SLS-PROCESS MONITORING AND ADAPTIVE CONTROL

A monitoring system was developed to control the process of Selective Laser Sintering (SLS). Surface temperature distribution at the sintering zone was registered by the spectral ratio method using a two-channel spectral high-speed intensified video camera and two wavelengths pyrometer. Deviation of maximum surface temperature from its optimal value was chosen as a criterion for the express method of quality control.
Principles of adaptive control of the sintering of two powder layers (particle size about 100 μm) by pulsed-periodic laser radiation in directed mode are discussed.

Introduction

At latest years a methods and apparatus for surface temperature monitoring during laser machining are developed [1, 2]. Next step is the development of appropriate monitoring systems and their integration with laser technological equipment. In the present paper the development of a monitoring system adapted for SLS-process and basics of real time adaptive SLS-process control are discussed.

The SLS-systems are intended for sintering a wide range of materials with greatly different properties including melting point. To control the correct choice of process parameters and to visually inspect the process quality, a Monitoring System for the Sintering Process (MSSP) was designed and fabricated. The monitoring of the sintering process is based on measurements of temperature distribution at the sintering zone by the spectral ratio method. The maximum surface temperature is calculated from the measurements of two wavelengths pyrometer and its values are used for the express control of manufacturing quality.

Fabrication of medical implants with a given value of porosity from Ti allows is one of the actual applications of SLS technology. Utilisation of particles with relatively large size (100-200μm) provides certain advantages to obtain regular porosity. It was found that about 85 % of laser radiation is absorbed in the first two powder layers. In this case laser beam should be directed at the contact points between the particles. The principles of adaptive SLS process supported by real-time optical monitoring are developed.

1. SLS- process monitoring system

MSSP implements the following functions:

- visual observation of the sintering zone;
- measurements of the surface distribution of brightness temperature at the sintering zone;
- pyrometer measurements and further calculation of the maximum temperature for on-line express control.

MSSP [3] consists of a visual observation system (VOS), a special Intensified CCD–camera (ICCD) and a two-wavelength pyrometer (TWP). VOS, ICCD, TWP and the overall optical scheme of MSSP compose an opto-mechanical unit which is arranged in a separate box and integrated with the optical system of originally developed SLS-machine (**Fig.1**).

Pulsed-periodic Nd:YAG laser with the following parameters was used for SLS of Ti powder with 100 μm size : Average power is 150 W, maximum power is 600 W, pulse duration is in the range 0.5 – 6 ms, beam spot size is 150-200 μm.

***Fig.1:** Opto-mechanical unit for process monitoring and on-line control of the SLS machine.*

1. 1 Visual control system

To discern defects of the deposition of the powder layer, to verify the position of laser scanning head and to control production quality, the visual observation system (VOS) continually monitors a 30 by 30 mm zone on the surface of the powder bed. VOS is efficiently protected from laser radiation and surface thermal radiation by a system of filters and dichroic mirrors (~ 10^{11} contrast).

The surface illumination is carried out using the Light-Emitted Diode (LED) ringlight system. The intensity of scattered LED's radiation at the video camera matrix exceeds the intensity of laser scattered radiation and the intensity of surface thermal emittance except the laser impact zone (**Fig.2**).

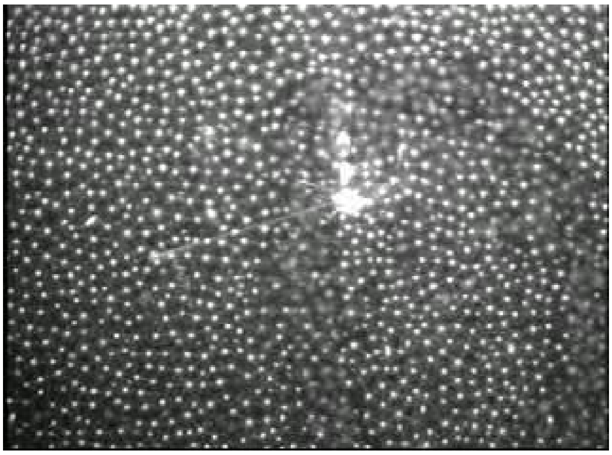
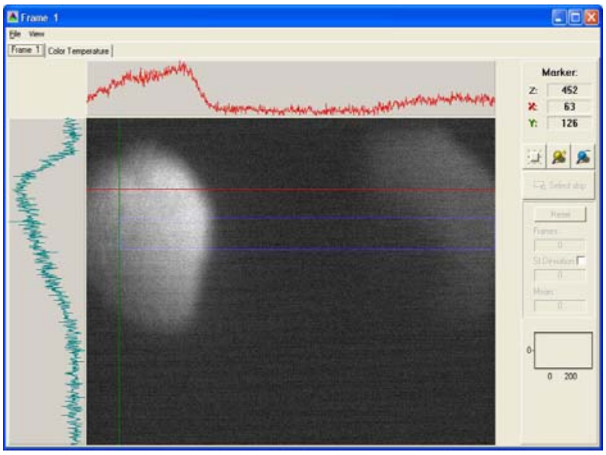


Fig. 2: *Image of the sintering process of 100 μm Ti-powder by visual observation system.*

1.2. System for temperature monitoring

The image of the sintering zone with a five times magnification is projected onto the photocathode plane of a gated microchannel plate (MCP). Wavelength bands of λ_1 = 0.55 μm and λ_2 = 0.7 μm (spectral band width is 20nm) are spatially separated when radiation passes through a prism and thus two images are obtained (**Fig.3).** The left image is recorded at λ_2 = 0.7 μm, the right one (with low intensity) at λ_1 = 0.55 μm. The intensity profiles along the selected straight lines (horizontal and vertical ones) can be measured (see the curves left and up). By this way the ratio of intensities at two wavelengths are obtained and colour temperature can be calculated.



Z: 452
X: 63
Y: 126

Fig.3: *Spatial distribution of thermal radiation intensity at two wavelengths (left image is recorded at λ_2 = 0.7 μm and right image is recorded at λ_1 = 0.55 μm) and intensity profiles along the selected straight lines.*

MCP with accusation period of 20-1000 μs is switched on at a predetermined instant relatively to the laser pulse. The resulting images of the digital video camera are scanned and colour temperature is calculated. Temperature distribution in the sintering zone is displayed with spatial resolution ~ 2 μm (**Fig.4**).

K= 0,04 Shift = 570 Row = 291 Smooth window = 11

☑ Autoscale 400

☑ Autoscale 0

X= 0 Y= 2454,53

Fig. 4: *Spatial profile of recalculated colour temperature at the irradiation spot.*

It should be noted that the video camera cannot provide the video-display processing at 50-100 Hz frequencies. In order to continuously monitor the values of maximum surface temperature (that is temperature in laser irradiated zone), a two-wavelength pyrometer based on two photodiodes registering the surface thermal radiation is fixed inside the opto-mechanical unit. The photodiodes signals are gated and the maximum colour temperature in the sintering zone is displayed on the monitor in digital format.

In is found that the value of maximum temperature is rather sensitive to detect deviation of SLS parameters from its optimum values. For example, the sharp temperature increase and its instability indicate that energy input per unit length of sintered line should be decreased.

The pyrometer calibration is performed using a temperature lamp the filament of which is housed in the focal plane of the focusing objective.

2. Principles of adaptive SLS process supported by real-time optical monitoring

In the present study, the adaptive method of the sintering of two powder layers by pulsed-periodic laser radiation in directed mode is proposed. As it was shown by numerical simulation [4], the optimal sintering regime, which is without particles melting, implies the directed focusing of the laser radiation at the space between the particles of the upper layer. This kind of a “redistribution” of the pulse energy in the powder layer provides an optimal surface heating of the particles contact areas and preserves porosity. Also it allows reducing laser power by 5-times [4].

Initially, the laser focus spot is moved over the surface along computer-programmed equidistant curves. Images of the digital video camera are identified in real time and coordinates of the points of laser action are determined. According to the determined coordinates, the points of laser impact are varied in real time under the conditions of 50 mm/s laser spot velocity and 50 Hz laser pulse frequency.

Real time treatment of digital image plays a decisive role in this technology. It is known that an object is identified via a set of its features such as colour, geometry, etc. In the present study statistical segmentation algorithms based on cluster analysis of image pixels were used [5].

The input data is a binary image. The filter parameters are the size and the form of the structuring element, the number of filter passes, the filter threshold value or the value of erosion and the dilatation thresholds if different threshold values are used.

After mathematical morphology filtering, segment measurements are carried out. Segment measurements allow obtaining information about segments shape and size that are semantic features of the segments. That is to identify objects under analysis [6]. The obtained results are represented in **Fig. 5**.

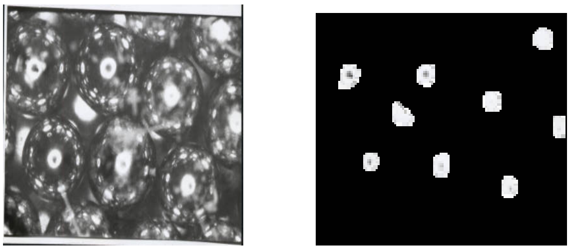

(a) (b)

***Fig.5:** Top image of the two consecutive powder layers, (a) and result of the image segmentation and the semantic filtering, (b).*

Estimations of the rapidity of the processing algorithms show that the software based on linear consecutive algorithm does not allow realising of continuous sintering process because of the excessive time needed for identification and calculation of coordinates of the laser impact points.

For this reason the parallel mainstreaming of the algorithm is used. The software contains three independent streams:

- 1st stream to define coordinates of the scanning laser head (CSLH);
- 2nd stream for image treatment and calculation of coordinates of laser impacts (CLI);
- 3rd stream for scanning mirror control (MC).

The first stream ensures the movement of scanning laser head along its trajectory and the calculation of movement vector. The second stream captures the frame and performs identification and calculation of coordinates of the points of the laser impact. The third stream permits to turn the mirror in order to move laser beam to the calculated points.

By limiting the laser pulse frequency (< 50 Hz), laser action points are calculated based on the frequency of operation f and the powder particles diameter d.

At the most compact packing of the powder particles – hexagonal configuration - the number of laser action points on one particle equals 6 and maximum CSLH speed is

$$V=d\cdot f/6 \qquad (1)$$

at $d = 600\mu m$, $f = 50Hz$ comes to 5 mm/s.

. The following procedure is used to calculate the coordinates of laser impact points. Geometrical centres of the triangles with vertices lying at a distance within 1.2 of the particles diameter from the motion axis are determined (**Fig.6)**. Of all the centres the points lying at a distance within 0.7 of the particles diameter from the motion axis are selected.

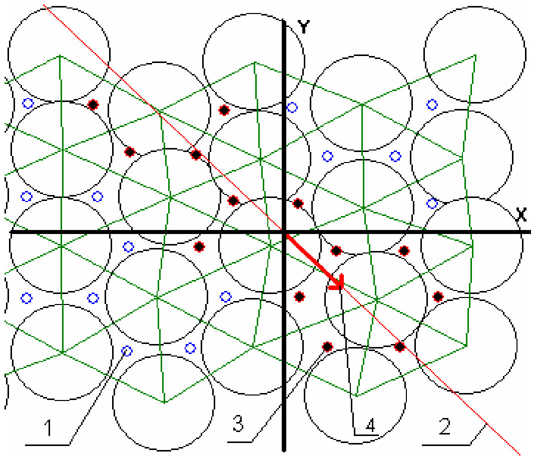


Fig.6: *Visualization of the results of the computation algorithm:*
1- sintering points; 2 – CSLH trajectory; 3 – laser impact points; 4 - CSLH movement vector.

Let us assume that at the moment of identification, *n* points with coordinates (*Xn,Yn*) are determined along the FOCS movement vector (**Fig.6**). At the instant of laser irradiation, the new coordinates of the points are:

$$X'n = Xn - Vx\cdot(n-1)/f\,;$$
$$Y'n = Yn - Vy\cdot(n-1)/f; \qquad (2)$$

were (*Vx,Vy*) is the velocity vector.
Transmission of the coordinates from the 2nd stream to the 3rd stream is realised using the approach "First In and First Out" (FIFO). At the instant when the only one point remains in queue, the 2rd stream turns on and a new point data are added to the queue. The new velocity vector ($V'x$, $V'y$) and the removal of the residuary points along the old displacement vector must be taken into account:

$$X''n = Xn - V'x\,(n-1)/f\; - Vx/f\,;$$
$$Y''n = Yn - V'y\cdot(n-1)/f - Vy/f\,; \quad (3)$$

Furthermore, the operational cycle is repeated up to the end of the trajectory.

Conclusion

The original optical monitoring system is developed and applied for on-line control in SLS. It consists of two-channel spectral high-speed intensified video camera, two wavelengths pyrometer and LED illumination source. The system provides the possibility to visualise the regularity of powder bed deposition, the progress of sintering process and its results (layer by layer), the spatial distribution of brightness temperature at two wavelengths and selected temperature profiles, the calculation of colour temperature and express analysis of possible deviations of maximum temperature from its optimal value.

Principles of adaptive control of the sintering of two powder layers (particle size about 100 µm) by pulsed-periodic laser radiation in directed mode are proposed. The algorithm is based on real time treatment of digital image to define the points of laser impact.

Bibliography

[1] Smurov I. Pyrometry applications in laser machining // V. Veiko (Edit.) Laser-Assisted Microtechnology 2000, Proceedings of SPIE, v. 4157, 2001, pp.55-66.

[2] Ignatiev M. , Smurov I., Flamant G. Surface temperature dynamics during pulsed laser action on metallic and ceramic materials, Applied Surface Science, vol.96-98, 1996, pp.505-512.

[3] Chivel Yu. , Uzunbadjakov A., Zatiagin D.Automated Complex for SLS-process Monitoring. Proc. V Int.Conf.Beam Technologies and Laser Applications.2006.108.

[4] Yu. Chivel, M. Petrushina, E. Pogudo. Modelling of spherical powders sintering by pulsed laser radiation. High Temperature, 2006, 44, № 1, 148-152.

[5] M. Voganti, F. Ercal, C. Dagli, S. Tsunekawa. Automatic PCI Inspection Algorithms: A Survey, Computer Vision and Image Understanding, 1996, 63, 287-313.

[6] Chivel Yu., Inyutin A., Vatkin M., Zatiagin D. Real Time Technology of Laser Sintering. Proc. Int. Conf. Real Time Technologies.2005.112.