SLS-process monitoring and temperature control

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Abstract

A monitoring system is developed to control the process of Selective Laser Melting (SLM). Visualisation is carried out at different scales; surface temperature distribution at the sintering zone is registered by the spectral ratio method using a two-channel spectral high-speed intensified video camera and a two-wavelength pyrometer. Deviation of maximum surface temperature from its optimal value is chosen as a criterion for the express method of quality control.

Keywords: Optical monitoring, selective laser melting, pyrometry, temperature control

1. Introduction

Methods and apparatus for surface temperature monitoring in laser machining were developed some years ago [1-6]. The next step is to develop appropriate monitoring systems and integrate them with laser technological equipment [7, 8]. In the present paper, development of a monitoring system adapted for SLM-process, and basics of real-time adaptive SLS-process control, are discussed.

SLS/SLM-systems are intended for sintering a wide range of materials with greatly different properties, including melting point. To control correctness of the choice of process parameters and to visually inspect process quality, a Monitoring System for Sintering Process (MSSP) was designed and fabricated. Its operating principle is to measure temperature distribution at the sintering zone by the spectral ratio method. Maximum surface temperature is calculated based on measurements of a two-wavelength pyrometer, and values obtained are used as criteria for express control of manufacturing quality.

2. Experimental set-up

Selective laser melting (SLM) is a manufacturing process where parts are made directly from 3D CAD data without any special tooling. Scheme of the selective laser melting system is shown in Fig. 1. SLM machine consists of a table to which two containers are attached. The bottom of each container is a piston. Initially, one of the containers (left) is filled with a powder and the other (right) is empty with the piston at the level of the table. The process is started with a thin powder layer deposition in the right container. First, the left piston is increased and the right piston is decreased by the layer thickness. Then, a roller scrapes powder from left to right. The deposited layer is scanned with a laser beam, which causes local heating and consolidation of powder. After the laser beam scanning of each cross-section, the manufacturing plate is lowered by the thickness of the layer to be deposited thus keeping the surface in the focal plane. The cycle of powder deposition/laser scanning is repeated many times resulting in a solid 3D part immersed into loose powder.

Experiments will be carried out on SLM machine PM 100 (Phenix Systems). The main characteristics of PM 100 machine are (Fig. 1): maximum laser power (YLR-50 CW Ytterbium fiber laser, IPG Photonics) 50 W; maximum laser scanning speed 3 m/s; laser
wavelength 1075 nm; diameter of manufacturing plate is 100 mm; maximum height of manufacturing part is 100 mm; the minimum layer thickness is 5 µm (for fine powders); precision of vertical position of manufacturing plate: ± 3 µm; accuracy of produced parts: ±50 µm per 100 mm; maximum volume of powder in supplying module: 1.6 l. Operational temperature of the internal chamber is up to 900°C; this allows manufacturing parts not only from metal powders but also from ceramics. The furnace provides a closed environment with inert gas inside (nitrogen or argon, maximum gas output 50 l/min).

Fig. 1. Scheme of selecting laser melting system.

The essential operations are deposition of a thin powder layer and laser beam scanning over its surface. Powder binding mechanisms strongly depend on laser induced heating and applied powder.

One of the principle criteria of SLM is the accuracy of fabrication with respect to the desired dimensions of the final product. SLM technology is applied for fabrication of elements for mechanical, chemical, nuclear, aircraft industries and bio-medical applications. SLM technology shows considerable progress to meet the challenge for fabrication of complex shape functional objects from commercial metallic and ceramic powders.

3. Results and discussion

SLS - process monitoring system

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

MSSP 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 constitute an opto-mechanical unit which is arranged in a separate box and integrated with the optical system of PHENIX PM-100 machine.

3.1. Visual control system

To discern defects of deposition of a powder layer, to verify position of the 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 (~ 10¹¹ contrast).

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

![Fig. 2. Visualisation of SLM process: powder INOX 316L, layer thickness 50 µm, laser power 50 W, scanning velocity is 130 mm/s (a) and 120 mm/s (b), the shift between the vectors is 120 µm, shift between the zones is 60 µm.](image)

3.2. **System for temperature monitoring**

An image of the sintering zone at five-time magnification is projected onto the photocathode plane of a gated microchannel plate (MCP). Wavelength bands λ₁ = 0.55 µm and λ₂ = 0.7 µm (spectral band width is 20 nm) are spatially separated when radiation passes through a prism and, thus, two images are obtained (Fig. 3). The image to the left is recorded at λ₂ = 0.7 µm, the image to the right (with low intensity) at λ₁ = 0.55 µm. Intensity profiles along selected straight lines (horizontal and vertical) can be measured (see curves, left and upper). By this way, ratio of intensities at two wavelengths is obtained, and colour temperature can be calculated.

MCP with accusation period of 20-1000 µs is switched on at a predetermined instant. 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).
Fig. 3. Spatial distribution of thermal radiation intensity at two wavelengths (image to the left is recorded at $\lambda_2 = 0.7 \, \mu m$, and image to the right is recorded at $\lambda_1 = 0.55 \, \mu m$) and intensity profiles along selected straight lines.

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

It should be noted that the video camera cannot provide video-display processing at 50-100 Hz frequencies. In order to continuously monitor values of maximum surface temperature (that is, temperature in the laser irradiated zone), a two-wavelength pyrometer based on two photodiodes registering surface thermal radiation is fixed inside the opto-mechanical unit. Photodiodes signals are gated, and maximum colour temperature in the sintering zone is displayed on the monitor in digital format. It is found that the maximum temperature value is rather sensitive to detect deviation of SLM parameters from their optimum values. For example, a sharp temperature increase and its instability indicate that energy input per unit length of the line to be sintered should be decreased. Pyrometer calibration is performed using a temperature lamp whose filament is housed in the focal plane of the focusing objective.

Visualisation of the SLM process was carried out by an infra-red camera FLIR Phoenix RDASTM with InSb sensor: 3 to 5 $\mu m$ band pass arranged on 320x256 pixels array. The camera was aimed at a rectangular area to be scanned by the laser beam with the size close to its vision window. The applied acquisition time was 50 $\mu s$, and the size of the window was 136x64 pixels. Transient phenomena at the beginning (Fig. 5a) and at the end (Fig. 5d) of the melting line can be easy seen: increasing of the size of the heat affected zone and, in particular, growing of the “temperature tail” along the melting line. Ejected liquid droplets can be seen as well. An overall estimation of stability or instability of the melting process versus operating conditions can be made. Along with the above mentioned advantages of modern infra-red cameras, one may note that it is not always easy to decode obtained images and to identify related physical phenomena.
Fig. 5. Grey levels image of SLM process: (a) beginning of the laser scanning line; (b-c) micro-explosions and droplets removal; (d) end of the laser scanning line. Size of the vision zone is 6.4 by 13.6 mm.

4. Conclusion

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

References