Automatic system of temperature control at laser cladding

A F Glova\textsuperscript{1,4}, A Yu Lysikov\textsuperscript{1}, S S Nelyubin\textsuperscript{1}, I D Klochkov\textsuperscript{1}, L K Baldaev\textsuperscript{2}, Yu A Novinkin\textsuperscript{2} and M A Stogov\textsuperscript{3}

\textsuperscript{1}CA “State Research Center of Russian Federation Troitsk Institute for Innovation and Fusion Research”, Moscow, Troitsk, Pushkovykh st., 12, 108840, Russia
\textsuperscript{2}LC “Technological Systems for Protective Coatigs”, Moscow, Shcherbinka, Yuzhnaya st., 9A, 108851, Russia
\textsuperscript{3}LC “Advanced Magnetic Technologies and Consultations”, Moscow, Troitsk, Promyshlennaya st., 4, 108840, Russia

\textsuperscript{4}E-mail: afglova@triniti.ru

Abstract. An automatic system for monitoring the true temperature of the surface of a heated body based on a small-sized spectrometer has been developed and created. The system operates in real time with a speed of 30 ms. The system has been tested in laboratory conditions and tested in pilot production with laser cladding of metal powder.

1. Introduction
The complexity of the equipment used and the high quality requirements for products obtained at laser cladding or sintering the powder lead to the necessity to control the process in real time\cite{1,2}. The controlled parameters are the temperature of electrons in the plasma flame in the case of surfacing \cite{1}, the shape and quality of the next layer at visual observation \cite{3}, brightness \cite{4} or color \cite{5} surface temperature. Some of the developed systems are feedback systems (eg, \cite{3,5,6}). Temperature control is the simplest in technical design. However, the desire to control the true temperature leads to the necessity to use the emissivity data, which are unknown for most of the materials used.

The purpose of this work is to develop a system for real time temperature control without using the emissivity data and its application in laser cladding of powder.

2. System description

2.1. System diagram
The diagram is shown in figure 1. An image of a fragment of a heated sample 1 with a lens 2 is built on the entrance area of an optical fiber 3 and is transmitted to the entrance slit of a small-sized spectrometer with a diffraction grating 5. Mechanical translator 4 is used to change the area of the fragment. In a personal computer 6 with a specially developed program installed, spectra are processed, and the temperature measurement results in real time are displayed on the computer monitor and in the form of a binary code at the output connector of unit 7. The maximum speed of the system is determined by the speed of the spectrometer used and does not exceed 30 ms.
2.2. **Temperature measurement technique**

Temperature measurement is based on its calculation by expression [7]

$$ T = \frac{hc}{k} \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \frac{1}{\ln \frac{b(\lambda_1, T)\varepsilon(\lambda_1, T)}{b(\lambda_2, T)\varepsilon(\lambda_2, T)} + 5 \ln \frac{\lambda_1}{\lambda_2}} $$

where $h$ is Planck's constant, $c$ is the speed of light, $k$ is Boltzmann's constant, $\varepsilon(\lambda_1, T)$, $\varepsilon(\lambda_2, T)$ and $b(\lambda_1, T)$, $b(\lambda_2, T)$ are, respectively, the emissivity and spectral energy brightness for wavelength $\lambda_1$ and $\lambda_2$. Since the coefficients $\varepsilon(\lambda_1, T)$ and $\varepsilon(\lambda_2, T)$ as a rule are unknown, they were excluded in the calculations, setting $\varepsilon(\lambda_1, T) = \varepsilon(\lambda_2, T)$ for close wavelengths $\lambda_1$, $\lambda_2$, and instead of the ratio $b(\lambda_1, T)/b(\lambda_2, T)$ the ratio $I(\lambda_1, T)/I(\lambda_2, T)$ was used of the measured radiation intensities, which are proportional to the corresponding brightness [8]. To improve the measurement accuracy, it is possible to find the average temperature value for several pairs of close wavelengths $\lambda_1$, $\lambda_2$ selected from the interval $\Delta \lambda = \lambda_1 - \lambda_2 < \Delta \lambda = 50$ nm.

When developing the system it was assumed that it is sufficient to measure the temperature not exceeding $T_{\text{max}} = 3000$ K. The spectrometer chosen for measurements with a CCD rule sensitive up to $\lambda_{\text{max}} = 1$ μm corresponds to the measurements in the Wien region, since even for the indicated maximum values the inequality $T_{\text{max}} \lambda_{\text{max}} = 3 \times 10^4$ μm K $< h c / k = 1.5 \times 10^4$ μm K performs. Note that in paper [9] another method is presented for eliminating the unknown coefficient $\varepsilon(\lambda, T)$ when measuring the temperature in the Wien region with a spectrometer. It is based on measuring the brightness $b(\lambda, T)$ and plotting the dependence $\ln[\lambda^4 b(\lambda, T)] = \ln[2\varepsilon(\lambda, T)hc^2] - hc/(kkT)$. The existence of a linear section on the obtained dependence in a certain wavelength interval indicates the constancy of the coefficient $\varepsilon(\lambda, T)$ in this interval, which does not affect the slope of the section and the value of the temperature determined by the value of the slope.

The sensitivity of the pixels of the CCD rule of the spectrometer depends on the wavelength therefore the calibration of the spectrometer is necessary. The purpose of calibration is to obtain the dependence $\xi(\lambda) = b_0(\lambda) b_{\text{msl}}(\lambda)$, by which it is necessary to multiply the measured spectrum of the heated sample in order to obtain its real spectrum (here $b_0(\lambda)$ is the radiation spectrum of the standard lamp, $b_{\text{msl}}(\lambda)$ is the spectrum of the lamp measured by the spectrometer).

2.3. **Control program**

The program interface is shown in figure 2. In the upper right window 1 the currently measured radiation spectrum of the object is displayed. Using sliders 2,3 the wavelength values at the boundaries of the interval $\Delta \lambda$ are selected which displayed in windows 4,5. Next, the measured spectrum is multiplied by the calibration dependence $\xi(\lambda)$ and in the lower right window 6 the result of calculating the temperature according to expression (1) is given in dependence on the number of selected intervals $\delta \lambda$ designated as steps. The number of steps is set using the slider 7 and is shown in window 8. The temperature value averaged in steps is displayed in window 9. This averaged value is represented as a dot in the left window 10. For a family of measured spectra a continuous temperature dependence on time is obtained. In digital form it is the output signal of the electronic unit 7 in figure 1.
When we press the "Start" button a single spectrum is processed. In this mode we can pre-select the boundaries of the interval $\Delta \lambda$, the number of steps for it and estimate the value of the temperature averaged over steps. When the "Continuous" checkbox is checked the array of spectra is processed. The temperature dependence on time displayed in window 10 can be saved at any time by clicking on the "Save" button. To clear window 10 the "Reset" button is used. In the "Exposure time" window the selected time is set by the corresponding slider and cannot be less than the accumulation time of the spectrometer. When the "Auto tuning" checkbox is selected the exposure time is determined automatically.

3. **System testing in laboratory conditions**

Heating of the samples the temperature of which is to be measured is carried out by laser radiation. When heated to a temperature not exceeding the melting point, the system readings were compared with the results of thermocouple measurements. The thermocouple junction is welded to a flat surface of a vertical steel St.3 sample, this surface is directed to the lens 2 (see figure 1), the junction is centered relative to the optical axis. In the temperature range $(750-950)^\circ$C the system readings coincide with the thermocouple readings with an accuracy of 5%.

When measuring under conditions where surface melting is achieved, the thermocouple is not used. Samples in the form of plates made of steel St.3 or alloy ChS70U-VI are oriented horizontally. A stepwise laser heating is used with an increased laser radiation power at each subsequent stage with the same duration of each stage $\tau \geq 10$ s. The duration of the rise in power on the steps does not exceed 10 $\mu$s. The radius of the laser beam on the surface is equal to 5 mm. The choice of a stepwise heating method with relatively long step duration was dictated by the desire to obtain a horizontal section corresponding to melting in the dependence of $T$ on the laser radiation power $P$. The results of measurements for a plate of steel St.3 $1.5$ mm thick and $15$ mm in diameter at $\tau = 10$ s are shown in figure 3. The constant value $T = 1400^\circ$C at $P$ $=$ $(150-160)$ W in figure 3 corresponds to melting and agrees with the reference data [10]. Similar measurements were carried out for more massive samples of steel St.3. For the ChS70U-VI alloy with a thickness of 5 mm and transverse dimensions of 50 mm $\times$ 50 mm, the horizontal section on the dependence of $T$ on $P$ at $\tau$ $=$ $60$ s was obtained at $P$ $=$ $(1-1.1)$ kW and corresponds to a temperature of $T$ $=$ $1450^\circ$C.

Note that another evidence of the possibility of using this technique for measuring the temperature of heated bodies is the results of measuring the temperature of AlN particles moving in nitrogen at atmospheric pressure in the form of a free vertical jet and irradiated by a horizontal laser beam [11]. When the radiation intensity in the beam is close to the calculated value at which the particles evaporate, the measured temperature corresponds to the AlN evaporation temperature.
4. System testing in pilot production conditions

Figure 4 shows the connection of the optical elements of the system (objective 1 and spectrometer 2) to the nozzle unit 3 with a combined coaxial supply of powder, shielding gas and laser radiation. The nozzle block is mounted on the arm of the robot manipulator which is part of the laser cladding complex. The objective contains a shaping lens and output connector for connection with a fiber input. For alignment of the objective lens, coincidence is achieved on the plane under the nozzle of the spot of auxiliary laser radiation passing along the fiber and through the lens with the spot of adjusting laser of the nozzle unit. The spots alignment is achieved by rotating the console 4 along two angular coordinates in the adjusting unit 5. By moving the objective along the console 4, we can change the size of a fragment of the surface heated by laser radiation, the image of which is built on the input end of the fiber.

The system was tested with a stationary nozzle block. The radiation source is a Yb fiber laser with a pulse duration of 20 s. The size of the focusing spot of the laser radiation on the surface of the steel plate 6 is equal to 1 mm.
Figure 5 shows the time dependence of the plate surface temperature at $P = 400$ W in the absence of powder supply. In 1–2 s after switching on the laser, the temperature reaches an almost stationary regime and its value at a given power is less than the melting temperature during the entire heating cycle. A slight increase in temperature to the end of the cycle is associated with heating of the back side of the plate surface and partial reflection of the heat wave towards the front side [12].

![Figure 5](image)

**Figure 5.** Dependence of the temperature of the heating zone of the plate without melting on time in the absence of powder. $P = 400$ W.

The dynamics of temperature changes with the supply of powder at $P = 600$ W is shown in figure 6. We used Inconel-625 powder with a melting point (1290-1350)$^\circ$C, its feeding begins on the 2nd s.

![Figure 6](image)

**Figure 6.** Time dependence of the temperature of the melt zone when feeding Inconel-625 powder. $P = 600$ W.

After a transient mode associated with the formation of a bath of a powder melt, the surface temperature increases for a time $t = (7-10)$ s and then a monotonic decrease in temperature occurs until the end of the pulse. The mentioned increase in temperature may be a consequence of a decrease in the rate of heat removal into the base due to an increase in the deposition height. To maintain a constant temperature value it is necessary to promptly decrease the laser radiation power by introducing
feedback into the channel “surface temperature - radiation power” (see, for example, [6]). For the development of work in this direction the electronic unit 7 in figure 1 is used. The decrease in the measured temperature in the time interval \( t = (10-20) \) s is a hardware-controlled effect. Since the stationary nozzle unit does not track the change in the distance between the nozzle exit and the melt surface during surfacing, the spectrometer receives radiation from the cooling fragment of the surfacing localized near the surface of the plate 6 which over time does not overlap with the melt surface with a higher temperature.

5. Conclusions
An automatic system for real time control of the temperature of a heated surface has been developed and created. System readings agree well with thermocouple measurements and melting point reference data. The system was tested in a pilot production with laser cladding of metal powder.

Acknowledgments
We thank the staffer of LC "TSPC" A.A. Matsaev for help in testing the system.

References
[1] Ya W, Konuk A R, Aarts R et al 2015 J. Mater. Proc. Technol. 220 276
[2] Everton S K, Hirsch M, Stravloulakis P et al 2016 Materials and Design 95 431
[3] Hofman J T, Pathiraj B, van Dijk J et al 2012 J. Mater. Proc. Technol. 212 2456
[4] Doubenskaia M, Bertrand Ph and Smurov I 2004 Thin Solid Films 453-454 477
[5] Salehi D and Brandt M 2006 Int. J. Adv. Manuf. Technol. 29 273
[6] Bi G, Sun C N and Gasser A 2013 J. Mater. Proc. Technol. 213 463
[7] Lebedeva V V 1977 Optical Spectroscopy Technique (Moscow: Moscow State University Press)
[8] Malyshev V I 1979 Introduction to Experimental Spectroscopy (Moscow: Nauka Press)
[9] Magunov A N 2009 Instrum. and Experim. Tech. 4 5
[10] Kikoin I K 1976 Tables of Physical Quantities (Moscow: Atomizdat Press)
[11] Glova A F, Lysikov A Yu, Nelyubin S S, Peretyatko P I, Ryzhkov Yu F and Turundaevskii V B 2016 J. Phys.: Conf. Ser. 751 012026
[12] Duley W W 1986 Laser Processing and Analysis of Materials (Moscow: Mir Press)