Journal of Engineering Physics and Thermophysics, Vol. 74, No. 3, 2001

WIDENING THE SCOPE OF WORKING OF SOLID-STATE Nd-GLASS LASERS

S. V. Kayukov, S. I. Yares'ko, and P. A. Mikheev

UDC 621.373.826.038.025:621.791.725:621.78

With the example of the serial model of a pulsed Nd-glass laser, it is shown that the use of an unstable resonator with a semireflecting homogeneous exit mirror makes it possible to significantly decrease the laser-beam divergence and increase the uniformity of the radiation-intensity distribution in the near zone. We were the first to obtain a laser-beam quality of ~(40–50) mm·mrad for technological glass lasers and to attain a depth of fusing of of ~6.3 mm for steel (aspect ratio ~10) for an energy of ≈ 23 J. The obtained uniformity of the radiation-intensity distribution was estimated at the level of ±10%. The beam-quality level attained for the Nd-glass laser beam allows us to recommend it for both realization of deep-fusion regimes and laser hardening without the use of external integrating optical elements.

Introduction. Solid-state pulsed Nd-glass lasers are traditionally used for surface heat treatment of metals and alloys. They have found the widest application in the technology of hardening of cutting edges of metal-cutting tools and press tools and hardening of the surface regions of machine elements, which are subjected to the heaviest wear [1]. The presence of nonuniformities in the radiation-intensity distribution in the near zone of lasers of this type limits their technological capabilities significantly, since the allowable deviation of the hardening temperature from its maximum value is no more than ±10% for heat-resistant tool steels [2]. To solve this problem, additional integrating optical elements [3–6], such as a prism focusing raster [5, 6], are usually used.

The high beam divergence (quality factor 250–300 mm·mrad) characteristic of glass lasers practically rules out the possibility of using them for solution of problems concerned with deep penetration of radiation into a material, in particular, for welding of metals [7].

The use of an unstable resonator with a semireflecting homogeneous exit mirror (URSHEM) and a magnification close to unity makes it possible to improve significantly the laser-beam quality with minimum changes in the resonator design [8]. When the Fresnel numbers of the resonator are large (≥ 10), the radiation intensity distribution in the near zone is uniform and fills the entire cross section of the active element [8, 9], which is an additional advantage of laser heat treatment.

The aim of the present work is to show with the example of the serial model of a Kvant-16 laser facility that the use of an unstable resonator with a semireflecting homogeneous exit mirror makes it possible to improve the uniformity of the radiation-intensity distribution in the cross section of the glass-laser beam and decrease its divergence to such a degree that it turns out to be possible, without additional changes in the optical scheme of the laser, to perform technological processes of welding in a deep-fusion regime and punching of holes and also processes of hardening without the use of additional external optical elements.

Experimental Setup and Technique. The experiments were carried out with the use of a Kvant-16 technological laser facility (TLF) assembled on the basis of a solid-state pulsed laser with an active element

Samara Branch of the P. N. Lebedev Physical Institute, Russian Academy of Sciences, Samara, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 74, No. 3, pp. 207–211, May–June, 2001. Original article submitted February 29, 2000.

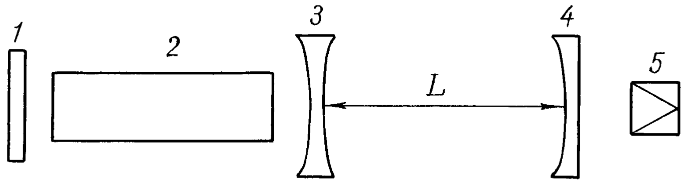

Fig. 1. Optical scheme of a laser with a URSHEM: 1) exit mirror; 2) active medium; 3) lens; 4) back-surface mirror; 5) photodiode.

of GLS-9P soda-lime glass with Nd of size ∅12 × 260 mm. The standard stable resonator of the facility of length 394 mm was formed by totally reflecting and semireflecting (R = 65%) spherical mirrors with a radius of curvature of 1.2 m. The unstable resonator with a semireflecting homogeneous exit mirror used in the experiments was formed by a totally reflecting mirror with a radius of curvature of 1.0 m, a plane semireflecting exit mirror with a reflection factor of 50%, and a lens with $f = -0.4$ m (Fig. 1). The magnification of an unstable resonator with a semireflecting homogeneous exit mirror depends on the power of an equipotential thermal lens characterizing phase distortions arising in the active medium under pumping radiation. For this reason, the magnification M was chosen experimentally by changing the length of the inactive arm L from 56 to 65 cm (Fig. 1) in accordance with the results of measurement of the beam divergence and the pulse energy. Depending on the value of L, the resonator could be stable or unstable. The pulse energy was monitored using a calibrated FD-24K photodiode. The voltage across the storage of the technological laser facility was varied from 1200 to 2050 V in the experiments.

The beam divergence was measured by the method described in [10]. In the case where the unstable resonator with a semireflecting homogeneous exit mirror was used, radiation was focused on a thin metallic foil 0.2 mm in thickness by an objective with a focal distance of 100 mm; in the case of the standard resonator the radiation was focused by an objective with a focal distance of 75 mm and punched a hole in this foil. We measured the diameter of this hole and the portion of the power of the next pulse transmitted through it. In the experiments, 80–90% of the pulse energy was transmitted through the hole.

The uniformity of the hardening-zone depth was estimated by the depth of occurrence of the hardening zone in the microsections of annealed R9M4K8-steel samples using a Neophot-30 light microscope and by the microhardness distribution measured at different distances from the sample surface. The microhardness was measured by a PMT-3 hardness gauge with a load of 100 g. The initial microhardness of the steel was $H_\mu = 230 \pm 10$ kg/mm^2.

The uniformity of the energy-density distribution in the cross section of the laser beam was estimated for the Kvant-16 technical laser facility with a stable resonator incorporated in the design of the serial model of the facility and an objective with f = 70 mm. We also investigated the radiation-intensity distribution in the near zone for the laser with an unstable resonator with a semireflecting homogeneous exit mirror and a collimator decreasing the size of the spot by a factor of ~3. For the energy-density obtained in this case, the temperature on the surface of the samples corresponded to the hardening temperature of the given steel (1215–1235^{o}C [2]). As an alternative method of equalizing the energy density distribution in the cross section of the laser beam, we considered the use of a focusing prism raster [5] forming a spot of size □4.5 × 4.5 mm in the treated zone.

In the experiments, the size of the hardening zone was chosen from the condition that the temperature on the surface of the sample must be lower than the melting temperature of its material by ~5–6%. This was provided by regulating the pumping energy and the size of the radiation spot.

The geometric parameters of the zone of a solidified melt were investigated by a technique analogous to the technique of [11], in accordance with which the conditions of butt welding were modeled on ground ShKh15-steel tiles. The longitudinal cross sections of the solidified-melt zones on the faces of the tiles were

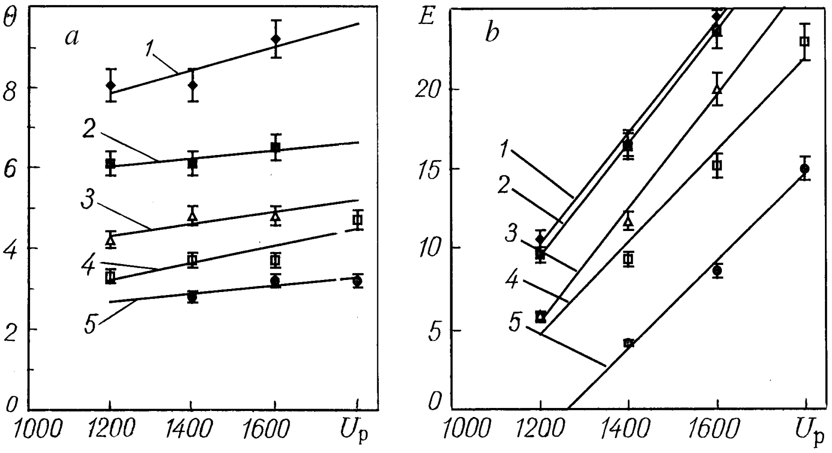

Fig. 2. Dependence of the beam divergence (a) and the output energy of a glass laser with a URSHEM (b) on the pumping voltage for different magnifications of the resonator: 1) $M \sim < 1$; 2) ~1; 3) ~1.68; 4) ~1.87; 5) ~2.04. θ, mrad; U_p, V.

investigated using the Neophot-30 microscope. The microsections were prepared by a customary technique with etching in a 4% alcoholic solution of nitric acid.

Experimental Results and Discussion. For the standard stable resonator of the Kvant-16 technical laser facility, the beam divergence was measured beginning from the pumping level U_p = 1400 V (radiation energy E = 21.5 J). This is a minimum voltage across the storage, at which a hole of diameter ~1.8 mm was formed in the foil. The divergence $\theta \sim 24$ mrad obtained at the pulse-energy level of 86% did not change throughout the range of pumping voltage up to U_p = 2000 V (E = 65 J). The energy density in the treated zone increased by a factor of 3 (from ~8.5 J/mm^2 for U_p = 1400 V to ~25.5 J/mm^2 for U_p = 2000 V).

The dependence of the beam divergence of the laser with an unstable resonator with a semireflecting homogeneous exit mirror on the pumping energy, measured at the energy level of 86%, is presented in Fig. 2. The magnification of the resonator M was calculated without regard for the lens induced in the active element of the laser; it changes from $M \sim < 1$ for L = 65 cm to $M \approx 2.04$ for L = 56 cm. It is seen from Fig. 2a that the use of the unstable resonator with a semireflecting homogeneous exit mirror made it possible to decrease the beam divergence by almost an order of magnitude as compared to the standard stable resonator.

The experiments carried out have shown that as the distance L decreases (this corresponds to passage from the stable to an unstable resonator and an increase in the resonator magnification at the same pumping level) the beam divergence decreases by more than a factor of three: from 9.2 mrad ($M \sim < 1$, U_p = 1600 V) to 3.0 mrad (M = 2.04, U_p = 1600 V). In this case, the radiation energy decreases by a factor of 1.8–4.0 depending on the pumping level. In particular, at U_p = 1600 V, E = 24.5 J for the stable resonator ($M \sim < 1$) and E = 8.6 J for the unstable resonator with M = 2.04, i.e., the energy decreases by a factor of ~2.8. When the pumping level is U_p = 1400 V, the energy decreases by a factor of ~4.0 (Fig. 2b). For a given distance L, a change in the pumping energy throughout the range under study causes an increase of no more than 20% in the beam divergence (except for L = 57 cm). Taking into account that the treatment-energy density is $\varepsilon \sim E/\theta^2$, one would expect that in the case where an unstable resonator with a semireflecting homogeneous exit mirror is used, this parameter can be increased by almost an order of magnitude and the regime of deep welding with an aspect ratio of > 3 can be realized.

(a) Analysis of the depth of holes. Of greatest interest are such regimes of metal melting, in which a large deflection of the melt surface occurs as well as an increase in the vapor-gas channel that acts as a light guide transporting laser radiation. In this case, a large depth of penetration of the melting front is attained. As is shown in [7], such regimes can be realized only with a rather high quality of the initial laser beam. As

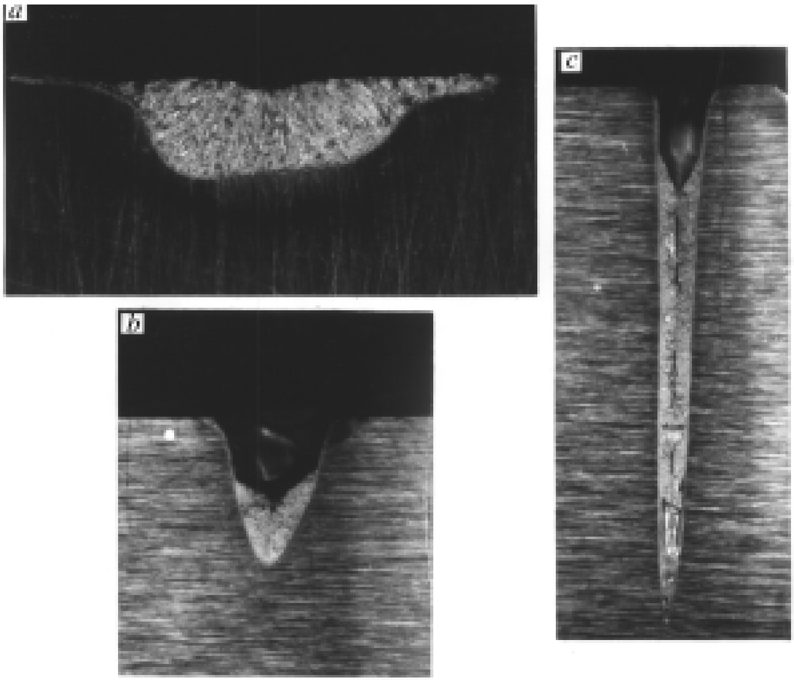

Fig. 3. Characteristic forms of the holes in ShKh15 steel for a pumping voltage of U_p = 1800 V: [(a) stable resonator of the Kvant-16 TLF, ×32; b, c) URSHEM, ×16]: a) h = 0.6 mm; $h/d \approx 0.2$; E = 50.0 J; $h/E \approx 0.012$ mm/J; θ = 24 mrad; $\varepsilon \approx 6.5$ J/mm^2; b) L = 65 cm ($M \sim < 1$); $h \cong 1.7$ mm; $h/d \approx 1$; E = 37.9 J; $h/E \approx 0.045$ mm/J; θ = 9.2 mrad; $\varepsilon \approx 29.7$ J/mm^2; c) L = 57 cm ($M \cong 1.87$); $h \cong 6.3$ mm; $h/d \approx 10$; E = 22.9 J; $h/E \approx 0.27$ mm/J; θ = 4.7 mrad; $\varepsilon \approx 55.5$ J/mm^2.

has been noted above, the value of the beam-quality factor of serial glass lasers with a stable resonator does not allow us to say that lasers of this type can be used for deep melting of metals. Figure 3a shows the characteristic form of the longitudinal section of the melting zone obtained on the Kvant-16 facility without a telescope (beam divergence 24 mrad) for an energy contribution of 6.5 J/mm^2 (total energy 50 J) and a pulse duration of 10 msec. It is seen that despite the rather high pulse energy, the melting front penetrates to a depth of less than 0.8 mm; the aspect ratio is less than 0.5.

In analysis of the processes of metal melting by single laser radiation pulses, a very informative parameter is the ratio of the depth of penetration of the melting front to the applied energy h/E [7, 12], which characterizes the efficiency with which the radiation energy is used in the deep-melting regime. In the experiment (Fig. 3a), this parameter was equal to 0.012 mm/J. For the single-mode radiation of YAG lasers it reaches 0.4 mm/J. The improvement of the laser-beam quality in the case where an unstable resonator with a semireflecting homogeneous exit mirror is used makes it possible to obtain higher values of the efficiency parameter, the aspect ratio, and the melting-zone depth. Figure 3b shows the longitudinal section of the melting zone for the length of the inactive regulated arm of the resonator L = 65 cm (region of the stable resonator). In this case, the total radiation energy decreased as compared to the previous case (Fig. 3a); its value was 37.9 J, and the direct-beam divergence was 9.2 mrad. As is seen from Fig. 3b, in this case, the melting front penetrated to a depth of 1.7 mm, the aspect ratio was ~1, and the efficiency parameter h/E was ~0.045 mm/J.

Passage to the region of an unstable resonator due to the decrease in the inactive arm length L makes it possible to decrease the beam divergence to 3–4 mrad and obtain a melting-zone depth of 6.3 mm for a pulse energy of 22.9 J (Fig. 3c). In this case, the efficiency parameter is rather high: $h/E \approx 0.27$ mm/J, aspect

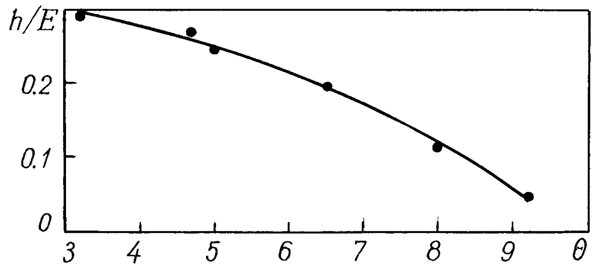

Fig. 4. Dependence of the efficiency parameter *h/E* changed due to the length of the URSHEM inactive arm on the laser-beam divergence (U_p = 1800 V). *h/E*, mm/J; θ, mrad.

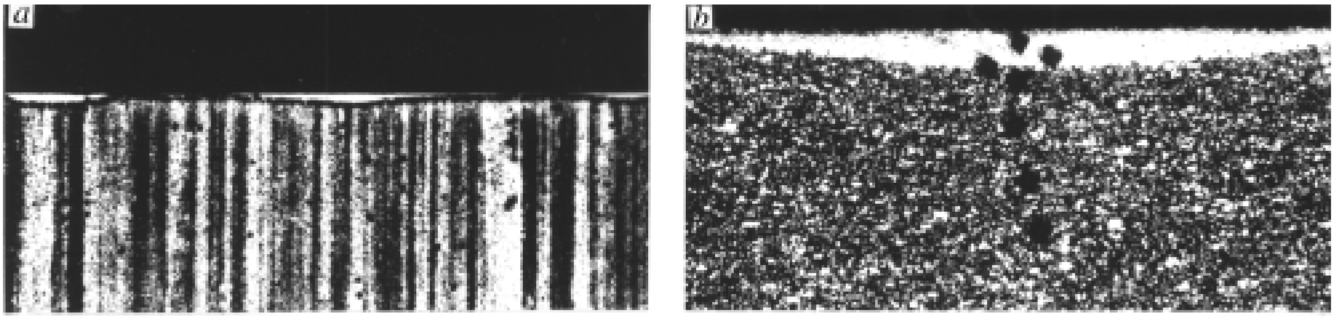

Fig. 5. Hardening zone on the annealed R9M4K8 steel in using of the stable resonator of the Kvant-16 TLF, ×25 (a) and the URSHEM, ×160 (b).

ratio around 10. Figure 4 shows the dependence of the efficiency parameter *h/E* on the beam divergence. It is seen that *h/F* increases with decrease in the divergence and attains values close to the values obtained in the experiments with the pulsed radiation of YAG lasers [7, 12].

In the experiments with the unstable resonator with a semireflecting homogeneous exit mirror (see Fig. 3b and c) the melting process was accompanied by the ejection of a large amount of liquid metal, and the corresponding regimes of melting, even if they provide a rapid growth in the vapor-gas channel and a large depth of penetration of the melting front, must be classified as overthreshold [12]. To suppress the ejection of liquid metal at the level of laser-beam quality of 40 mm·mrad attained using the unstable resonator with a semireflecting homogeneous exit mirror [7, 12], it is necessary to carry out additional optimization of the shape of the radiation pulses.

(b) Analysis of the uniformity of the energy-density distribution. The use of a raster made it possible to successfully solve a number of problems of laser heat treatment [13, 14]. When it is used in the optical scheme of a technological laser facility as the equalizing element, the nonuniformity of the energy-density distribution is no more than ±5%.

As the experiments have shown, in laser heat treatment using the Kvant-16 technological laser facility with a standard stable resonator, the uniformity required for efficient hardening of steels was not attained (Fig. 5a), while in the case where the glass laser with an unstable resonator with a semireflecting homogeneous exit mirror was used, the uniformity of the distribution of the laser-radiation intensity in the beam cross section was much higher (Fig. 5b). In both cases, the treatment was carried out for an energy density of ~1.4 J/mm^2 without surface fusion. In such an irradiation regime, the maximum temperature on the surface of the laser-action zone is slightly lower (by 5–6%) than the melting temperature of the material. It is seen that in this case, in contrast to the laser treatment without external integrating elements, there are no nonhardened regions where the surface temperature is lower than the hardening temperature. The depth of the laser action zone (z) increases and the deviation of the value of z from its maximum value decreases significantly.

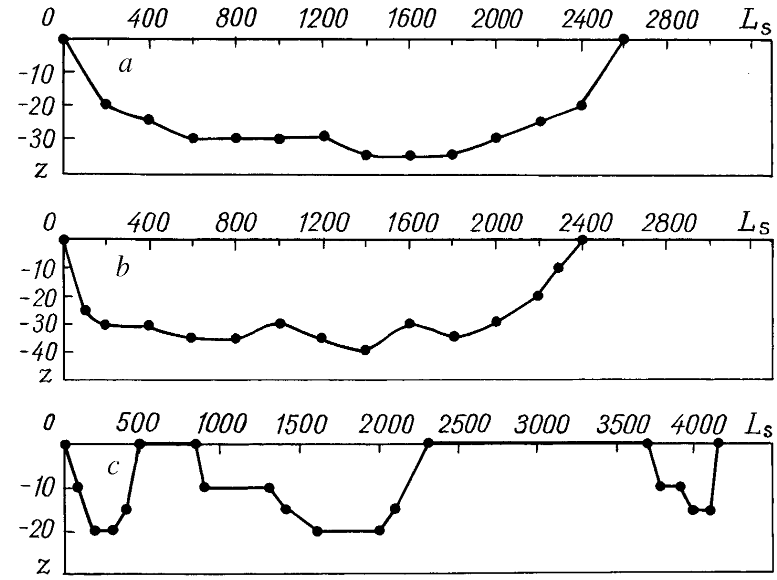

Fig. 6. Profile of the hardening zone in the case of treatment with a raster (a) and a URSHEM (b) and without external equalizing elements (c).

The results of measurement of the depth of the laser-action zone in the microsections have shown that in the case where the hardening is carried out using an unstable resonator with a semireflecting homogeneous exit mirror and in the case where a raster is used, the depths of the hardened zones are comparable and equal to ~35–40 μm (Fig. 6). The estimations performed show that in the case where the treatment is carried out with a raster, the standard deviation of the treated-zone depth from its mean value is $\sigma_1 \approx \pm 2.6$ μm at a distance of ±25% of the total length of the laser-action zone on the surface (L_s = 2.6 mm) from its center, and in the case where an unstable resonator with a semireflecting homogeneous exit mirror is used, $\sigma_2 \approx \pm 3.5$ μm under analogous conditions (L_s = 2.4 mm). When the length of the analyzed zone increases to ±42% of L_s, the values of σ_1 and σ_2 become equal to each other: $\sigma \approx \pm 5.2$ μm. In both cases, the nonuniformity is estimated at the level of ±(10–15)%, which practically corresponds to the requirements imposed upon the quality of the beam in laser hardening of tool steels.

The experimentally determined relation between the nonuniformity of the energy distribution in the heating spot and the microhardness in the laser-action zone [15] allowed us to compare the degree of uniformity of the radiation-intensity distributions in the near zone in the case where the treatment was carried out with a raster and in the case where an unstable resonator with a semireflecting homogeneous exit mirror was used and obtain the numerical characteristics of the observed microhardness distribution in the depth of the laser-action zone. The uniformity of the energy distribution over the beam cross section was estimated by the microhardness distribution at a certain distance from the surface of the laser-action zone. When the unstable resonator with a semireflecting homogeneous exit mirror was used in the laser treatment, the microhardness in the hardening zone was (325±35) kg/mm^2 and (300±30) kg/mm^2 at a depth of 30 and 40 μm, respectively. The uniformity of the microhardness distribution at the given depth was ~(10–12)%. The microhardness in the laser-action zone increased by a factor of ~1.3 as compared to the microhardness of the basic metal. In the treatment with the raster, the microhardness was (450±80) kg/mm^2 at a depth of 30 μm and (400±60) kg/mm^2 at a depth of 40 μm. The uniformity of the microhardness distribution at the given depth was ~(15–17)%. The total increase in the microhardness was ~2 times. The observed difference in the maximum values of the microhardness (by more than 30%) is explained by the fact that in the case of treatment with a raster the energy contribution is large and exceeds the energy contribution in the case where an unstable resonator with a semireflecting homogeneous exit mirror is used by almost a factor of 1.7 (2.4 J/mm^2 in the laser heat treatment with a raster against 1.4 J/mm^2 in the laser heat treatment with an unstable resonator with a semireflecting homogeneous exit mirror). As the depth increases, the uniformity of the microhardness distribution increases moderately, which, in all probability, is caused by the equalization of the temperature field due to heat conduction upon completion of the pulse action. It should be noted that the scatter in the obtained values of the microhardness is due not only to the nonuniformity of the energy distribution in the beam cross section but also to the structural inhomogeneity of the hardening zone. Because of this, nonuniformity of the energy distribution in the beam cross section, in particular, in hardening with a raster, can in fact be estimated at the level of 10%.

Thus, the use of an unstable resonator with a semireflecting homogeneous exit mirror makes it possible to increase the uniformity of the radiation-intensity distribution in the near zone to such a degree that it becomes possible to carry out laser hardening without additional equalizing optical elements.

CONCLUSIONS

1. It is shown that the use of an unstable resonator with a semireflecting homogeneous exit mirror in solid-state pulsed Nd-glass lasers makes it possible to decrease the laser-beam divergence to a level sufficient for realization of deep-melting processes and decrease the nonuniformity of the distribution of the laser-radiation intensity in the near zone to a level sufficient for realization of laser surface heat-treatment processes without external integrating elements.

2. We were the first to obtain a beam quality of ~(40–50) mm·mrad for technological glass lasers. In this case, the depth of fusion of steel was ~6.3 mm (aspect ratio ~10) for a laser-beam divergence of 4.7 mrad and an energy of 22.9 J.

3. In the case where the unstable resonator with a semireflecting homogeneous exit mirror was used in laser heat treatment, we obtained a high degree of uniformity of the radiation-intensity distribution in the near zone, which was estimated at the level of ±10%. This allows us to recommend the base Kvant-16 technological laser facility free of external integrating optical elements for laser heat treatment of metal-cutting tools.

NOTATION

R, reflection factor; f, focal distance; M, magnification of the unstable resonator with a semireflecting homogeneous exit mirror; L, length of the inactive arm of the unstable resonator with a semireflecting homogeneous exit mirror; H_μ, microhardness of the steel; U_p, pumping voltage; E, laser-radiation energy; θ, laser-beam divergence; ε, density of the laser-treatment energy; h, depth of penetration of the melting front; z, depth of the laser-action zone; L_s, reabsverse dimension of the laser-action zone on the surface of the sample; σ, standard deviation of the depth of the laser-action zone from its mean value; d, fusion-channel diameter. Subscripts: 1, treatment with a raster; 2, treatment with an unstable resonator with a semireflecting homogeneous exit mirror.

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