ALT 12
Advanced Laser Technologies
2 – 6 September 2012, Thun, Switzerland

ALT 12
c/o Bern University of Applied Sciences
Engineering and Information Technology
Pestalozzistrasse 20, CH-3400 Burgdorf
info@alt12.org, www.alt12.org
0041 (0) 34 426 42 06

OBSERVATION OF THERMOCAPILLARY EFFECT IN GAS -ASSISTED CO2 LASER CUTTING OF STEEL

Authors:

A. V. Dubrov, Y. N. Zavalov, V.D. Dubrov

DOI: 10.12684/alt.1.48

Corresponding author: V.D. Dubrov

e-mail: vddubrov@mail.ru

Observation of Thermocapillary Effect in Gas -Assisted CO_2 Laser Cutting of Steel

A. V. Dubrov, Y. N. Zavalov, V. D. Dubrov
Institute on Laser and Information Technology of Russia Academy of Science -ILIT RAS
1 Svyatoozerskaya St., Shatura, Moscow Region, 140700 Russia

Abstract

Investigations of melt's dynamics have been performed with pyrometer in the gasjet-assisted CO_2 laser cutting. Pyrometer consists of 4 sensors and local luminosity of metal melt has been measured precisely on different depth along front of cutting with long dimension resolution about 0.1 mm and with time resolution as short as 0.06 ms. The results of data processing of brightness temperature are reported for laser cutting of mild-steel plate 3 mm, 6 mm and 10 mm thick, that allows obtaining spectra of melt's surface deformation for different values of cutting velocity and assisted gas pressure. The generation of capillary-wave turbulence following thermo-capillary effect can be observed in the locations, where intensity of radiation of CO_2 laser on melt's surface exceeds 1 MW/cm^2. The R-M-S of temperature fluctuations is greater than 10 *K* in the range of sub-millimeter capillary waves. Thus, an additional mechanism of the anomalous absorption on the front of cutting can compensate the low absorption of the metal in case of 10.6 μm laser in comparison with the absorption of the metal in the near infrared range.

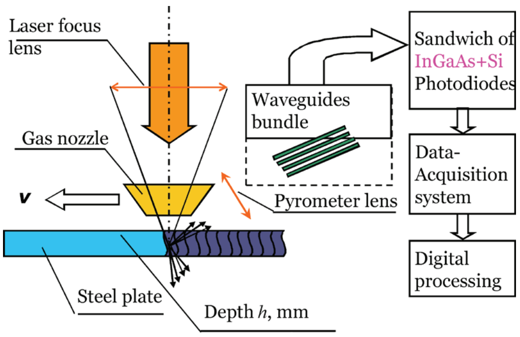
Introduction

An investigation of the dynamics of the laser radiation action on the material and a development of the monitoring systems is one of the directions of quality improvement in laser-thermal technology [1-4]. We have previously carried out the comparison studies on the pulsation spectrum of integrated luminosity of emission from the laser cutting zone [5], the spectrum of brightness temperature under two-color pyrometry [6], and the spectrum of the side edge roughness, resulting from laser cutting [7]. This paper reports the results of measuring by a four-channel two-color pyrometer of pulsations of local temperature in the region of exposure of mild- steel plate by radiation of CO_2 laser.

Experimental setup

The experiments were made used "Trumatic L2530" machine (Trumpf GmbH, Germany) with a CO_2 laser of 1500 W power. Cuts of a low-carbon steel sheet of 10 mm thick were made. The "optimal" cutting parameters were used with the lens of 127 mm focus. The cutting velocity was varied in range of ±20 % from the recommended velocity being 20 mm/s. Oxygen was used as an assist gas, its pressure being varied in range of (0.03…0.08) MPa. Experimental cuts of 6 mm- or 3 mm- thickness sheets of low-carbon steel were made with "optimal" cutting parameters too. The cutting velocity was varied (26…40) mm/s for 6 mm steel plate. The pressure of oxygen was varied (0.1…0.6) MPa. The cutting velocity was varied (35…60) mm/s for 3 mm steel plate, and the pressure of oxygen was varied (0.1…0.25) MPa.

Figure 1 Experimental set-up (scheme)



Measurements of time fluctuations of local luminance of metal melt were performed during cutting (fig.1-3). Thus the brightness temperature *T* has been taken from small illuminated areas located on different depth on the front of cut:
-in the samples of 3 mm thick the depth was 0.6, 1.5 and 2.3 mm;
-in the samples of 6 mm thick the depth was 0.6, 1.5, 2.3 and 4 mm;
-in the samples of 10 mm thick the depth was 1.5, 2.3, 3.2 and 4.8 mm.

Figure 2. Temporal oscillations of temperature on depth of 0.8 mm(bottom line); 2.4 mm and 4 mm (upper line). The cutting of 6 mm thick plate of mild steel with cutting velocity 33 mm/s and oxygen pressure of 6 bar

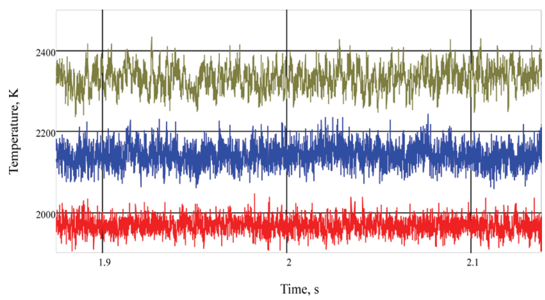
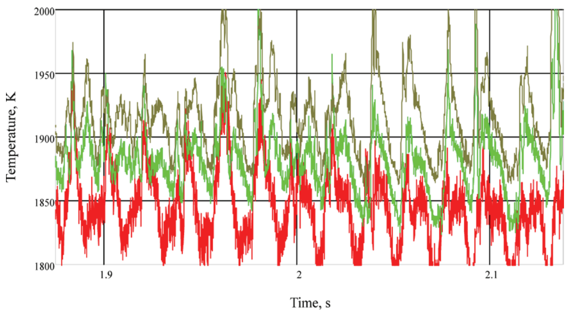
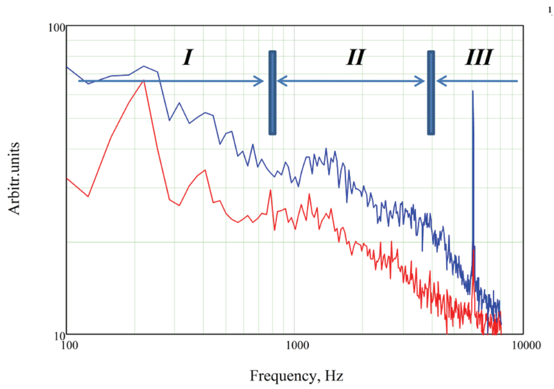


Figure 3. Temporal oscillations of temperature on depth of of 1.6 mm (bottom line); 3.2 mm and 4.8 mm (upper line). The cutting of 10 mm thick plate of mild steel with cutting velocity 18 mm/s and oxygen pressure of 0.8 bar



These data permitted to determine temporal spectra of pulsations of brightness temperature. The procedure of data processing has been described in [8]. The variance spectrum of temperature fluctuations on local surface $E_T(\omega)$ were obtained at various depths along cutting front for cutting parameters mentioned above (fig.4).

Figure 4. Temporal spectra of pulsations of brightness temperature for 6 mm sample, v=33 mm/s; p[O_2]=0.45 MPa, depth is 0.8 mm and (upper line) 2.4 mm.



Results and discussion

The spectrum of variance of temperature pulsations we obtained (fig.4) can be divided into three regions. Each of them derived from the different physical process. The low-frequency region ***I*** (below 300…700 Hz) coupled with cutting velocity and with transverse striations on the side edge of the plate [2, 7]. Region ***II*** includes frequency of melt ejection $f_t = v_m/h$ (v_m is melt velocity, h -sample thickness). The temperature pulsations associated here with more detail peculiarities of the melt flow. It includes, for instance, the longitudinal striation on the side edge [9]. One should note that the melt flow has complicated formation similar to a mountain stream. The spectrum of variance of temperature pulsations in range ***II*** is deformed with increasing pressure of assisted gas in experiments. We will take a special attention in this paper to region ***III***, in which the pulsations originated from capillary-wave turbulence on melt's surface [10].

The energy of melt's surface deformation

It is shown early [8] that local fluctuations of T are related to local melt's surface deformations due to unequal radiation absorption. Thus, variance spectrum of temperature fluctuations on local surface $E_T(\omega)$ is related with spectrum of density of energy of surface deformation, caused by forced turbulent pulsation of melt flow (***II***) and local non-uniformity of surface tension (***III***). The function $\varepsilon = E_T(\omega)\cdot\omega^2$, having the meaning the density of dissipation of turbulent energy of surface deformation, was calculated from experimental estimation of $E_T(\omega)$. This function has the maximum in hydrodynamic turbulence on the boundary between inertial and viscosity domains and must tends to zero in high-frequency area. The measurements show the existence of conditions of developed turbulent flow in case of cutting samples of 6 mm thick (fig.5), in contrast to the data measured during cutting samples with thickness of 10 mm (fig.6).

Figure 5. The spectrum of density of dissipation energy. The notation used as the same as on fig.4.

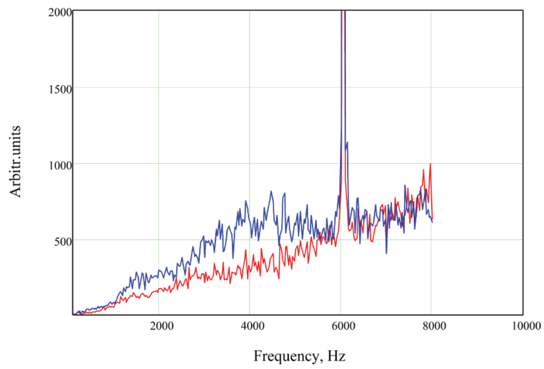
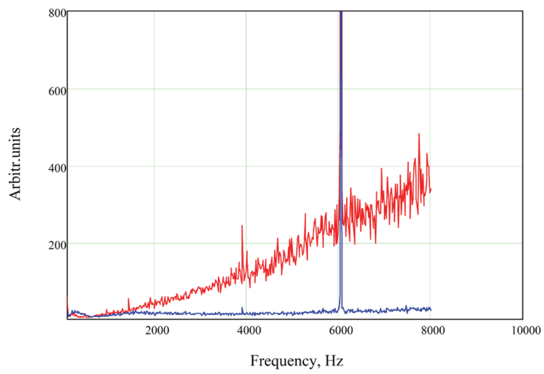


Figure 6. The spectrum of density of dissipation energy for 10 mm sample, v=18 mm/s; p[O_2]=0.8 bar, depth is 1.6 mm [upper line] and 3.2 mm.

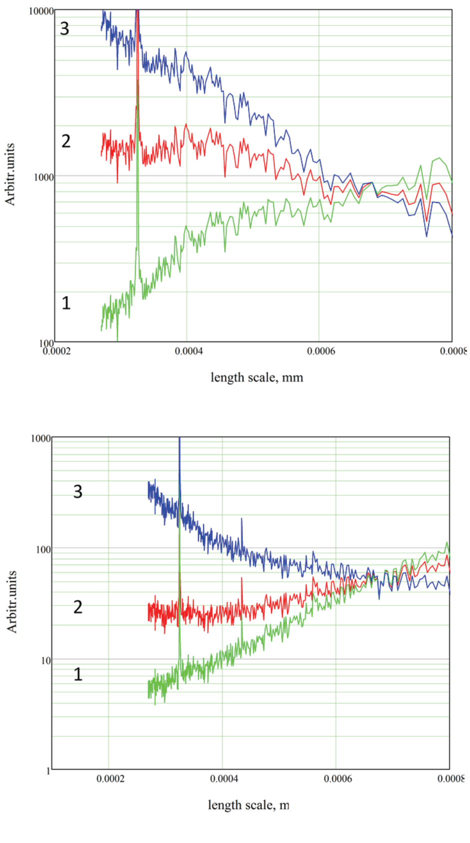


The transmission of energy of capillary waves throughout turbulent spectrum

The measured estimation of spectrum ε in some cases does not tend to zero in the area of viscosity dissipation of hydrodynamic turbulence. Thus the capillary –wave turbulence reveals itself. Let's consider another auxiliary functions $\Psi(k) = E_T(k)\cdot k^{7/4}$ and $\Theta = E_T(k)*k^5$, where k is capillary –wave number with dispersion $k^3 = \omega^2(\rho/\sigma)$ (ρ is melt density, σ is melt surface tension). Function Ψ would be constant in case of capillary –wave turbulence with so- called inverse cascade: energy of capillary waves is transferring from short-length wave up to long-length capillary waves due to decay instability [10]. Function Θ is near to constant in case of capillary–wave turbulence with low frequency energy input [11].

As we see in our case, fig.7, the inverse cascade of capillary –wave turbulence is realized.

Figure 7. The spectra of E_T [1], $\Psi = E_T(k)*k^{7/4}$ [2] and $\Theta = E_T(k)*k^5$ [3]; selective channel only is used: a) 0.8 mm for 6 mm thickness sample and b) 1.6 mm for 10 mm thickness sample



Thermocapillary phenomenon

The spectra of ε do not tend to zero in the area of viscosity dissipation of hydrodynamic turbulence in specific cases of cutting namely in case of present of focused radiation in local zone of measurements. Function Ψ has small value of the same units if it measured in unfocused zone where capillary –wave turbulence weakened. We suppose the thermocapillary phenomenon of abnormal absorption [12] occurs in zone of presence focused, intensity above 1 MW/cm^2, 10.6 μm radiation. The main reason of thermo-capillary effect is presence of thermal dependence of surface tension as showed in [13]. For mild steels: $\partial\sigma/\partial T \approx -0.6\,\mathrm{mN/(m\cdot K)}$, and estimation of Marangoni number is Ma~10, taken into account next data for liquid mild steel: $\sigma \approx 1.5\,\mathrm{N}/m$, melt density $\rho \approx 7000\,\mathrm{kg}/m^3$. The phase velocity of capillary waves varies (2-16) m/s in frequency range of 7 kHz to 3 MHz for mild steel, relatively wavelength varies in range of (300-5) μm [the case of "deep" liquid was calculated]. In case of using CO_2 laser with focus intensity of 1 MW/cm^2 (estimation is done with laser power 1200 W and lens with F=127 mm) special regime of small-scale capillary waves generation occurs. These waves form so-called capillary-wave turbulence spectrum [10].

Thus, an additional mechanism of the anomalous absorption of radiation can compensate the low absorption of the metal in case of 10.6 μm laser in comparison with the absorption of the metal in the near infrared range.

Conclusion

The measurements of local pulsations of brightness temperature T of melt radiance along the front of the cut of metal sheet by CO_2 laser are carried out. Both spectrum regions of hydrodynamic and capillary turbulence of temperature fluctuations are shown with experimental estimation of threshold of thermocapillary effect of absorption as 1 MW/cm^2. The results of investigation can be useful for development of monitoring and quality control system of laser cutting process. The R-M-S of temperature fluctuations is greater than 10 K in the range of sub-millimeter capillary waves. Thus, an additional mechanism of the anomalous absorption on the front of cutting can compensate the low absorption of the metal in case of 10.6 μm laser in comparison with the absorption of the metal in the near infrared range.

Acknowledgement

The authors wish to thank the Russian Foundation for Basic Research for financial support (grant N 11-08-01094-a).

References

[1] M. Hansmann, I. Decker, J. Ruge (1987), On-line control of the laser cutting process by monitoring the shower of the sparks, Power Beam Technology, Brighton, England, 10-12 Sept. 1986, p.440-445

[2] P. Sforza, V. Santecesaria (1994), Analytical dependence of the roughness of the cut edge on the experimental parameters and process monitoring, in Proc. SPIE, Vol. 2207, pp. 836-847

[3] J. R. Duflou, E. Fallahi Sichani, J. De Keuster, J. -P. Kruth (2009), Development of a Real Time Monitoring and Adaptive Control System for Laser

Flame Cutting, ICALEO, LIA Publication N 102, Paper #1203

[4] F. Dorsch, H. Brauna, S. Keßlera, et al. (2012), NIR-camera-based online diagnostics of laser beam welding processes, in Proc. SPIE, Vol. 8239, 82390T1-11

[5] R. V. Grishaev, V. D. Dubrov, N. G. Dubrovin, Yu. N. Zavalov (2005), Using optical pyrometer in gas assisted laser cutting of steel sheets, J. of Guangdong Non-Ferrous Metals, 3, pp.635-637.

[6] V. S. Golubev, A. V. Dubrov, Yu. N. Zavalov, V. D. Dubrov (2010), Diagnostics of laser radiance penetration into material by multi-channel pyrometer, In: Thesises of 5th International Conference on Advanced Optoelectronics and Lasers (CAOL'2010), Sept. 10 - 14, 2010, Sevastopol, Ukraine, IEEE CN: CFP10814-PRT, pp.182-184.

[7] V. S. Golubev, R.V. Grishaev, V.D. Dubrov et al. (2008), On-line diagnostic in technology of the gas - jet assisted laser fusion cutting, in: Thesises of XIId International Conf. on Physical and Chemical processes in selection of atoms and molecula, March 31- Apr 4, 2008, Zvenigorod, Russia, TsNIIAtomInform: Moscow, ISBN 978-5-89513-133-6, pp.255-260 -in Russian

[8] A. V. Dubrov, V. D. Dubrov, Y. N. Zavalov V. Ya. Panchenko (2011), Application of optical pyrometry for on-line monitoring in laser-cutting technologies, Applied Physics B, 105, pp. 537-543

[9] V. S. Golubev (1995), Possible models of hydrodynamic nonstationary phenomena in the processes of laser beam deep penetration into materials, in Proc. SPIE, vol. 2713, pp.219-230.

[10] V. E. Zakharov, V. S. L'vov, G. Falkovich, [Kolmogorov spectra of turbulence I. Wave turbulence], Springer Series in Nonlinear Dynamics. Berlin: Springer-Verlag. xiii, 264 p. (1992)

[11] L. V. Abdurakhimov, M. Yu. Brazhnikov, A. A. Levchenko, L. P. Mezhov-Deglin (2008), Developed Capillary Turbulence on the Surface of Normal and Superfluid 4He, J. of Low Temperature Physics, 150, pp. 426-430

[12] F. Kh. Mirzoev, V. Ya. Panchenko, L. A. Shelepin (1996), Laser control processes in solids, Phys. Usp., vol. 39, pp. 1–29

[13] S. A. Akhmanov, V. I. Emel'yanov, N. I. Koroteev, V. N. Seminogov (1985), Interaction of powerful laser radiation with the surfaces of semiconductors and metals: nonlinear optical effects and nonlinear optical diagnostics, Sov. Phys. Usp. 28 1084–1124