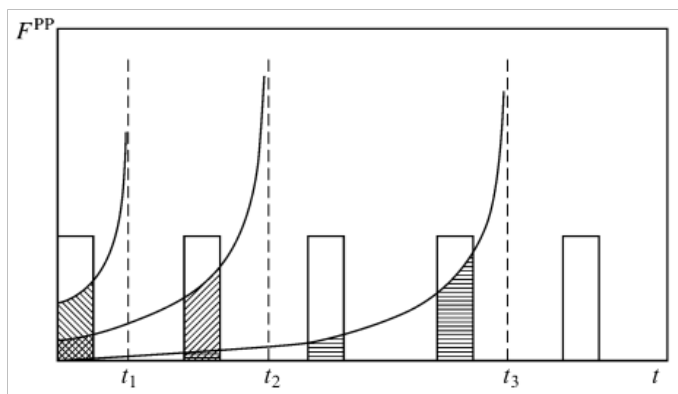


Figure 11 Geometrical interpretations of Duhamel's integrals.

Temperature field

The expression for the temperature has the form²¹

$$T^* = \frac{1}{2\pi i} \int_{\sigma_i - i\infty}^{\sigma_i + i\infty} dp \psi(p) e^p \int_0^\infty \frac{e^{-V} J_0(\sqrt{V} \delta_r) \exp[-\sqrt{V}(\sqrt{V} + \delta_z)]}{\sqrt{8/F_0 + V}} dV, \quad (26)$$

since for a train of pulses

$$\psi(p) = \frac{[1 - \exp(-p\tau)] \{1 - \exp[-p(N+1)T]\}}{p[1 - \exp(-pT)]} \quad (27)$$

is the image of the Laplace transform of $f(t)$; and N is the number of propagated laser pulses.

In the centre of the irradiation region the temperature reaches a maximum value by the time the next pulse terminates ($F_0 > 1$):

$$T_{\max}^* = \sqrt{\pi} SQV + \frac{2}{\sqrt{\pi}} \arctg \sqrt{F_0 SQV}, \quad (28)$$

where SQV is the off-duty ration of the temporal structure of radiation.

Thermoelastic stresses

Maximum values of the radial and circumferential tangential stress are achieved in the centre of the irradiation region, where they are equal to each other:

$$\sigma_{ii}^{PP} = \int_0^t f(t-\tau) \frac{\partial \sigma_{ii}^{cw}}{\partial \tau} d\tau \quad (29)$$

[σ_{ii}^{cw} is determined from (16)]. The field distribution of stresses σ_{ii}^* on the surface by the time when the next laser pulse terminates has the form:

$$\sigma_{ii}^* = SQV \sigma_{ii}^{*(1)} + \sum_{n=0}^N \Theta(n+1-t^*) \left[\Theta(t^*-n) \sigma_{ii}^{*(2)}(t^*-n) - \Theta(t^*-n-SQV) \sigma_{ii}^{*(2)}(t^*-n-SQV) \right], \quad (30)$$

where $\sigma_{\phi\phi}^{*(1)}$ and $\sigma_{rr}^{*(1)}$ are determined from (16), and $\sigma_{rr}^{*(2)} = \sigma_{\phi\phi}^{*(2)}$ – from (21). Because in the steady stress state σ_{zz} and σ_{rz} are identically zero, their values in the case of repetitively pulsed irradiation are the same as in the case of pulsed irradiation (accuracy $\sim SQV$).

Deformation of the surface

The displacement of a solid-body surface exposed to repetitively pulsed radiation also has stationary and pulse components:²¹

$$W^* = SQV W^{(1)*} + W^{(2)*}.$$

When the quasi-stationary state is reached

$$W^* = -SQV \ln 2 \sqrt{F_0} F_1 \left(\frac{3}{2}; 1; -\frac{\delta_r^2}{\pi} \right) - \frac{F_0}{2} \sum_{n=0}^N \Theta(n+1-t^*) \left[\Theta(t^*-n) (t^*-n) - \Theta(t^*-n-SQV) (t^*-n-SQV) \right] \exp(-K_0 r^2). \quad (31)$$

Criteria for the optical surface stability

Expressions given for the characteristics of the thermal stress state of a solid whose surface is irradiated by high-power cw, pulsed and repetitively pulsed laser radiation allowed us to determine the limiting intensities corresponding to different stages of the optical damage of mirror surfaces.^{21,29} To this end, the parameters of the optical surface stability include not only the thermo physical and mechanical properties of the material but also the parameters of a Gaussian-like beam, namely the intensity in the centre of the irradiation region, the size of the irradiation region and the duration of a single pulse and, in the case of repetitively pulsed irradiation, – the pulse train off-duty ratio. The stability parameters of the reflector contain the ratio of a maximum value of the thermal stress state characteristic to its value at which the solid material experiences irreversible macroscopic changes – melting, plastic (brittle) or fatigue deformation or achievement of a critical value $\lambda_0/20$ by the amplitude of thermal deformation of the optical surface, where λ_0 is the wavelength of the laser used. The thus introduced stability parameters of mirrored POE surfaces made it possible not only to compare different pure metals and their alloys in terms of applicability in power optics but also to create specific types

of combined POEs capable of withstanding high-power fluxes of cw, pulsed and repetitively pulsed laser radiation.

Continuous-wave regime

A solid body whose surface is exposed to cw laser radiation is destroyed when the temperature field in the centre of the irradiation region reaches the melting point of the material and the components of the stress field reach the yield point. The stability of the optical surface under cw irradiation is characterised by the parameters

$$\gamma_{T_{\text{melt}}}^{\text{cw}} = \frac{\sqrt{\pi} I_0 A}{2\lambda \sqrt{K_0 T_{\text{melt}}}}; \quad \gamma_{\sigma_T}^{\text{cw}} = \frac{\sqrt{3\pi}(1+\nu) I_0 A G \alpha_T}{2\lambda \sqrt{K_0 \sigma_T}}. \quad (32)$$

If $\gamma_{T_{\text{melt}}}^{\text{cw}}$ and $\gamma_{\sigma_T}^{\text{cw}} < 1$, the material will undergo no irreversible changes. The values of these parameters in the case of cw laser radiation at a power density $I_0 A = 1 \text{ kW cm}^{-2}$ and $K_0 = 8 \cdot 10^2 \text{ m}^{-2}$ are shown in Table 1 for Cu, Al and Mo. The main reason for the damage of the optical surface can be determined from the relation

$$\gamma_{\text{rel}}^{\text{cw}} = \frac{\gamma_{\sigma_T}^{\text{cw}}}{\gamma_{T_{\text{melt}}}^{\text{cw}}} = \frac{\sqrt{3}(1+\nu) G \alpha_T T_{\text{melt}}}{\sigma_T}. \quad (33)$$

If $\sigma_{\text{rel}}^{\text{cw}} > 1$, the material will be destroyed when the component σ_{ii} reaches the yield point, or when the melting point of the material, $T(0,0,\infty)$ is reached.

For the materials in question (Table 1), the main reason for the deterioration of the optical surface at lower laser intensities is irreversible plastic deformations of the POE in the centre of the irradiation region. There is another important reason for the deterioration of the optical surface – excess of the critical value $\lambda_0/20$ by the value of thermal deformation of the optical surface – which is implemented at long exposure times of high power laser radiation and in the range of the parameters corresponding to the elastic deformation of the material. In this case, phase and energy characteristics of the reflected laser beam are markedly impaired. The criterion for the optical surface stability to such changes in the optical characteristics of the reflector is given by parameter

$$\gamma_{\lambda_0/20}^{\text{cw}} = \frac{20(1+\nu) \alpha_T I_0 A}{\lambda K_0 \lambda_0} \ln 2 \sqrt{F_0}. \quad (34)$$

The value $\gamma_{\lambda_0/20}^{\text{cw}} < 1$ can be reached if use is made of some types of reflector designs with efficient cooling.³⁰

Pulsed regime

The parameters of the optical surface stability under pulsed irradiation by a Gaussian-like laser beam having a duration t_0 and intensity I_0 in the centre of the irradiation region, determined by the ability to reach critical values T_{melt} , σ_T and $\lambda_0/20$ by temperature $T(0,0,\tau)$, thermoelastic stresses $\sigma_{ii}(0,0,\tau)$ and thermal deformations $W(0,0,\tau)$, have the form:^{27–29}

$$\begin{aligned} \gamma_{T_{\text{melt}}}^P &= \frac{2 I_0 A}{\sqrt{\pi} \lambda T_{\text{melt}}} \sqrt{a^2 \tau}, \\ \gamma_{\sigma_T}^P &= 4 \sqrt{\frac{3}{\pi}} \frac{I_0 A G \alpha_T (1+\nu)}{\lambda G_T (1-\nu)} \sqrt{a^2 \tau}, \\ \gamma_{\lambda_0/20}^P &= \frac{40(1+\nu) I_0 A \alpha_T a^2 \tau}{\lambda \lambda_0}. \end{aligned} \quad (35)$$

Table 1 Parameters of stability and threshold intensities for Al, Mo and Cu at $I_0 A = 1 \text{ kW cm}^{-2}$, $r_0 = 5 \text{ cm}$ and $t = 5 \times 10^{-5} \text{ s}$

Parameter	Material		
	Cu	Mo	Al
CW regime			
$\gamma_{T_{\text{melt}}}^{\text{cw}} = \frac{\sqrt{\pi} I_0 A}{2\lambda \sqrt{K_0 T_{\text{melt}}}}$	0.74	0.8	2.3
$I_{th} = \frac{1}{\gamma_{T_{\text{melt}}}^{\text{cw}}} / \text{kW cm}^{-2}$	1.4	1.3	0.44
$\gamma_{\sigma_T}^{\text{cw}} = \frac{\sqrt{3\pi} I_0 A G \alpha_T (1+\nu)}{2\lambda \sqrt{K_0 \sigma_T}}$	19.3	10^4	38.3
$I_{th} = \frac{1}{\gamma_{\sigma_T}^{\text{cw}}} / \text{kW cm}^{-2}$	0.05	10^{-4}	2.6×10^{-2}
Pulsed regime			
$\gamma_{T_{\text{melt}}}^P = \frac{2 I_0 A \sqrt{a^2 \tau}}{\sqrt{\pi} \lambda T_{\text{melt}}}$	2.0×10^{-3}	1.45×10^{-3}	5.4×10^{-3}
$I_{th} = \frac{1}{\gamma_{T_{\text{melt}}}^P} / \text{kW cm}^{-2}$	500	700	190
$\gamma_{\sigma_T}^P = \left(\frac{3a^2 \tau}{\pi} \right)^{1/2} \frac{2 I_0 A E \alpha_T}{\lambda (1-\nu) \sigma_T}$	0.16	55	0.28
$I_{th} = \frac{1}{\gamma_{\sigma_T}^P} / \text{kW cm}^{-2}$	6.3	1.8×10^{-2}	3.6
$\gamma_{\lambda_0/20}^P = \frac{40(1+\nu) I_0 A \alpha_T a^2 \tau}{\lambda \lambda_{c02}}$	0.013	4.6×10^{-3}	2.6×10^{-2}
$I_{th} = \frac{1}{\gamma_{\lambda_0/20}^P} / \text{kW cm}^{-2}$	80	230	39
$\gamma_{\sigma_b}^P = \frac{40 I_0 A E \alpha_T a^2 \tau \sqrt{K_0}}{(1-\nu) \lambda \sigma_b}$	2	1.6×10^{-2}	7.4
$I_{th} = \frac{1}{\gamma_{\sigma_b}^P} / \text{kW cm}^{-2}$	0.5	6.3×10^{-4}	0.14
$\gamma_{\sigma_f}^P (\sigma_{rz}) = \frac{I_0 A G \alpha_T (1+\nu) F_0}{2\lambda \sqrt{K_0 \sigma_f}}$	1.8×10^{-4}	0.04	2.7×10^{-4}
$I_{th} = \frac{1}{\gamma_{\sigma_f}^P} / \text{kW cm}^{-2}$	5.5×10^3	25	3.7×10^3

Table Continued

Parameter	Material		
	Cu	Mo	Al
CW regime			
$\gamma_{\sigma_f}(\sigma_{zz}) = \frac{2I_0 A G \alpha_T (1+\nu) F_0}{\lambda \sqrt{K_0} (1-\nu) \sigma_f}$	1.2×10^{-3}	0.26	1.8×10^{-3}
$I_{th} = \frac{1}{\gamma_{\lambda_0/20}} / kW cm^{-2}$	830	3.8	560

The values of these parameters, found for copper, aluminium and molybdenum at $I_0 A = 1 \text{ kW cm}^{-2}$, $K_0 = 2.82 \times 10^2 \text{ m}^{-2}$ and $\tau = 50 \mu\text{s}$, and the heat flow values $I_0 A$, at which $\gamma_i^P = 1$, are presented in Table 1. In the cw regime, the optical surface properties are mainly degraded due to irreversible plastic deformations in the centre of the irradiation region. Under pulsed irradiation the behaviour of the thermal stress state is more complicated than under cw irradiation. Thus, in contrast to the stationary thermal stress state, the nonstationary state in the material of a solid is characterised by the presence of the nonzero components σ_{zz} and σ_{rz} . In this case, the highest value is reached by the component σ_{zz} on the z axis at a distance of $\sim 0.66 r_0$ from the optical surface. If at some level of these $I_0 A$ values the component σ_{zz} is greater than the strength σ_b , it is possible to implement the conditions of brittle fracture, at which the surface layer of the POE material will be detached. For this type of destruction the parameter of the optical surface stability has the form:

$$\gamma_{\sigma_b}^u = \frac{4I_0 A E \alpha_T a^2 \tau \sqrt{K_0}}{(1-\nu) \lambda \sigma_b},$$

and the stability parameter defined with respect to plastic deformation, has the form:

$$\gamma_{\sigma_T}^P = \frac{\sqrt{3} I_0 A E \alpha_T F_0}{\lambda \sqrt{K_0} (1-\nu) \sigma_T} \left(1 + 2 \sqrt{\frac{F_0}{3\pi}} \exp\left(-\frac{\sqrt{3}}{2 F_0}\right) \right). \quad (36)$$

The values of the parameters and their corresponding intensities for Al, Mo and Cu are listed in Table 1.

Repetitively pulsed regime

The state of a solid body, whose surface is irradiated by repetitively pulsed laser pulses, combines the characteristic features of thermal stress states implemented under pulsed and cw irradiation. In this case, for the temperature fields, the fields of the components σ_{rr} and $\sigma_{\phi\phi}$, the stress tensor and the thermal deformation fields the realisable temperature and thermal stress states are a combination of stationary and nonstationary states. In this regard, the stability parameters of the reflecting surfaces, defined by the ability of the temperature to reach the melting point of the material, of the components σ_{rr} and $\sigma_{\phi\phi}$ to reach the yield point and of thermal deformation to reach the threshold $\lambda_0/20$, are as follows:²¹

$$\gamma_i^{PP} = SQV \gamma_i^{cw} + \gamma_i^P. \quad (37)$$

Under repetitively pulsed irradiation, a nonstationary, cyclically repeated stress state arises on a solid surface in the material. As a result, the material of the solid body may experience irreversible fatigue damage. The conditions under which the POE surface undergoes macroscopic fatigue fracture can be assessed by Wöhler curves, determining the dependence of modulus of the amplitude of

fatigue stresses on the number of cycles of the loading pulses N_p .²¹⁻³¹

Irreversible changes of the optical surface

Dynamics of the fatigue and brittle fracture is characterised by the emergence and extension of microcracks. Therefore, inadmissibility of destruction of the optical POE surface is dictated by the need to preserve the diffusely scattered component of laser radiation at negligible levels. Moreover, the origin and development of microcracks is accompanied by microstructural and phase transformations of the material, leading to a change in the structural and phase composition of the reflecting surface and, as a consequence to an increase in its absorption coefficient A , whereas the adsorption of various substances on the resulting system of microcracks initiating an optical breakdown leads to a decrease in radiation resistance of the reflecting surface. Furthermore, the optical breakdown of air near the target can occur without the segregation of impurities directly in the vicinity of emergence of microcracks, because they become the nucleus of the electric fields, etc. We considered sequentially the basic mechanisms of microstructural and phase transformations preceding the stage of plastic, fatigue and brittle fracture or accompanying these stages, as well as analysed the possible reasons for the change in the optical surface quality. The expressions obtained are important not only for the problems of power optics. They are effectively used today for the analysis of the conditions of fracture of solids of different nature due to excess of limiting stresses for the various components of the stress tensor.

Conclusion

In conclusion, one very important and true to our life relationship should be mentioned in this rather difficult time for science. The resources invested effectively in the development of any field of advanced technology will as a rule afford a feedback in a number of ancillary applications in other ancillary and sometimes rather remote fields of science and technology. Thus, phase-locked 1-d and 2-dLD arrays with high level of radiation fluxes and new configuration of solid - state laser—single module scalable disk laser— appears to be due in part to achievements in the field of HPO. HPO is a universally recognized contributor to other advanced laser systems and applications for the 21st century.

Acknowledgements

None.

Conflict of interest

Author declares that there is no conflict of interest.

References

1. Apollonov VV. High-power optics and its new manifestations. *Laser Phys.* 2013;23(6).
2. Barchukov AI, Karlov NV, Konyukhov VK, et al. Moscow: FIAN Report; 1968–1970.
3. Barchukov AI, Konev YuB, Prokhorov AM. *Radiotekh Electron.* 1970;15:2193.
4. Apollonov VV, Barchukov AI, Konyukhov VK, et al. Moscow: FIAN Report; 1971.

5. Apollonov VV, Barchukov AI, Konyukhov VK, et al. Moscow: FIAN Report; 1972.
6. Apollonov VV, Barchukov AI, Konyukhov VK, et al. *Pis'ma Zh Eksp Teor Fiz.* 1972;15:248.
7. Apollonov VV, Barchukov AI, Prokhorov AM. Proceedings on First European Conference on Lasers and Applications, Drezden: GDR; 1972.
8. Apollonov VV, Barchukov AI, Konyukhov VK, et al. *Sov J Quantum Electron.* 1973;3(3):244.
9. Apollonov VV, Barchukov AI, Prokhorov AM. Proceedings on Second European Conference in Lasers and Applications. Drezden: GDR; 1973: Moscow: Preprint FIAN No 157; 1973.
10. Apollonov VV, Barchukov AI, Lubin AA, et al. Moscow: FIAN Report; 1973.
11. Glass AJ, Guenther AH. *Appl Opt.* 1973;12:34.
12. Cytron SJ. Memorandum Report M73-17-1, Philadelphia, PA; 1973.
13. Jacobson DH, Bickford W, Kidd J, et al. AIAA paper No. 75-719;1975.
14. Apollonov VV. High power optics. *Springer.* 2014.
15. Apollonov VV, Barchukov AI, Prokhorov AM. *Radiotekh Electron.* 1974;19:204.
16. Apollonov VV, Barchukov AI, Prokhorov AM. Characteristics of a high-power nitrogen laser. *J Quantum Electron.* 1974;10: 505.
17. Apollonov VV, Shefter EM. Proceedings on Second European Conference in Lasers and Applications. Moscow: Preprint FIAN No. 105; 1974.
18. Barchukov AI. Doctoral Dissertation. Moscow: FIAN; 1974.
19. Apollonov VV, Barchukov AI, Karlov NV, et al. *Sov J Quantum Electron.* 1975;5:216.
20. Apollonov VV. Candian Dissertation. Moscow: FIAN; 1975.
21. Apollonov VV. Doctoral Dissertation. Moscow: FIAN; 1982.
22. Parkus H. Thermoelasticity. Moscow: Fizmatgiz; 1963.
23. Nowacki W. Problems of Thermoelasticity. Moscow: Izd. AN SSSR; 1962.
24. Jahnke E, Emde F, Lusch F. Special functions. Moscow: Nauka; 1964.
25. Tsesnek LS, Sorokin OV, Zolotukhin AA. Metal mirrors. Moscow: Mashinostroenie; 1983.
26. Apollonov VV, Barchukov AI, Prokhorov AM. Proc. V All-Union Meeting on Nonresonant Interaction of Optical Radiation with Matter. Leningrad: 1977.
27. Apollonov VV, Barchukov AI, Kir'yanova LT, et al. Moscow: FIAN Report; 1977.
28. Apollonov VV, Barchukov AI, Ostrovskaya LM, et al. Patent No. 103162.
29. Apollonov VV, Barchukov AI, Prokhorov AM, et al. *Letters to JTP.* 1978;4:433.
30. Apollonov VV, Barchukov AI, Borodin VI, et al. *Letters to JTP.* 1978;4:1193.
31. Apollonov VV, Barchukov AI, Ostrovskaya LM, et al. *Sov J Quantum Electron.* 1978;5:446.