Quantum Electronics 30 (4) 337 – 341 (2000)

PACS numbers: 42.62.Cf; 42.60.Lh
DOI: 10.1070/QE2000v030n04ABEH001727

Influence of the aperture angle on the efficiency of the melting of steel by millisecond laser pulses

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Abstract. The influence of the divergence and aperture of millisecond laser pulses on the efficiency, the dynamic characteristics, and the depth of the molten zone in steel under conditions ensuring the rapid growth of a vapour – gas channel was investigated experimentally. It was established that the dependence of the efficiency on the aperture angle passes through a maximum, the efficiency and depth-of-melting maxima being attained for an aperture angle of 75 – 80 mrad. The highest rate of growth of the vapour – gas channel is also achieved for these aperture angles. It is pointed out that this aperture angle is optimal and that it should be aimed at in the design of pulsed industrial laser systems.

1. Introduction

Free-running optical-pumped solid-state lasers have been used in industrial applications involving the melting and removal of material (welding, precision machining) for a longer time than lasers of other types. However, the range of such problems is limited and pulsed neodymium glass and YAG lasers are used mainly in hardening metal-cutting tools and in spot welding [1, 2]. This arises primarily because of the discrepancy between the rate of injection of the radiation energy into the metal and the rate of hydrodynamic and thermophysical processes in the molten bath, which limits the maximum depth of ejection-free melting of the metal to 1 – 2 mm.

It has been established [3, 4] that, in order to suppress the ejection of liquid-metal particles in the stage involving the formation and growth of a vapour – gas channel, the preliminary formation of a molten bath with a sufficiently large volume (molten buffer volume) is essential. The intensity of the laser radiation at this stage should not exceed the critical intensity $q_{\rm cr}^{(3)}$ [2], which is $\sim 10^6$ W cm^{-2} for steel.

In the stage involving the growth of a vapour – gas channel, the radiation intensity should be sufficiently high to ensure a large depth of the molten zone, since it has been shown [4, 5] that, other conditions being equal, the depth is virtually proportional to the rate of growth of the vapour – gas channel. The latter is determined in its turn by the radiation intensity. As a result, a single pulse can produce a molten zone, the depth of which exceeds appreciably the limiting depth indicated above and the ejection may be suppressed by a transition to turbulent flow in the buffer volume.

Thus the effect of the radiation pulse in the optimised regime can be divided into two stages: the heating of the metal with formation of the molten buffer volume by the leading edge of the pulse and the growth of the vapour – gas channel under the influence of the main peak of the radiation pulse with migration of the effective heat source to a considerable depth. Melting, resulting from the effect of the radiation pulse profiled in this way, will henceforth be called ‘deep melting’. In the deep-melting regime, the critical intensity on the irradiated surface, corresponding to ejection of the melt, increases appreciably.

For a total energy in the pulse of 34.0 J, the threshold intensity has been found [3] to be 6×10^6 W cm^{-2}. In another study [4], this parameter was increased to 8×10^6 W cm^{-2}; a depth of the molten zone of 6.5 mm was then obtained for a pulse energy of 17.5 J. Fig. 1 illustrates the longitudinal section through the molten zone in chrome steel, corresponding to the given case, and the section through the molten zone for an unprofiled pulse and an energy of 15.0 J. A large penetration depth of the melting front (Fig. 1a) was obtained because, owing to the optimisation of the radiation-pulse profile and improvement of the laser-beam quality, the regime involving the rapid growth of the vapour – gas channel was

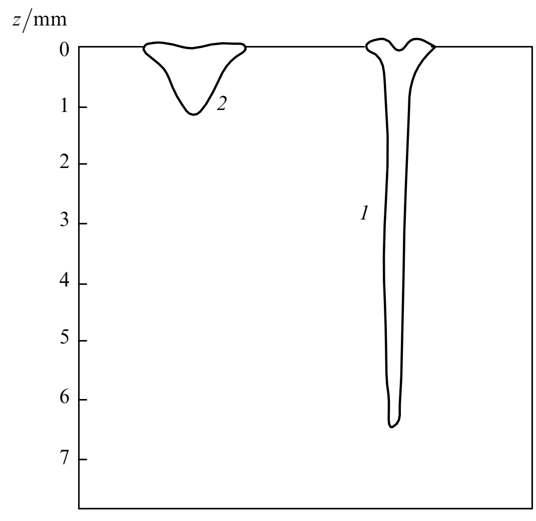

Figure 1. Longitudinal sections through the molten zone in chrome steel for a deep melting regime with an energy of 17.5 J (1) and for an unprofiled pulse with an energy of 15.0 J (2).

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Received 9 November 1999
Kvantovaya Elektronika **30** (4) 337 – 341 (2000)
Translated by A K Grzybowski

achieved. As a result of this, the effective heat source rapidly migrated from the irradiated surface to the bulk of the sample.

Since the vapour – gas channel has a diameter of 10 – 30 μm at its leading edge [5], it must be regarded as a hollow waveguide. The fraction of the radiation energy absorbed at the bottom of the channel then depends on the divergence of the radiation and its angle of convergence after a focusing objective (henceforth the 'aperture angle'). This paper describes a study of the influence of these two main spatial parameters of the laser beam on the dynamic characteristics of the growth of the vapour – gas channel and on the geometrical parameters of the molten zone.

2. Experiment

The experiments were performed on a bench, where an experimental laser, permitting the variation within wide limits of the profiles of the radiation pulses and their duration, was used as the radiation source [3, 4]. The length of the stable cavity formed by nontransmitting spherical (radius of curvature 1.2 m) and plane semitransparent mirrors was 0.92 m. The two Nd : YAG active elements with a diameter of $\varnothing 6.3 \times 100$ mm were located in the immediate vicinity of the spherical mirror; mode selection was achieved with the aid of a replaceable stop 1.5, 2.0, 2.5, or 3.8 mm in diameter.

The radiation emerging from the cavity was transformed by a telescope and was directed to an objective, which focused it onto the surface of the test sample. The focal length of the objective was $F = 100$ or 150 mm. The diameter d of the radiation-focusing zone on the sample surface and the aperture angle β for the specified divergence θ_0 and aperture A_0 of the direct beam are determined from the following evident relationships:

$$\frac{d}{2} = \theta_0 \frac{F}{K}, \quad \beta = K\frac{A_0}{F}. \tag{1}$$

The coefficient K, equivalent to the telescope magnification, varied in discrete steps: 1, 2, 4, 6, 7.2, 8.4, 10.8, and 12.6. By virtue of the independent variation of the diameter of the intracavity stop and the coefficient K, 48 versions of the combinations of different aperture angles β and divergences θ of the radiation within the ranges 0.01 rad $< \beta <$ 0.5 rad and 0.08 mrad $< \theta <$ 4.0 mrad were implemented experimentally.

A stop 1.5 mm in diameter ensured the generation of the TEM_{00} fundamental mode of the entire accessible range of pump intensities. The radiation passing through a stop 2.0 mm in diameter consisted of a superposition of modes with indices not exceeding 1. For a stop diameter greater than 3 mm, multimode radiation was produced. The strongest dependence of the divergence on the stop diameter occurs in the range of small stop diameters. All the experiments were performed for a fixed pulse profile optimised for radiation with the worst beam quality, i.e. without an intracavity stop. A radiation-pulse oscillogram is illustrated in Fig. 2.

The method used to determine the dynamic characteristics of the growth of the vapour – gas channel, described in Ref. [6], is based on the fact that the thickness $x(z)$ of the layer bounded by the melting front whose temperature is T_m and by a certain isotherm T_h has a single-valued relationship with the duration of the operation of a heat source at a specified depth z. The lower limit of the quenching temperature range was adopted as T_h for steels, since the quenched zone was distinctly revealed on metallographic sections. The time $t(z)$ of the existence of the melt at a given depth and the rate $V_f(z)$ of the migration of the melting front along the z axis were determined from the experimental dependence of the thickness $x(z)$ of the quenching layer on the depth z:

$$t(z) = \frac{1}{\xi}x^2(z), \quad V_f(z) = \frac{\xi}{2}\left(x\frac{dx}{dz}\right)^{-1}, \tag{2}$$

where $\xi = 0.1 - 0.2$ cm^2 s^{-1} is a constant, which is different for each experiment and which has the dimensions of thermal diffusivity.

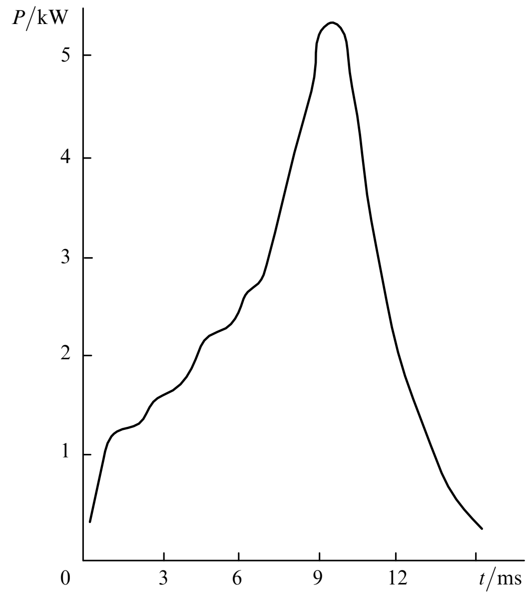

Figure 2. The investigated profile of the laser-radiation pulses.

3. Experimental results and their discussion

Fig. 3 presents the dependences of the depth h of the molten zone on the energy E in the pulse for an intracavity-stop diameter of 2 mm with θ and β varied by varying the magnification of the telescope. Evidently, these dependences are satisfactorily fitted by linear functions. The slope of the $h(E)$ straight line is used, as in Ref. [5], as a characteristic of the efficiency of the utilisation of the radiation energy (the efficiency parameter η).

It is seen from Fig. 3 that, with decrease in divergence, i.e. on passing from curve 1 to curve 3, the efficiency parameter η increases. However, a further decrease in divergence (curves 6 – 8) leads to the opposite effect, i.e. to a decrease in η and hence to a decrease in the melting depth. The $h(E)$ relationships have a similar form also for other stop diameters.

Fig. 4 presents the experimental dependences of the efficiency parameter η on the aperture angle β, varied by varying the telescope magnification, for different stop diameters. It is seen that in all cases the $\eta(E)$ curves have a maximum in the range 0.05 rad $< \beta <$ 0.1 rad. Since the divergence of the radiation diminishes in proportion to the increase in β, the above finding implies that the melting depth h and the efficiency parameter η increase with decrease in the divergence θ only for $\beta <$ 0.1 rad. A further decrease in θ, accompanied by an increase in β, leads to a diminution of h and η. This result is not entirely evident and requires further

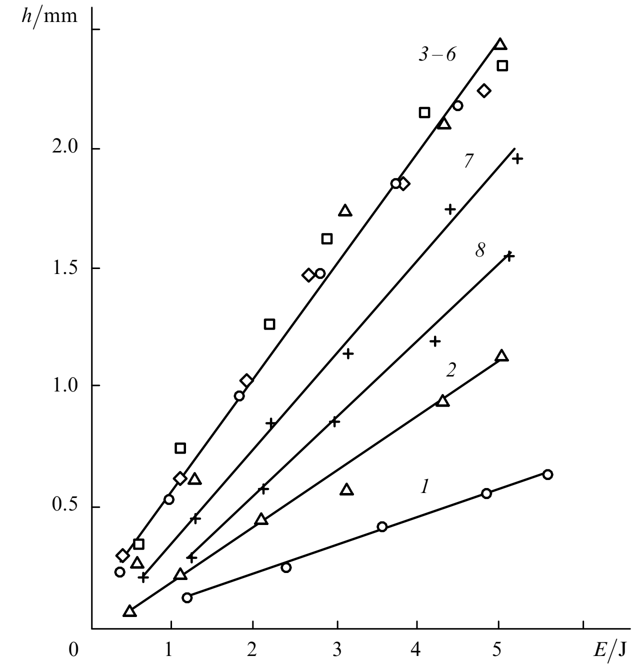

Figure 3. Dependences of the depth h of the molten zone on the energy E in the pulse for an intracavity-stop diameter of 2 mm and the aperture angle varied as a result of the variation of the parameter $K = 1$ (1), 2 (2), 4 (3), 6 (4), 7.2 (5), 8.4 (6), 10.8 (7), and 12.6 (8).

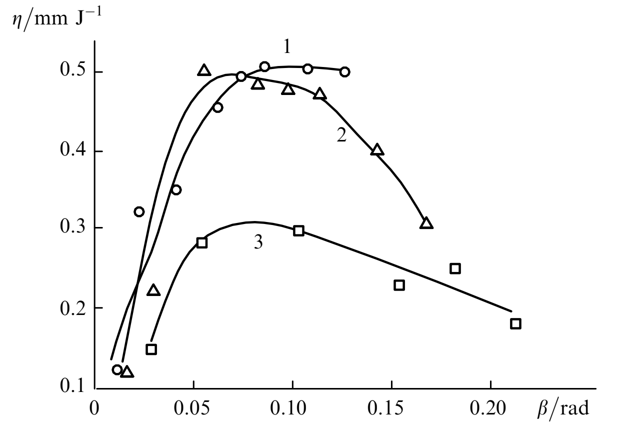

Figure 4. Dependences of the efficiency parameter η on the aperture angle β for intracavity-stop diameters of 1.5 mm (1), 2 mm (2), and 3.8 mm (3) and with the aperture angle varied as a result of the variation of the telescope magnification.

consideration.

Since variation of the telescope magnification entails the simultaneous variation of both the divergence and the aperture of the beam, a series of experiments in which either θ or β were kept constant were selected for the separate analysis of the above two parameters from the whole database of 48 versions of the combinations of β and θ for different stop parameters and coefficients K.

Fig. 5 presents the dependences of the efficiency parameter η on the divergence of the transformed beam for certain fixed aperture angles. It is seen that in all cases the melting efficiency increases monotonically with decrease in divergence, which appears quite natural. The efficiency parameter η is then a maximum for single-mode radiation

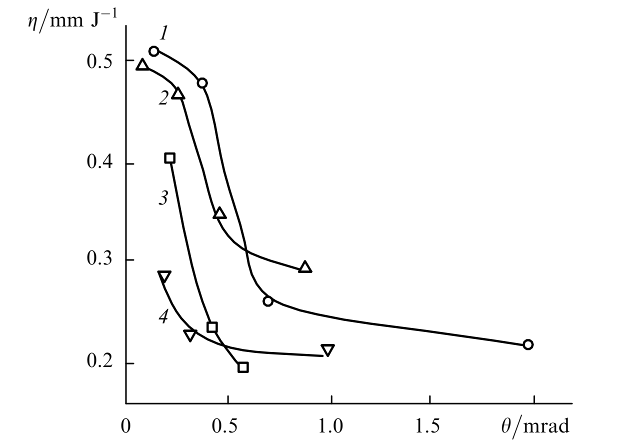

Figure 5. Dependences of the efficiency parameter η on the divergence θ of the transformed beam for aperture angles $\beta = 0.080 - 0.085$ rad (1), 0.11 – 0.12 rad (2), 0.14 – 0.15 rad (3), and 0.16 – 0.17 rad (4).

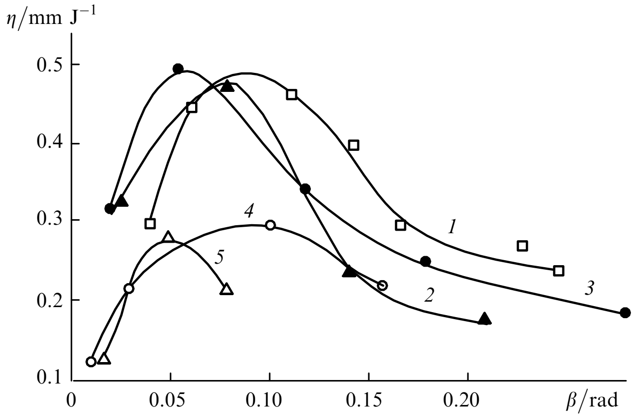

Figure 6. Dependences of the efficiency parameter η on the aperture angle β for the divergence of the transformed beam $\theta = 0.2$ mrad (1), 0.4 mrad (2), 0.5 mrad (3), 1.0 mrad (4), and 2.0 mrad (5).

with $\beta = 0.08$ rad (curve 1) and 0.11 rad (curve 2). The deviation of the aperture angle towards a decrease or an increase leads to a decrease in the efficiency parameter η and in the melting depth.

The $\eta(\beta)$ relationships are shown explicitly in Fig. 6. The presence of maxima in the $\eta(\beta)$ curves is clearly revealed for all the radiation divergences. The maximum in the efficiency parameter $\eta \sim 0.5$ mm J^{-1} is attained in the range 0.05 rad $< \beta <$ 0.1 rad; the average aperture angle, corresponding to the maximum in the efficiency parameter, is 0.075 – 0.08 rad.

The presence of a maximum in the dependence of the melting efficiency on the aperture angle is not evident, since it follows from geometrical considerations [5, 7] that the efficiency of the radiation propagation to the bottom of the vapour – gas channel should increase monotonically with decrease in the angle β. For the coefficient of reflection R from a smooth metal surface, one may write [8]

$$R = 1 - \left(\frac{2\omega}{\pi\sigma}\right)^{1/2} \cos\left(\frac{\pi}{2} - \beta\right) ,$$

where σ is the conductivity of the metal; ω is the plasma frequency. With decrease in the aperture angle β, the coefficient of the reflection of laser radiation from the walls of the vapour – gas channel increases monotonically; furthermore, the effective number of reflections from the channel walls, necessary to reach the bottom of the channel, diminishes.

Since the leading edge of the vapour – gas channel has a diameter of 10 – 30 μm [4, 5], the concepts of geometrical optics are not applicable to the consideration of the propagation of radiation in a channel more than 1 mm long, because $d^2/\lambda < 1$ mm. The problem of the propagation of an electromagnetic wave in a metal capillary has been considered in fair detail in Refs [9, 10], where explicit expressions are presented for the attenuation coefficients of the E and H eigenmodes, as well as superposition modes. The E modes are rapidly attenuated and cannot make an appreciable contribution to the energy transport to the bottom of the channel. For the H mode, the attenuation coefficient has a minimum for the aperture angle

$$\beta \approx 1/(kr_0)^{1/2} , \qquad (3)$$

where k is the wave number; r_0 is the channel radius. After substituting in formula (3) the average aperture angle corresponding to the maximum in the efficiency parameter η according to the data in Fig. 6 ($\beta \approx 0.08$ rad), we obtain the following estimate of the radius of the vapour – gas channel:

$$r_0 \approx 1/(k\beta^2) \approx 25 \text{ μm} . \qquad (4)$$

This estimate agrees well with the diameter of the channel in its narrowest part indicated above: $d = 10 - 30$ μm.

Thus the waveguide approximation to the propagation of radiation in the vapour – gas channel in the experiment under consideration is satisfactory. The experimental dependence of the melting efficiency parameter on the aperture angle can be explained within the framework of this approximation (Fig. 6). The experimental aperture angle, corresponding to the maximum in the parameter η ($\beta \approx 0.075 - 0.08$ rad), should be regarded as optimal for the determination of the conditions in pulsed-laser welding and in the design of industrial apparatus.

Using the experimental maximum efficiency parameters for different laser beam quality parameters, it is possible to estimate the maximum melting depth for single millisecond laser pulses with any specified energy. For example, according to the data in Fig. 6, the efficiency parameter reaches 0.5 mm J^{-1} for the smallest radiation divergence and the optimal aperture angle.

However, it is difficult to obtain a fairly large pulse energy for a divergence of the direct beam of ~1 mrad in pulsed laser systems. As a more realistic example, one may consider the experiment [4] (Fig. 1a) where a melting depth of 6.5 mm was obtained on application of a radiation pulse with an energy of 17.5 J for a divergence of the direct beam of 4 mrad after a telescope with fourfold magnification and $\beta = 0.07$ rad. In this case, $\eta \approx 0.37$ mm J^{-1}, which agrees quite well with the results of the present study presented in Fig. 6.

Analogous dependences of the rate of growth of the vapour – gas channel correspond to the dependences of the efficiency parameter η on the aperture angle (Fig. 6). Fig. 7 presents the rate of growth of the channel V_f at a depth of 1 mm as a function of the aperture angle calculated for curves 1, 2, 3 in Fig. 6, i.e. for divergences of 0.2, 0.4, and 0.5 mrad. It is seen from the comparison of Figs 6 and 7 that they agree qualitatively: a higher rate of growth of the vapour – gas channel corresponds to the conditions in the experiment where a higher efficiency parameter η was achieved. This result appears natural bearing in mind that the lifetime of the vapour – gas channel is approximately the same for nearly optimal regimes [6] and amounts to 2.5 – 3.0 ms for the pulse in Fig. 3.

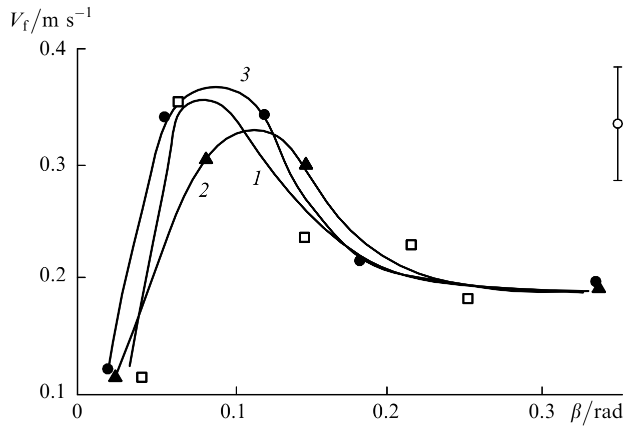

Figure 7. Dependences of the rate of growth of the vapour – gas channel V_f at the depth $z = 1$ mm on the aperture angle β calculated for curves 1, 2, and 3 in Fig. 6, respectively.

Thus the beam quality parameter $\theta_0 A_0$, widely used to characterise the properties of laser radiation, is not adequate for the consideration of the transport of radiation in the vapour – gas channel formed in the metal by millisecond pulses in the deep-melting regime. It follows from the foregoing that the aperture and divergence of the beam must be optimised independently in this case. Nevertheless, for the solution of practical problems it is of interest to point out that the maximum parameter $\theta_0 A_0$ leads to the achievement of deep melting on the basis of the characteristics of serially manufactured industrial equipment. An expression defining the beam quality parameter can be easily obtained from the relationship (1):

$$\theta_0 A_0 = \tfrac{1}{2}\beta d . \qquad (5)$$

Bearing in mind that the diameter of the focusing zone must be not more than 0.3 mm, it is easy to find from formula (5) that the beam quality parameter must not exceed 12 mm mrad if the aperture angle is close to the optimal value. For a standard active element 6.3 mm in diameter, this corresponds to a divergence of the direct beam of about 2 mrad. It is essential to note that $\theta_0 A_0 \approx 60$ mm mrad is characteristic of industrial pulsed YAG lasers.

4. Conclusions

Thus the dependences of the efficiency parameter, the melting depth, and the rate of growth of the vapour – gas channel on the aperture angle β pass through a maximum for single millisecond laser-radiation pulses under the conditions of the rapid growth of the length of the vapour – gas channel and hence for a large depth of penetration by the melting front (deep melting). The maxima in the parameters listed above are obtained for $\beta = 0.080 - 0.075$ rad. This result is a consequence of the fact that, in the experiments under consideration, the diameter of the vapour – gas channel is fairly small and the electromagnetic optical wave propagates in it as if in a hollow waveguide. The efficiency parameter

$\eta \approx 0.5$ mm J^{-1} was reached for the first time for millisecond laser pulses.

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