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Peculiarities of welding of metals by a low-power repetitively pulsed Nd : YAG laser

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Abstract. **Dependences of the depth and width of a welded joint on the displacement velocity of stainless steel and aluminium alloy samples irradiated by a 5 – 15-W repetitively pulsed Nd : YAG laser are obtained. It is shown that for pulse repetition rates of 25 – 50 Hz and an off-duty ratio of 150 – 300, the specific power losses on penetration are one – two orders of magnitude lower than in the case of welding by cw and repetitively pulsed CO$_2$ lasers.**

Keywords: *repetitively pulsed laser, welding, weld depth, specific power losses.*

1. Introduction

Apart from the quality of a welded joint, an important parameter of laser welding of metals is the specific power losses (SPLs) W/h, defined as the ratio of the average laser power W to the weld depth h. The lower this ratio, the deeper the welded joint produced by a laser of a given power. Another important factor is the dagger ratio h/b, i.e., the ratio of the weld depth h to its width b.

It is known that upon welding by cw laser radiation, the ratio $h/b > 1$ is achieved when the power density at the metal surface exceeds a certain threshold due to the appearance of a key-hole (KH) in the melt through which the radiation penetrates inside the sample [1, 2]. In this case, the transport of metal from the front wall of the KH to the rear wall is cyclic [2 – 4], and the average temperature of the KH walls is close to the boiling point of the metal [5]. Typical values of the SPL upon welding by cw laser radiation are 300 – 1000 W mm^{-1}, while the dagger ratio varies from 3 to 8 [2].

The use of repetitively pulsed CO$_2$ and Nd : YAG lasers with pulse durations ~ 10 ms and an off-duty ratio of 2 – 10 led to a decrease in the SPLs (to 200 W mm^{-1}) without deteriorating the quality of the welded joint and the dagger ratio [2, 6 – 8]. High-speed X-ray photography of the melt bath showed [8] that upon such irradiation, the KH is formed about 1 ms after the beginning of the laser pulse and is filled with the melt within 1.5 ms after the termination of the pulse. In this case, the average temperature of the KH walls proves to be lower than upon welding by cw radiation.

For an off-duty ratio of 40 – 200, the melt is formed at the front wall of the KH and is transported to its rear wall during a period much shorter than the interval between pulses; after termination of the laser pulse, the KH is not filled with the melt [9 – 12]. The specific power losses are minimum in this case and amount to 40 – 60 W mm^{-1}, while the dagger ratio achieves 20.

In the limit of slow displacement velocities of the target, the depth of the weld produced by a repetitively pulsed laser is described by the approximate relation [2]

$$h = \frac{E}{\pi d c \rho T_{\mathrm{b}} (\chi\tau)^{1/2}} + \frac{W}{2\pi k T_{\mathrm{b}}} \ln\left[\frac{h}{d/2 + (4\chi/f)^{1/2}}\right], \quad (1)$$

where E and τ are the energy and duration of the laser pulse, respectively; f is the pulse repetition rate; $W = Ef$; d is the diameter of the focal spot; T_{b} is the boiling point of the metal: and c, ρ, k and χ are the specific heat, density, thermal conductivity and diffusivity of the material, respectively. Note that, the dependence of h on E and f described by (1) corresponds to the measurements made in [11], while its dependence on other parameters has not been studied in fact.

Expression (1) gives the estimate for the SPL:

$$\frac{W}{h} = \pi d c \rho T_{\mathrm{b}} f (\chi\tau)^{1/2}$$

$$\times \left\{1 + \frac{df}{2}\left(\frac{\tau}{\chi}\right)^{1/2} \ln\left[\frac{h}{d/2 + (4\chi/f)^{1/2}}\right]\right\}^{-1}. \quad (2)$$

One can see from (2) that as the diameter d of the focal region is decreased, the SPLs also decrease. For $d < d^*$, this decrease is described by a linear dependence, where

$$d^* = \left(\frac{\chi}{\tau f^2}\right)^{1/2} \ln^{-1}\left[\frac{h}{d/2 + (4\chi/f)^{1/2}}\right]. \quad (3)$$

Estimates show that for the parameters of our problem, the experimental values of d are much lower than d^*, which leads to a decrease in W/h with decreasing d. In addition, the increase in the surface optical breakdown threshold with decreasing the laser wavelength [2] gives promise that the high quality of the weld will be preserved.

The aim of our paper is to study the dependence of the SPL on the parameters of metal welding by a low-power repetitively pulsed Nd : YAG laser.

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2. Experimental

We used in our experiments a multimode pulsed Nd : YAG laser with the following parameters: laser pulse duration $\tau \approx 140$ μs, pulse repetition rate $f = 25$, 33 and 50 Hz, and the corresponding mean power of the radiation incident on a target $W = 4.2$, 8 and 13.4 W, respectively. A disproportionate increase in the mean power observed with increasing the pulse repetition rate is explained by an increase in the energy in an individual pulse. We used 3.2-mm thick stainless steel targets and 4.6-mm thick targets made of the AD16 aluminum alloy. The velocity V of their displacement (welding rate) varied from 0.1 to 1 mm s^{-1}. Radiation was focused by a quartz lens of focal length 56 mm. The focusing angle was 0.11 rad, the focal spot diameter was $d = 0.2$ mm for $f = 25$ and 33 Hz and 0.4 mm for $f = 50$ Hz, respectively.

3. Results and discussion

Figure 1 shows photographs of the cross-sectional view of welded joints for different welding rates. The main results of measurements of weld parameters obtained for stainless steel samples are presented in Figs 2–5.

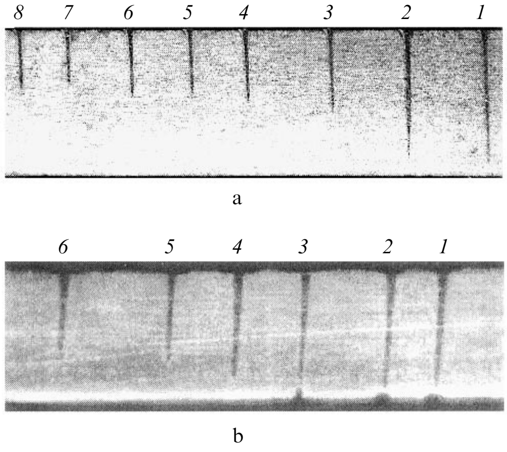

Figure 1. Photographs of the cross-sectional view of welds in a (a) 4.6-mm-thick AD16 aluminium alloy sample and (b) 3.2-mm-thick stainless-steel sample for $W = 8$ W, $f = 33$ Hz, and $V = 0.1$ (*1*), 0.2 (*2*), 0.3 (*3*), 0.4 (*4*), 0.5 (*5*), 0.6 (*6*), 0.8 (*7*) and 1 mm s^{-1} (*8*).

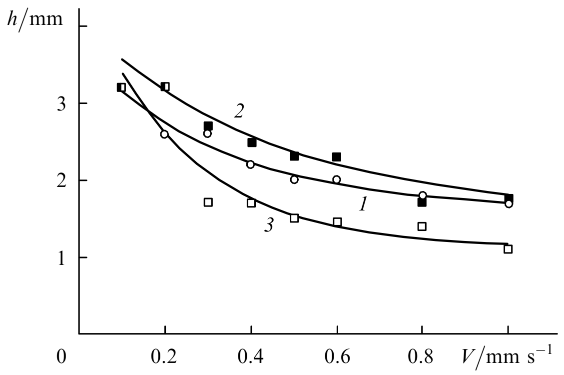

Figure 2. Dependence of the weld depth h of a steel sample on its displacement velocity V for $W = 4.2$ W, $f = 25$ Hz [curve (*1*)], $W = 8$ W, $f = 33$ Hz [curve (*2*)], and $W = 13.4$ W, $f = 50$ Hz [curve (*3*)].

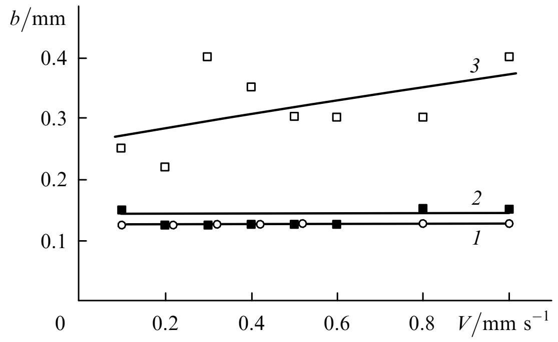

Figure 3. Dependence of the width b of a weld in a steel sample on its displacement velocity V for $W = 4.2$ W, $f = 25$ Hz [curve (*1*)], $W = 8$ W, $f = 33$ Hz [curve (*2*)], and $W = 13.4$ W, $f = 50$ Hz [curve (*3*)].

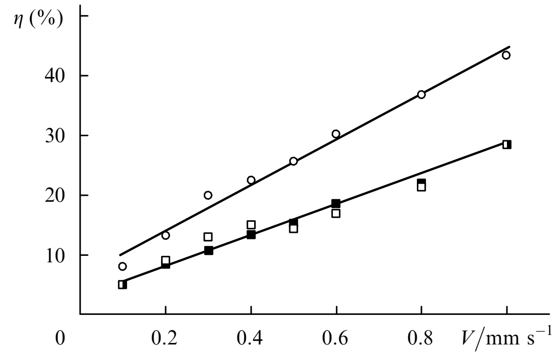

Figure 4. Dependence of the welding efficiency η in a stainless steel sample on its velocity V for $W = 4.2$ W, $f = 25$ Hz (circles), $W = 8$ W, $f = 33$ Hz (dark squares), and $W = 13.4$ W, $f = 50$ Hz (light squares).

Figures 2 and 3 show the dependences of h and b on V, measured with an error of 15 %, for three modes of laser operation. The dependences presented in these figures show that the weld depth decreases with increasing the welding rate V, while its width is independent of V for $f = 25$ and 33 Hz and is almost the same.

The total efficiency η of the welding process, defined as the ratio of the energy required for heating and melting of the weld to the total energy is shown in Fig. 4. With increasing the welding rate, the efficiency increases and achieves 45% for $f = 25$ Hz and $V = 1$ mm s^{-1}.

The specific power losses W/h (Fig. 5) also increase with increasing the welding rate, but in all cases remain much lower than in the case of welding by using a pulsed $\mathrm{CO_2}$ laser with a high off-duty ratio of pulses [curve (4) in Fig. 5] [10]. Thus, for $V = 0.1$ mm s^{-1} in our experiments, the minimum value of $W/h = 1.3$ W mm^{-1} corresponds to $f = 25$ Hz, while for $V = 1$ mm s^{-1}, the maximum value of $W/h = 12$ W mm^{-1} corresponds to $f = 50$ Hz. Note that in the case of welding by a cw $\mathrm{CO_2}$ laser, the SPL is again considerably higher than the value obtained in our work. For example, for welding by a 1.2-kW cw $\mathrm{CO_2}$ laser at a comparatively low welding rate $V = 3.2$ mm s^{-1}, the SPL of $W/h = 220$ W mm^{-1} was obtained [13]. Note also that for pulse repetition rates $f = 25$ and 33 Hz, the divergence of radiation for the laser used in our experiments was smaller than for $f = 50$ Hz, as indicated by a decrease in the focal spot diameter with decreasing the pulse repetition rate. As a result, the SPLs decrease faster than linearly with decreasing the pulse repetition rate [see curves (*1*) and (*3*) in Fig. 5].

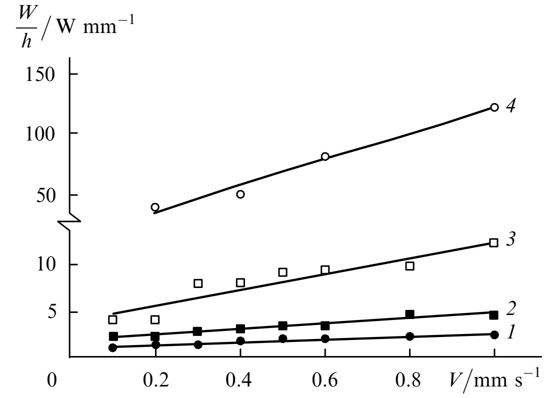

Figure 5. Dependence of the specific power losses W/h for a steel sample on its displacement velocity V during welding by a Nd : YAG laser for $W = 4.2$ W, $f = 25$ Hz [curve (*1*)], $W = 8$ W, $f = 33$ Hz [curve (*2*)], and $W = 13.4$ W, $f = 50$ Hz [curve (*3*)], and by a pulsed CO$_2$ laser [10] [curve (*4*)].

The dependences of the SPL on V can be used to estimate the welding efficiency hV/W, i.e., the magnitude of the welded area per joule. The maximum efficiency obtained in our experiments was 0.4 mm^2 J^{-1}, while its value for welding by cw and pulsed CO$_2$ lasers [according to the dependence (*4*) in Fig. 5] is ~ 0.04 [2] and 0.01 mm^2 J^{-1}, respectively.

The values of welding parameters h, b, η and W/h are presented in Table 1 for various values of V for an AD16 aluminium alloy sample at a pulse repetition rate $f = 33$ Hz and $W = 8$ W. Note that the values of the parameters, except the efficiency of the process are close to the corresponding values of parameters for a stainless steel sample. The estimates of W/h obtained from (2) are also close for both samples. A lower efficiency for the AD16 sample is explained by a higher thermal conductivity and a lower absorption coefficient of the aluminium alloy.

Table 1. Welding parameters h, b, η and W/h for different values of V for an AD16 aluminium alloy sample for $f = 33$ Hz, $d = 0.2$ mm, and $W = 8$ W.

V/mm s^{-1}	h/mm	b/mm	η (%)	$\frac{W}{h}$ / W mm^{-1}
0.1	4.1	0.15	2.05	1.95
0.2	4.0	0.15	4.0	2.0
0.3	2.7	0.15	4.2	3.0
0.4	2.3	0.15	4.7	3.5
0.5	2.1	0.15	5.3	3.8
0.6	2.1	0.15	6.3	3.8
0.8	1.7	0.15	6.8	5.7
1.0	1.9	0.15	8.7	4.2

4. Conclusions

The main results of the paper can be formulated as follows:

(i) The welding of stainless steel and AD16 aluminium alloy samples having a thickness of 3–4 mm by using repetitively pulsed Nd : YAG laser radiation of average power 5–10 W is demonstrated.

(ii) Specific power losses in the case of welding by a tightly-focused low-power Nd : YAG laser beam are lower by one–two orders of magnitude than upon welding by cw or pulsed CO$_2$ lasers.

(iii) The use of repetitively pulsed Nd : YAG lasers with a higher output power can increase the efficiency of the welding process, and such lasers can be used in compact and efficient laser complexes for welding of metals.

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