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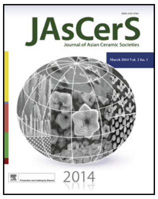

Monitoring of temperature profiles and surface morphologies during laser sintering of alumina ceramics

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ABSTRACT

Additive manufacturing of alumina by laser is a delicate process and small changes of processing parameters might cause less controlled and understood consequences. The real-time monitoring of temperature profiles, spectrum profiles and surface morphologies were evaluated in off-axial set-up for controlling the laser sintering of alumina ceramics. The real-time spectrometer and pyrometer were used for rapid monitoring of the thermal stability during the laser sintering process. An active illumination imaging system successfully recorded the high temperature melt pool and surrounding area simultaneously. The captured images also showed how the defects form and progress during the laser sintering process. All of these real-time monitoring methods have shown a great potential for on-line quality control during laser sintering of ceramics.

1. Introduction

The term “laser sintering”, when used in this article, is an empirical term, which includes solid state sintering, liquid phase sintering or partial melting and melt-solidification processes. Laser sintering is belonging to the family of Laser Additive Manufacturing (LAM). This is a well-known technology for the fabrication of complex functional parts [1]. By using a combination of computer aided design (CAD) and computer aided manufacture (CAM) bodies can be “printed” directly into their final shape. A controlled high-energy laser beam is used to fuse particle granules directly into complex net-shaped 3D-components in a layer-by-layer manner. When the laser beam spot scans over the particle granules, they consolidate either through sintering or melting/solidification reactions [2]. Often the components include designed functional features that otherwise are difficult or even impossible to fabricate by other methods. In addition, this bottom-up approach allows the use of different laser scanning parameters in different parts of the consolidated body to fit with different quality parameters [3]. Thus, overhanging structure parts are compensated for over-heating that might induce deformation or curving [4]. Real-time monitoring of the process has become important for detection of any unpredicted fault and for continuous control of the interior quality.

Laser sintered plastic and metal parts, but no ceramic parts, have been produced in industrial scale. To prepare ceramic bodies efficient lasers are needed with carefully controlled parameters. The high melting point, low thermal conductivity and poor thermal shock resistance are examples of the intrinsic difficulties common for laser sintering of ceramics [5]. Alumina (Al_2O_3) is one of the most widely used ceramics because of its good mechanical strength, thermal and wear resistance properties, and the use of laser sintering for alumina is reported [6,7]. Laser-materials interactions, however, for different ceramics are much more complicated than for metals and are yet to be clearly understood in detail. Therefore, real-time monitoring of the laser process would be important to control the more sensitive ceramics sintering process. Measuring of temperatures and/or surface morphologies is used in metal laser sintering, but is less common for ceramics [8,9]. Real-time monitoring techniques are expected to become important tools for ceramic laser sintering and the different monitoring techniques need to be evaluated with respect to their performances. A control technique and general and better understandings of the laser–ceramic interactions will be important for further progress.

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In this study, three different monitoring methods were examined and compared during laser sintering of alumina ceramics. The main target is to evaluate real-time measurements by pyrometer, spectrometer and a surface imaging system. Their ability for controlling the laser process in production will be observed and to what extent they might be used for a better understanding of the fundamental phenomena taking place.

1.1. *Laser sintering principles*

1.1.1. *Standard parameters*

Most important parameters in laser sintering of ceramics are usually laser power, focal spot size, scanning speed, hatch line pattern and scan distances. The total energy input *Q* (unit J/m) from the laser beam can be easily calculated as Eq. (1) shows.

$$Q = \frac{P}{v} \tag{1}$$

where *P* is the laser power and *v* is the scanning speed [10].

All these parameters can be set in the laser sintering program and kept constant or varied during the process. The complexity of laser sintering of ceramics, however, demands a detailed control obtained by real-time monitoring to set proper parameters and to avoid processing faults.

1.1.2. *The detecting element*

In principle, the detecting element can be installed either in a co-axial or an off-axial manner [9,11,12]. An appropriate example for explaining the difference of these two modes is the temperature monitoring. The co-axial set-up refers to the same scanning unit for material processing and monitoring, while off-axial set-up only uses the laser beam without an additional scanning system. The advantage of a co-axial set-up is that the detector element is always focusing on the current process zone, but must consider the restriction of the optical components. The semi-reflective mirror could reflect almost all light from the laser wavelength and can transmit the melt pool radiation in other spectral ranges. The off-axial set-up does not have restrictions in system design, but the thermal radiation is captured from the entire heat-affected zone. Thus, the obtained temperature would be lower than the maximum temperature within the focal spot, but the average temperature still reflects the overall thermal state.

1.1.3. *Optical imaging*

The co-axial imaging system records the real-time information from the melt pool and when coupled with a high-speed CMOS camera a monitor system will be achieved [13–15]. The melt pool geometry and evolution during the laser sintering process can be extracted from the 2D images. Simultaneous observation of the high and low temperature areas is difficult. It is possible to reduce the laser radiation intensity by a filter, but the captured images will then reflect the brightness contrasts and to enhance the signals of cooler areas an additional diode illumination (LED) is used. The off-axial imaging system can be used for flaw detection by identifying any deviations in the powder bed before the laser scanning and inspect the same consolidated surface morphology after laser sintering.

2. Experiments

The precursor material used in experiment was high purity α-alumina powder (99.99% Al_2O_3 from TAIMEI CHEMICALS Co., Ltd, ultrafine grade TM-DAR) with a mean particle size of 0.10 μm. An X-ray diffraction (XRD) analysis of the powder (XRD equipment from Seifert, Ahrensburg, Germany) proved a single-phase corundum structure with narrow and strong peaks and no detected crystalline contaminants. Alumina powder was pressed into tablets by uniaxial dry-pressing at 50 MPa. The density of pressed pellet is 2.26 g/m^3.

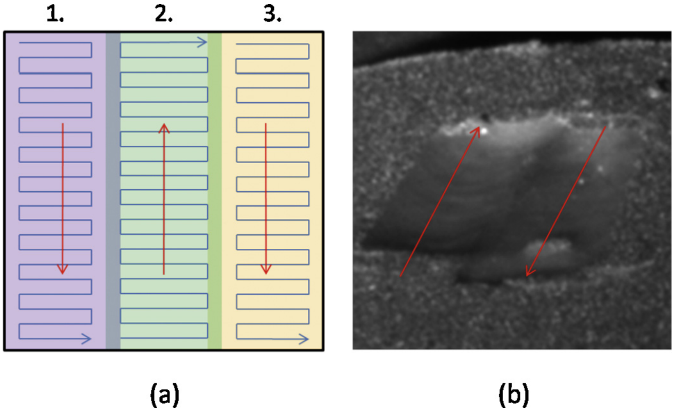

Fig. 1. (a) The schematic diagram of the hatch line laser-scanning pattern is illustrated. The hatch lines in the stripes are close (0.05 mm), whereas the strip width is 2 mm. (b) An illumined surface where a 4 mm square of alumina powder is laser sintered with a heat input of 400 J/m. The image was captured by a CCD-camera imaging system and the illumination came from a strong LED laser source.

To evaluate the different real-time monitoring techniques, the top layer of these alumina tablets is consolidated. Consolidated alumina pieces were cleaned in an ultrasonic bath with a mixture of alcohol and water and characterized with optical microscopy (OM, Olympus SZX12) and scanning electron microscopy (SEM, JEOL JSM-7000F).

All studies described in this paper were made by using an EOSINT M 270 Selective Laser Sintering system from EOS GmbH. The laser was a 200 W continuous wave Nd:YAG fiber laser with a Gaussian intensity profile operating at a wavelength of 1070 nm and the typical focal spot diameter is 70 μm. All the tests were based on laser sintering of one alumina layer at a time of the pressed green bodies. The scanning hatch line pattern used in all tests is schematically illustrated in Fig. 1. The hatch line distance was fixed at 0.05 mm and the stripes can width was 2 mm, where this scanning pattern was set to a 4 mm square surface. The XRD analysis of a flat surface of laser sintered alumina after cooling showed that the only crystalline phase was α-alumina, with an obvious texture of along [1 1 3]. The sintered alumina had a brittle fracture and SEM inspection of fracture sections revealed that very few pores was present, indicating a fully dense alumina.

The active illumination imaging system (manufactured by Cavitar) consists of a control unit, lighting system, control software and a CCD-camera. The imaging system mounted to the laser sintering equipment is shown in Fig. 2a and b. The optics and the camera are fixed outside the laser sintering machine. To prevent the cameras CCD-array to solarize/over exposure, an additional lighting is done by a strong 810 nm light source (diode laser, Cavilux HF) attached to the laser unit *via* optical fiber. This laser has a light with much higher intensity compared to the thermal radiation [16,17]. The camera has an optical filter with transmission mainly to this wavelength and will decrease the light emission of the laser spot. Thus, the contrast in image is related to the absorption and reflection properties in this wavelength. The camera can expose up to 30 frames per second and from time-expended videos it is possible to detect rapid phenomena.

A pyrometer (Temperature-Control-System, TCS) is calibrated and used for on-line temperature measurement and control of the laser process. The optical head of the pyrometer, attached to support, was mounted inside the chamber and it was adjustable