Optical in-process temperature monitoring of selective laser melting

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Abstract

Investigation of the melting of overhang layers has been conducted under full temperature monitoring. Mechanisms of the melt penetration into loose powder bed have been determined. Temperature regimes of the selective laser melting process of the 3D object from steel 316L powder also have been investigated.

1. Motivation / State of the Art

SLM technology has difficulties in building an overhang plane due to the process definition of layered wise production in a powder bed. Mechanism of the melt penetration into loose powder bed has not been investigated and threshold conditions have not been determined. One way to solve consists in investigation of the this phenomena under monitoring and control of the melting process [1-2]. Using a calibrated pyrometer and CCD camera fully control the process of sintering/ melting of the overhang layers and 3D object melting has been conducted. The results of studies are presented in this paper.

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2. Experimental

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 elaborated [3] (fig.1b) and special optical schemes was designed [3]. Measurements are carried out at wavelengths close to laser wavelength (fig.1b) which are prominent using a gradient type dichroic mirrors and filters (fig.1a). A two-wavelength pyrometer (fig.2a) with time resolution 50 μs and spatial resolution 50 μm based on two InGaAs photodiodes registers the surface thermal radiation on two wavelengths in the range 900-1200 nm. The image of scanning area with diameter 130 μm is rendered on fiber diaphragm 8, diameter of which 100 μm fixes the area of signal integration. The monitoring of the temperature distribution in laser irradiation zone is based on high speed digital CCD – camera (pos.13). 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 850 nm and spatial brightness temperature distribution is determined (fig. 3a,b). Time resolution of the system – 50 μs, spatial – 20 μm. As the maximum colour temperature have been valued by pyrometry it is possible to have colour temperature distribution from brightness temperature distribution.

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. Previously lamp was calibrated with a black body model in the temperature range 1200-1800 K.

In these experiments, a some layer of Cu (25-50 μm), CoCr and 316 steel powder was used. The thickness of the loose powder bed was 3 mm. The source of radiation is a YLR-200 cw fiber laser with a maximum power P = 200 W, the wavelength λ = 1075 nm and the laser spot size d = 75 μm. Overhang layers were scanned with scan shift 30 μm. Only one cross-section 100 x 100 mm² was scanned with the scan speed 100 mm/s. Experiments was conducted in N₂ and Ar atmosphere.

3. Results and Discussion

When scanning the layer of powder with high thermal conductivity of the particles material (Cu) the front of melting moves directly ahead of the laser track (fig.4c) at our experimental conditions that is consistent with calculations. As was apparent after experiments accumulation of heat in the layer causes their overheating and affects the flow of the melting process, encouraging the development of the instability of the contact surface between the melt and powder [1] in a gravity field - Rayleigh - Taylor (RT) instability [4].
Observed structures on the contact surface between melt and powder (fig.2 a,b) are typical of the Rayleigh-Taylor instability. The main factors holding back the development of instability – viscosity and time. But at 2000K viscosity of copper melt is only $10^{-3}$ Pa·s, cooling rate of the melt $10^{-3}$ K/s [5] and the characteristic time of the penetration of the melt in the powder bed can be estimated from the characteristic time of entry of spherical bodies ~ 0.1s [6] which is consistent with the measured time of growth of structures on the surface (Fig.4).

3.1 Rayleigh Taylor instability modelling

Numerical simulation of the Rayleigh Taylor instability at the interface between the melt and the layer thickness of 4mm copper powder 20-40 in diameter which was considered as a liquid with a certain density and viscosity has been conducted. Program SOLA-VOF [7] has been used for modeling the motion of an incompressible viscous fluid taking into account heat conduction [8].

Temperature of the melt layer thickness of 0.5 mm was assumed to be 2200K. At this temperature, the dynamic viscosity of the molten copper is $2 \times 10^{-3}$ Pa·s. The viscosity of the powder was calculated from the dependence obtained for the viscosity of the powder bed when lowering a ball diameter D in powder bed [9]:

$$\eta = \mu \cdot g^{0.5} \cdot (\rho_m \cdot \rho_p)^{0.5} \cdot D^{1.5} / (1- p/p_c)$$  \hspace{1cm} (1)

where $\mu = \tan \alpha$, $\alpha$ - angle of repose, D - characteristic size of the structures of RT instability, $\rho_m$, $\rho_p$ - melt density and density of the powder bed, p and $p_c$ – packing fraction of powder bed and critical packing fraction when $\eta = \infty$ (taken to be 0.66 according [9]). As seen from the two powder viscosity depends on the
size of the penetrating body and for $D = 1 \text{ mm}$ is 5 Pa·s, but for $D = 0.3 \text{ mm}$ is 0.5 Pa·s. For comparison, the viscosity of fuel - oil - 3 Pa·s. The preliminary results of modeling are presented at Fig. 3. Despite the high viscosity instability develops starting from small scale as observed experimentally (Fig. 2 a) passing to the large-scale structure −1mm (Fig. 2 a,b).

3.2 Surface heating and thermal constants.

As follows from the experimental results due to the high heat conduction of copper and low-speed transverse movement of the laser spot the melting front in transverse direction is moving ahead the laser spot line (Fig. 4 c).

Fig. 4. Overhang layer melting. Frame recording: Cu powder with CuO coating. Exposure time: 0.01 s, 78 fps. Arrow-melting front.
To describe the surface heating the approximation of a moving linear source has been used [10]:

\[ T = \left( \frac{q}{2\pi \cdot \lambda} \right) \cdot \left[ \exp(V \cdot x/2a) \right] \cdot K_0 \left[ V \cdot x/2a \right] \quad (2) \]

where \( K_0 \) – Bessel function, \( x \)- transverse direction, \( V \)- velocity of the linear source. In our case \( q = 80 \text{ W/cm} \), \( V = 0,03 \text{ cm/s} \).

Using the value of an outrunning of the melting front and the temperature at the laser spot we get a system of two equations for the determination heat conduction and thermal diffusivity of the medium by which the heat source is moved. The solution of this system yields the following values - \( \lambda = 0,058 \text{ W/cm K} \) and \( a = 0,7 \text{ cm}^2/\text{s} \). The values obtained in two or more times greater than the approximative values obtained by calculation [11,12].

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Fig. 5. Overhang layer melting: (a) - frame recording, 1 – melt front; (b) - cross-section, (c) - spatial temperature distribution, (d) - reflectivity of the surface structures, 1 – surface of the powder bed, \( \Delta \) - in pits. Cu powder.

Emerged on the surface structures because of the instability (fig. 2) have high absorptivity (fig. 5 d) due to multiple reflections of the laser radiation in the pits (fig. 5 c). The result is the rise of surface temperature in these areas. High temperature fluctuations are observed during \( \sim 3 \text{s} \) (fig. 2 c).

When scanning a loose powder bed from powders of CoCr, steel 316 with low thermal conductivity and higher absorptivity the melt front did not overtake the scan track. Instabilities also are seen but in most cases at the border of the scan area where scan spot is stopped and overheating takes place. The second mechanism of super-deep penetration of the laser radiation in a powder bed is associated with balling effect. Large drops of melt draw nearby powder (Fig. 6) with resulting laser radiation penetration to powder bed at a depth up to 2 mm.

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Fig. 6. Surface structure resulting from the balling effect. a – top view, b – side view. Cu, \( P=89\text{W} \).
3.3 Monitoring of 3D object selective laser melting process

Direct temperature measurements during the 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 brightness temperature in the focal spot 100 μm in diameter did not exceed 1800-1900 K (Fig. 7 b), significantly below the theoretically predicted [12]. This is probably due to the inaccurate description of the powder consolidation kinetics with the resulting low dynamic thermal conductivity. Maximum brightness temperature at first and second scan differ little in value (Fig. 7 b). Distinction is observed in width of spatial temperature distribution - 300 μm at first scan, 200 μm at second one, that is a result of the heat removal.

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

**Conclusion**

It was determined that the destruction of overhang layer is associated with overheating and with the emergence of instabilities and their growth. At first experimentally the development of Rayleigh Taylor instability of the interface between the liquid (melt) and granular (powder) media has been set. The mechanisms of the melt penetration into loose powder bed have been determined: Accumulation of heat in the molten overhang layer results in the development of the instability of the contact surface between the melt and loose powder in a gravity field - Rayleigh-Taylor (RT) instability. RT instability progress under laser radiation action causes the complete loss of stability of the molten layer with a dip to the loose powder bed. The second mechanism of super-deep penetration of laser radiation in a powder bed has associated with balling effect. Large drops of melt draw nearby powder with resulting laser radiation penetration to a depth up to 2-3 mm.

In either case after a lapse of time the process passes to steady state with surface temperature for example ~1500 K for Cu powder because the previously melted material act as a heat sink. Experimentally the heat conduction and thermal diffusivity of the powder bed during the sintering process are defined. The values obtained in two or more times greater than the approximate values obtained by calculation. Direct temperature measurements during the selective laser melting process of the 3D object add considerable support for the determining role of the thermal conductivity in selective laser melting. Optimal conditions of selective melting are in the temperature range slightly above the melting point of the powder material.
References