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Optical monitoring and control in laser additive technologies

Yuri Chivel*

MerPhotonics,42100 Saint Etienne, France

Abstract

Advanced methods and systems for monitoring and control of laser additive technological processes in real time are designed and implemented. Precision control of the main physical parameters of these processes – maximum surface thermodynamic temperature , temperature distribution in the processing area , size of the melt and control their evolution are necessary. Also control of quality and geometric dimensions of 3D object is implemented using 2D image scanner.

Keywords: laser additive technologies, optical monitoring and control, thermodynamic temperature, melt pool dimensions, dimensions of 3D object ;

1. Introduction

Now the development of monitoring and control systems for monitoring and control of laser additive technological processes in real time are in progress. Precision control of the main physical parameters of these processes – maximum surface temperature , temperature distribution in the processing area , size of the melt and control their evolution are necessary. Also control of quality and geometric dimensions of 3D object are exceptionally significant.

Our elaborated methods and system allows control all parameters of the laser melting/sintering process - temperature distribution in processing zone with melt pool dimensions determination using a high speed digital CCD – camera and maximum temperature measurements by pyrometer, quality of the powder layer supply as well as geometric dimensions of 3D object using 2D image scanner , thus enabling full control of the technological process in real-time mode.

Growing demands on the quality of sintered product require reliable methods to monitor and optimize

* Corresponding author. Tel.:+330605611846;.
*E-mail address:*yuri.chivel@gmail.com.

the sintering process. In most papers [1-3] the evolution of the optical emission from the melt in one or more spectral range was recorded and the process was monitored from the level or character of the optical signal. There are only some papers [4-6] in which surface temperature was measured. Temperature at the top surface of the powder layer has been measured with the help of a pyrometer [4,5] or an infrared camera [6] . В работах [4,5] использованы coaxial sensor pyrometer systems. The spatial resolution at these measurements did not exceed 0,3-1mm as the focal plane in this experiments did not flat and time resolution was ~ 1 ms.

However for the precision control of the SLS/SLM processes the measurements of the main parameters of these processes – maximum surface temperature , temperature distribution in the processing area , size of the melt and control their evolution with spatial resolution 10-100 µm and time resolution not more 1-10мкс are necessary. The system was developed [7-8] for monitoring of temperature distribution in laser irradiation zone based on registration using a high speed digital CCD – camera and maximum temperature measurements in laser spot by pyrometer. Using a calibrated pyrometer and camera allows to fully control the process of sintering/ melting. Also the principles of measuring the surface temperature of powder bed in the focal spot of the laser radiation while scanning the surface using galvoscanner with F-teta lens have been designed [9].

2. Method and apparatus of the temperature measurements

To ensure the flatness of the focal surface when scanning with the help of galvanoscanners F-teta lens are used. The galvo scanner systems have a selective character of reflection depending of wavelength and angle of rotation , that must be take in account in deciding on a spectral range of temperature measurements. Also custom made F- teta lens are not achromatic usually. That causes image shift in coaxial set-up sensor positioning systems between the laser focus spot and its image at a wavelength different from the laser one (fig.1).

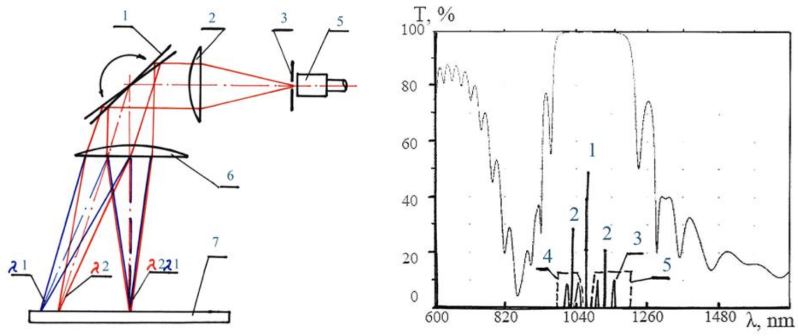

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Fig. 1. (a) Scheme of temperature measurements:
1- scan mirror; 2- lens ; 3- diaphragm 5 – pyrometer fiber; 6- F-teta lens ; 7- powder bed.
(b) - transmisivity of the scanner mirror:
1 – laser line ; 2 , 3 – lines of thermal radiation separated by filters.4,5 – lines of thermal radiation registered by CCD- camera.

This shift increases with the distance from the center of powder bed (~1 mm at distance 40 mm for 400 nm and 1064 nm laser wavelength) which leads to measurement errors if the temperature measurement is carried out correctly that is in a small region of the laser spot in the area of 20 - 100 microns.

2 D sensors (CCD) are more tolerant to such shifts and this is its major advantage over single spot sensors. But for the continuous control of melting process the measurement of maximum surface temperature with high accuracy in the heat affected zone is more preferable for manufacturing facilities. In principle, the F-teta lens can be colour corrected but only at a single wavelength and this greatly increases the price of the lens. Also standard scanner mirrors have the reflection band with width of about 250 nm centered at a wavelength of the laser (fig.1) and measurement outside this band leads to large losses in the sensitivity of the measurements.

The principles of measurements was devised [9-10] (fig.1) and special optical schemes was designed to minimize image shift [11] . Measurements are carried out at wavelengths close to laser wavelength which are prominent using a gradient type dichroic mirrors and filters (fig.2) .

The main optical elements of the scheme – gradient mirrors – pos.2. Laser radiation are fully reflected by central region of the mirror while circumference region are fully transparent in wide wave band.

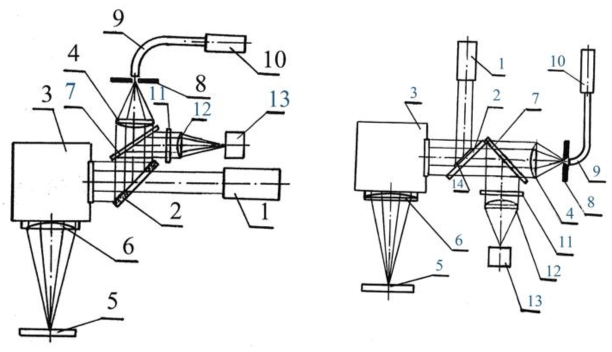

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Fig. 2. Variants of an optical scheme of the inventive device for optical monitoring.
Where 1 is a laser, 2 - rotary mirror, 3 – galvanometer scanner, 4 – lens, 5 - the surface being treated , 6 - F-teta lens,7 - dichroic mirror , 8 - the diaphragm of pyrometer , 9 - fiber , 10 – pyrometer, 11 – filters, 12 – lens, 13 – videocamera.

The device operates as follows. Radiation of laser 1 passes through the central area of the rotary mirror and is introduced onto galvanometer scanner mirror 3 and using F-teta lens 6 focuses on the surface 5 . When scanner mirrors rotate laser focus is moved over the surface 5 . Image of the focal region is projected on the diaphragm of the pyrometer 8 with F-teta lens and lens of the pyrometer 4. Pyrometer 10 detects the thermal radiation of the heated surface in narrow spectral regions from small surface area defined by the size of hole of diaphragm.

Using the lens 12 and F-teta lens image of the surface at a wavelength of filter 11 is recorded by camera 13 . The laser light is passed through central elliptical region with 100% transmittance . Since the measurements are made at wavelengths near the line of the laser , the small chromatic aberration of the F-teta lens will lead to negligible shift the image on the diaphragm of the pyrometer and minimal distortion of the image recorded by videocamera occurs.

That makes it possible to measure maximum temperature in laser spot and construct the distribution of the brightness temperature of the surface in the area of treatment. Multichannel pyrometer with 4 number of channels allows determine the emissivity of the surface, which allows to get distribution of the thermodynamic temperature .

A multi-wavelength pyrometer (fig.3) with time resolution 50µs and spatial resolution 50 µm based on InGaAs photodiodes registers the surface thermal radiation on two wavelengths in the range 900- 1300 nm. The image of scanning area with diameter 130 µm is rendered on fiber diaphragm 9, diameter of which 100 µm fixes the area of signal integration. The photodiodes signals are amplified ($k = 10^6$) and gated with the variable frequency and gate duration. The maximum brightness and thermodynamic temperature in the melting zone can be displayed.

3. High speed multiwavelenght pyrometry

To measure the thermodynamic temperature of objects with unknown emissivity, methods of polychromatic pyrometry are used . Recently pyrometers based on CCD matrices with the number of spectral channels up to 10^3 have found application. But the speed of reading information in such a pyrometer is not higher than 10^{-3} s. In laser technology selective sintering and surfacing should provide a temporal resolution of 10-100 µs, which can be achieved using high-speed photodetectors with a limited number of measuring channels. It was shown earlier that when the emissivity is represented as a polynomial in the wavelength, the thermodynamic temperature can be obtained as a function of the N values of the measured radiation intensities. In the works [11] it is shown that the instrumental error of temperature determination increases with the increase of the number of channels and even with an error of measuring intensity less than 1% it is not practical to use more than 4 channels. It is optimal to use N groups of 3 channels with the subsequent determination of the mean value, which reduces the instrumental error by $N^{1/2}$ times. In this case under logarithmic approximation of emissivity and Vin approximation of a intensities we have:

$$\ln\varepsilon = a+b\lambda$$
$$\ln I_1 = a_0 + a_1 \lambda_1 - C_2/\lambda_1 T$$
$$\ln I_2 = a_0 + a_1 \lambda_2 - C_2/\lambda_2 T$$
$$\ln I_3 = a0 + a_1 \lambda_3 - C_2/\lambda_3 T$$

Hence, we obtain the temperature value for each group of 3 channels by the method of least squares and determine the average value - the optimum thermodynamic temperature.

The main problem in measuring the surface thermodynamic temperature, determination surface emissivity, has been solved by measuring the brightness parameters of surface with high spatial (50 um) and time (50 us) resolution at 4 wavelengths followed by calculation the thermodynamic temperature by method of optimal pyrometry using software in real-time (Table 1):

Table 1. The multiwavelength high speed pyrometer with high temporal resolution provide following performances

1	Operational temperature interval, K	800 - 3500
2	Number of spectral channel	4
3	Working wavelengths (channel 1- 4), nm	1150, 1248,980,920
4	Instrumental uncertainty of brightness temperature measurements,%	+- 0.5
5	The measuring time , µs	20 - 200
6	Optical fiber diameter ,µm	50
7	Optical fiber length , m	5
8	The measuring distance ,mm	50
9	Spatial resolution, µm	50
10	Type of interface	RS485
11	Start-up time, min	10
12	Power	110-120 V, 50 - 60 Hz
13	Power consumption, W	30
14	Dimensions, (DxHxW) , mm	250x225x 110
15	Weight, kg	4

Pyrometer has built internal calibrator that allows calibrate optical channels of the pyrometer without black body.
The software allows to measure the brightness temperature of the object at 4 wavelengths and to calculate the value of the thermodynamic temperature.

The multiwavelength pyrometer viewes are shown in the photo 3 .

a b

Fig. 3. Control unit with optical head-(a). Rear panel of the control unit – (b).

Pyrometer consists of a control unit and optical head.
Optical and electronic components of the control unit placed in a metal case closed by sliding cover. The controls are located on the front and the rear panel of the case .Optical head of the pyrometer is connected to the control unit using fiber cable with fiber diameter 50 μm and 5 m long.

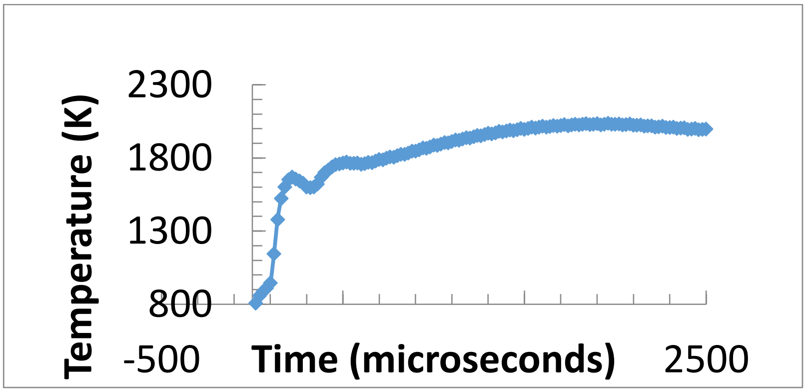
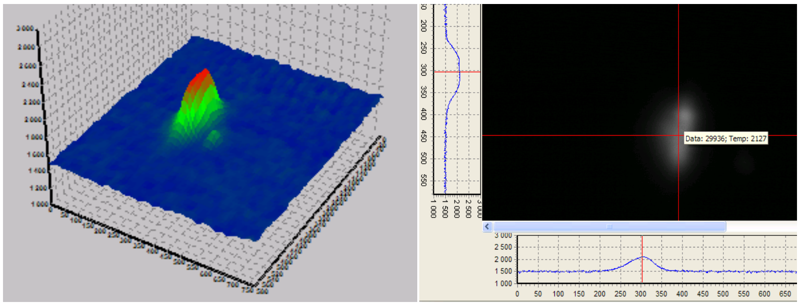


Fig. 4. Test of the pyrometer. Melting of AISI 403 steel by pulsed laser radiation.

4. Measurements of the temperature distribution

Since a photodetector can accurately record the temperature only in a small focal region but with a high time resolution for recording the temperature distribution in the laser exposure region 2D – sensors on the base of CCD or CMOS camera[12] are used.
The system for monitoring temperature distribution in laser irradiation zone is based on high speed

digital CCD - camera. The image of the melting zone with a five time magnification is projected onto the matrix plane of digital CCD camera through interference filter with 100 nm шириной на длине 900 нм and spatial brightness temperature distribution is determined (fig. 5a,b).



a. __ 100 µm b.

Fig. 5. (a) - Spatial distribution of brightness temperature at the irradiation spot in selective laser melting. Powder - Cu.P= 80W. Laser spot size -100 µm; scan speed -100mm/s, (b)- Spatial profiles of brightness temperature at the irradiation spot.

Time resolution of the system – 50 µs ,spatial – 20 µs. As the maximum thermodynamic temperature have been valued by pyrometry it is possible to have temperature distribution from brightness temperature distribution.

4.1. Calibration

All temperature sensors calibration is performed by using a W- halogen lamp with a transmitting diffuser. Lamp diaphragm 1 mm in diameter is housed in the laser spot at powder bed (fig.5c). Previously lamp was calibrated with a black body model in the temperature range 1200- 1800 K. Nonuniformity of the temperature distribution over the area of the diaphragm does not exceed 5 K.

5. Practical implementation of the optical monitoring systems

SLM experiments [13,14] were carried out on PM 100 machine using single-mode continuous-wave Ytterbium fiber laser operating at 1075 nm wavelength (IPG Photonics Corp.). The laser beam had a TEM_{00} Gaussian profile, 70 µm spot size, and 200 W maximum power. Argon and nitrogen was used as a protective atmosphere in all experiments

In these experiments, a some layer of Cu (25-50 µm), CoCr and 316 steel powder was used. The thickness of the powder bed was 3 mm. Layers were scanned with scan shift 30 µm which ensured the creation of a thin layer of the melt. Only one cross- section 100 x 100 mm^2 was scanned with the scan speed 100 mm/s.

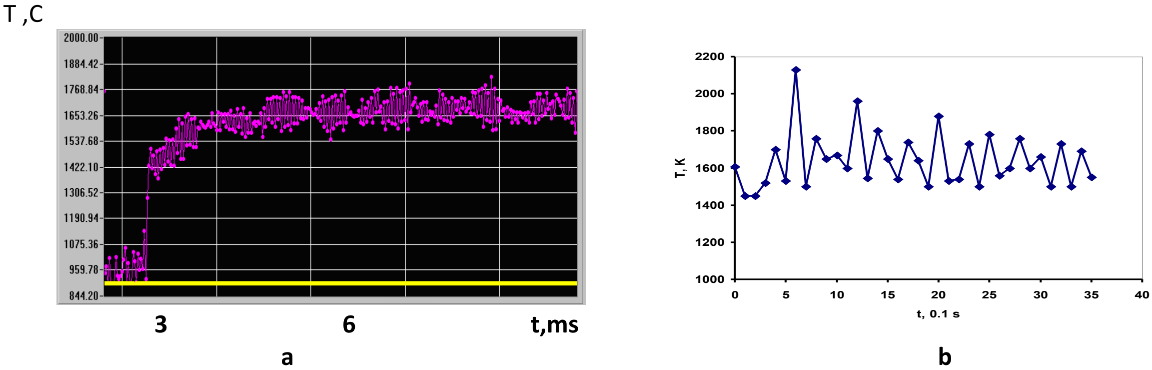


Fig. 6. Temperatures in melted area: (a) Pyrometer data; (b) CCD data. Material - CoCr, P= 80W. Scan speed 100mm/s

Direct temperature measurements during the standard selective laser melting process of the 3D object from steel 316L powder have been conducted. In these experiments, a layers of 50 µm thickness of 20 µm powder in diameter were scanned with velocity 100 mm/s and shift 120 µm. All layers were scanned doubly. Temperature measurements during all process showed that temperature in the focal spot 100 µm in diameter did not exceed 1800-1900K (Fig.7), Melt overheating was absent. . This mode of SLM process can be considered as optimum

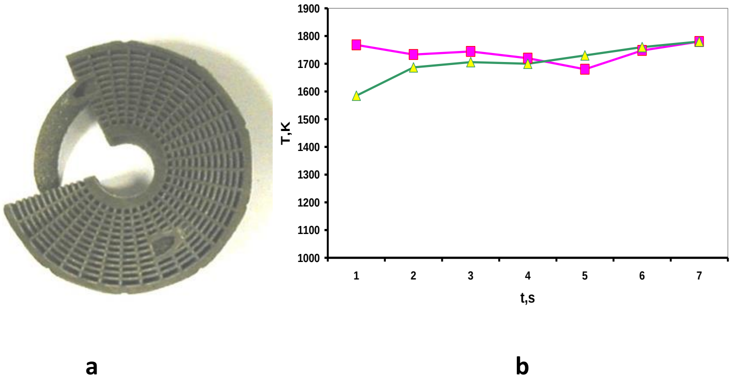
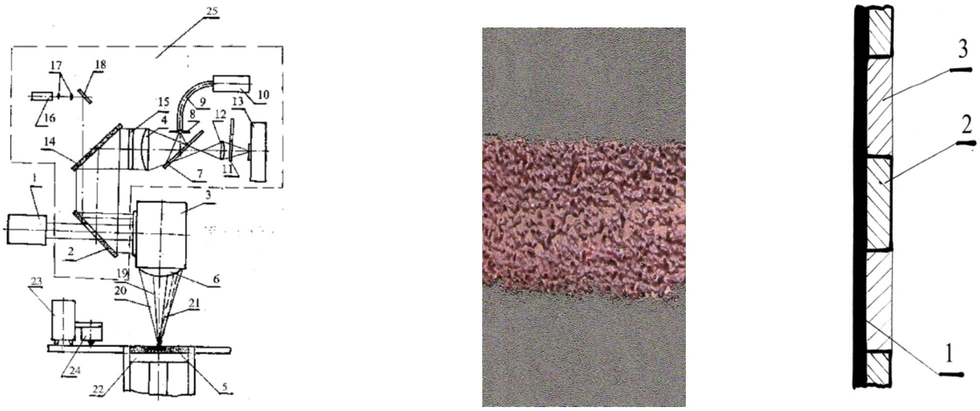


Fig. 7. 3D object selective melting : (c) – 3D object, (b)- Maximum melt temperature in focal spot : □ – first scan , Δ - second scan. 316L steel powder

6. 3D object quality control

For precise control of dimensions and quality of the 3D – object in the process of selective laser melting the new method and apparatus have been elaborated [13]. The process of melting is monitoring by measurements temperature distribution in laser irradiation zone using a high speed digital CCD – camera and maximum temperature in laser spot by pyrometer.

For monitoring of dimensions and quality the 2D scanner head is housed on re-coater powder feeding system (fig.8a). After sintering of each layer of the 3D object, when applying the next layer of powder, the image of the sintered layer is registered by scanner with a resolution of up to several microns [14]. The image is compared with the program-specified section and the exposure parameters (laser power, speed and the laser spot scanning software) can be adjusted before sintering the following layer. Also a quality of applied powder layer is controlled when re- coater moves back.



a. b c

Fig. 8. Optical monitoring system – (a), test of powder feeding-(b), test object –(c). 1- Inox powder, 2- sintered layer of Cu-powder, thickness- 400 µm. Scan resolution – 600 dpi.
1 - laser, 2, 18 - rotary mirror, 3 – galvanometer scanner, 4 – lens, 5 - the surface being treated , 6 - F-teta lens, dichroic mirror -7 , 8 - the diaphragm of pyrometer , 9 - fiber , 10 – pyrometer, 11 – filters, 12 – lens, 13 – videocamera, 14 – dichroic mirror , 15- filter , 16 –illumination laser ,17- telescope, 19 – housing, 22- piston , 23- re-coater , 24 – 2D image scanner.

moves back. Using 2D image scanner it is possible to obtain spatial resolution up to 10000 dpi, which is unattainable by other devices.

A illumination source 16 for backlight of the surface whose radiation using a telescope 17 and rotating mirror 18 and mirror 2 is introduced into galvanometer scanner and focuses in the treatment area. The surface image at source wavelength is constructed using the F-teta lens and lens 4 in the plane 12 of the matrix of videocamera 13 through the filters 11 which allocates either illumination laser radiation or thermal radiation of the surface.

Results of 2D scanner test applying for powder feeding on test object (fig.8b,c) are presented.

7. Conclusion

An elaborated and implemented optical methods and systems allows control all parameters of the laser melting/sintering process - temperature distribution in processing zone with melt pool dimensions determination using a high speed digital CCD – camera and maximum thermodynamic temperature measurements by pyrometer, quality of the powder layer supply as well as geometric dimensions of 3D object using 2D image scanner , thus enabling full control of the laser technological process in real-time mode.

References

[1] Kruth J.-P., Froyen L., Van Vaerenbergh J., Mercelis P., Rombouts M., Lauwers B.,2004 *Selective laser melting of iron-based powder.* Journal of Materials Processing Technology, Vol. 149, Issues 1-3, p.616.

[2] Craeghs T.; Bechmann F.; Berumen S.; Kruth J.-P. 2010. Feedback control of layerwise laser melting . In Physics Procedia, 5, p.505.

[3] Kruth J.-P., Mercelis P., 2011.Procedure and apparatus for in-situ monitoring and feedback control of selective laser powder processing. Patent EP 2 032 345 B1.

[4] Benda, J.A. 1994. Temperature-Controlled Selective Laser Sintering, Proc. of the SFF Symposium , University of Texas, Austin, Texas, USA. p.277 .

[5] S. Ahn, J. Murphy, J. A. Ramos, K. Wood, J. J. Beaman. 2002.Real-time measurement of temperature for control of laser surface modification process. , Proc. of the SFF Symposium , University of Texas, Austin, Texas, USA.p.150 .

[6] P. Fischer, M. Locher, S. Kolossov, R. Glardon, V. Romano, H.P. Weber.2004. Temperature measurement during selective laser sintering of titanium powder, International Journal of Machine Tools and Manufacture, 44 .p. 1293.

[7] Chivel Yu., Smurov I., Laget B. 2009. System for monitoring laser technological processes . Patent RU № 2371704 .

[8] Chivel Yu. 2010. Method and device for measuring the surface brightness and colour temperature in the area of the laser irradiation. Patent № 2460992.

[9] Chivel Yu., Smurov I. Temperature monitorig in selective laser sintering/ melting// Physics Procedia , V.5. pp. 515- 521. 2010

[10] Chivel Yu., Smurov I. 2011 . Temperature monitoring and overhang layer problem // Physics Procedia , v.12, part 1, pp.

[11] Snopko V.1999. Basics of a methods of pyrometry . NAS Belarus, p. 201. 12.Chivel Yu. 2012. Investigations of the temperature regimes of the selective laser melting . Proc. SPIE, v. 8433, p.340.

[12] Yu.Chivel. On-line temperature monitoring of the selective laser melting ,2013. Physics Procedia , 41, 897

[13] Chivel Yu. 2014. Method and device for optical monitoring and control the process of selective laser sintering 3D object from powders. Patent RU № 2640030 , WO 201512730,EP

[14] Chivel Yu. 2016. New approach to multi-material processing in selective laser melting. Physics Procedia . 83. p.89.