

DEVELOPMENT OF AN EXPERIMENTAL TEST SETUP FOR IN SITU STRAIN EVALUATION DURING SELECTIVE LASER MELTING

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Abstract

Selective Laser Melting (SLM) is an Additive Manufacturing (AM) process which still underlies a lack of profound process understanding. This becomes obvious when deformation and crack formation can be observed in SLM parts due to residual stresses. Controlling residual stresses is therefore an important topic of recent research in AM of metals. In order to minimize residual stresses further knowledge considering their cause and physical correlations of process parameters needs to be generated. In this paper an approach of measuring strains layer by layer during the SLM process by means of in situ X-ray diffraction is presented. For this purpose an experimental test setup is being constructed at the Technische Universität Berlin. The system requirements and operating principles are discussed in this paper. Furthermore, details of the current progress of the construction are highlighted.

Introduction

In metal based Additive Manufacturing (AM) a continuously growing market can be observed [1]. Among the variety of different AM technologies the powder bed fusion, especially the Selective Laser Melting (SLM), is the leading technology for metal parts [2]. However, there are still some characteristic drawbacks as a result of the physical processes during SLM. High thermal gradients during the building process are a result of the locally concentrated energy input by the laser source and lead to residual stresses in the part [3]. As a consequence, the mechanical properties as well as the geometrical accuracy are negatively influenced and deformation as well as crack formation is likely to occur. In state-of-the-art machinery the parts are fused on a substrate plate either directly or in combination with support structures. The connection between substrate plate and part leads to a better heat transfer and prevents deformations of the part. Still, the residual stresses can result in delamination of the SLM parts from the substrate plate as depicted in figure 1. Furthermore, by heating the substrate plate, and by that also the part, up to 550 °C [4] the temperature gradient and thus the thermal stresses are reduced. The use of brittle materials like carbide metals [5] or ceramics with increased melting points and therefore the likeliness of crack formation is still limited and could be improved by an enhanced high-temperature preheating of more than 1600 °C [6]. Other strategies to reduce residual stresses in AM parts have been investigated such as the scanning strategy [3] and the heat treatment after the building process [7, 8]. Though the mechanisms leading to residual stresses during SLM basically are known, a deeper understanding of their complex correlations with the SLM process

parameters and dependencies of magnitudes is needed for the improvement of process strategies leading to better part quality.

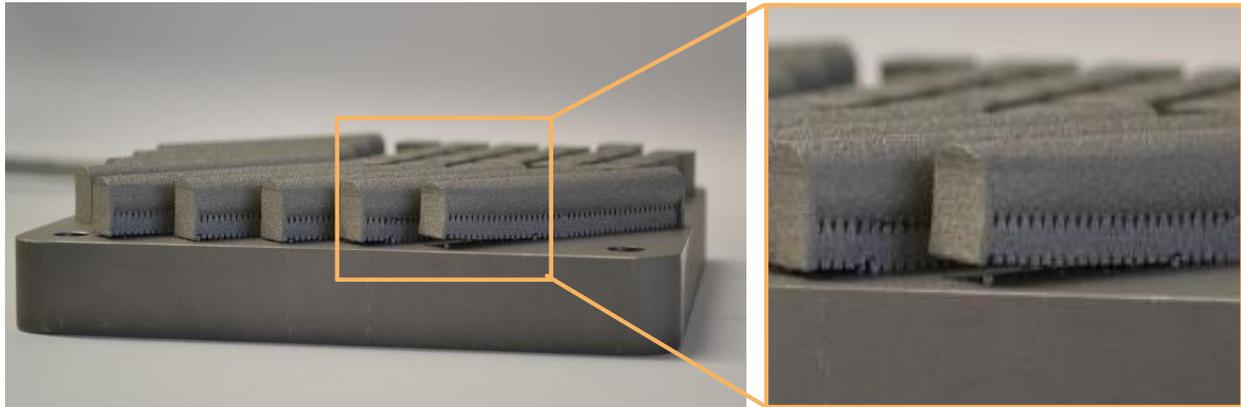


Figure 1: Delamination of Ti6Al4V SLM parts from the substrate plate

There are a number of approaches to evaluate residual stresses in AM parts reported in the literature. The different techniques are based on the measurement of strains or part deformations that are correlated to the compensation of internal stresses. A lot of experiments have already been conducted regarding the post-process measurement of strains in SLM-built parts by means of neutron diffraction [9, 10] or X-ray diffraction [11-13]. However, X-ray diffraction is only applicable to measure the remaining strains on the surface of the part. In addition, incorrect values may be obtained as the penetration depth of the X-rays often is comparable in magnitude to the values of surface roughness of metal AM parts [14]. While neutron diffraction is suited for deep measurements in components there are disadvantages regarding the relatively low time resolution as neutrons interact weakly with matter. Other methods like the crack compliance method [3, 15], contour method [10, 16], layer removal method [7, 17, 18] or the hole drilling method [14, 19] have been evaluated for SLM parts, but are destructive respectively semi-destructive methods and therefore have to be applied after the building process. An approach of investigating the stresses during the process was performed by attaching strain gauges to the bottom of the build plate [20]. By that the strains could be measured layer by layer during the process in order to evaluate the residual stresses. However, with this method a spatial resolved determination of stresses within the part is not possible as the stress components in part height direction cannot be measured. New measurement methods are required to clarify relationships between process parameters, signatures and part quality and the relative sensitivities of those relationships through experiments [21].

With brilliant synchrotron light sources a highly resolved spatial investigation of stress distribution and microstructural changes during dynamic production processes became possible [22] as already shown by investigations of the chip formation zone during in situ cutting experiments [23, 24]. In order to improve the understanding of the residual stress formation during SLM due to the complex interaction of the temperature gradient mechanism, subsequent thermal cycling, phase transition and recrystallization in a spatial resolved manner, a new test setup principle for in situ strain evaluation by means of synchrotron X-ray diffraction is presented in this paper.

Operating principle

With respect to the synchrotron X-ray diffraction method there are some major requirements for the design of the SLM process chamber which have to be fulfilled for the successful application of in situ experiments during SLM to collect spatial data of the stress distribution in the part. In the first place the transmission of X-rays must not be unnecessarily interfered throughout the process chamber to ensure a preferably unfiltered measurement and short acquisition times. Secondly, the synchrotron beam as well as the detector is stationary, meaning that the relative movement between powder bed and laser beam spot has to be established by a moving powder bed. The working principle of the test setup is shown in figure 2a. Pursuing this working principle the measuring mode depicted in figure 2b can be enabled.

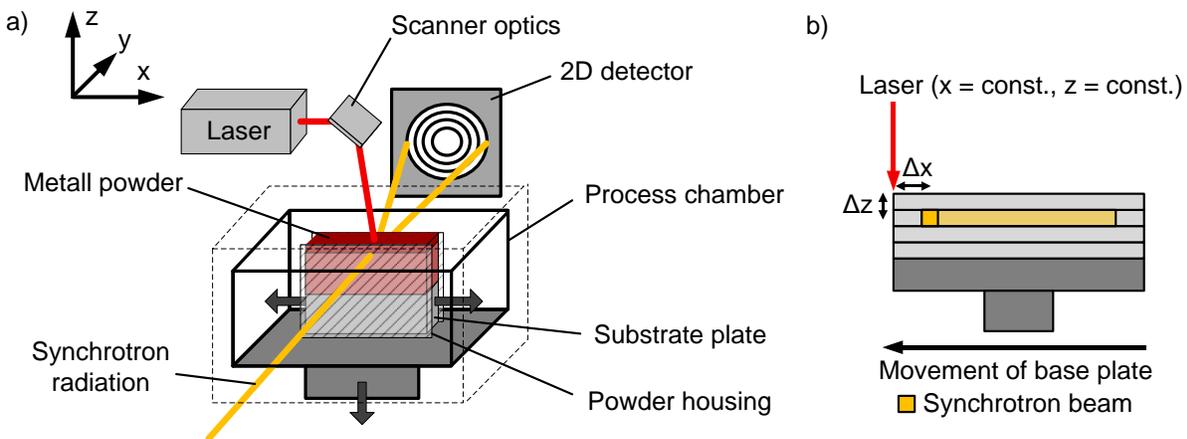


Figure 2: a) Operating principle; b) Measurement mode of the test setup

A measuring location in a horizontal distance Δx and a vertical distance Δz to the laser is defined. Due to the stationary synchrotron beam also the laser has to maintain its position in x and z direction to keep the distances Δx and Δz constant during measurement. The relative movement between powder bed and laser in x-axis direction is enabled by an actuated base plate. Since the base plate moves in x-axis direction, the laser oscillates in y-direction between the powder housing so the complete powder layer can be exposed to the laser and synchrotron beam while keeping a constant distance between part and detector. Thus the strains are measured integrally and sufficient diffraction intensity can be measured during exposure time. Regarding the depicted operating principle in figure 2a, the strains in part width direction i.e. y-direction cannot be measured because of the two-dimensional character of this measurement technique. By providing a possibility to rotate the test setup around its z-axis, further measurements under different incidence angles can be conducted and thus the stress state in part width direction can be deduced.

Functional Requirements

Considering the mentioned requirements due to the operating principle having an impact on the process itself, there are other requirements which have to be fulfilled on top. Owing to the available amount of space and weight limits of positioning systems in synchrotron laboratories,

e.g. an hexapod as stated in [24], the simple utilization of conventional SLM systems is not practicable for this purpose. As a result a SLM system with an adapted process chamber has to be designed. In table 1 the functional requirements determined for the system which is currently developed at the Technische Universität Berlin are listed.

Table 1: Functional requirements for the design of the in situ SLM system

Requirement	Specification
Build platform length l_b	140 mm
Build platform width w_b	3 mm
Build envelope height h_b	10 mm
Build platform heating temperature T_h	400 °C
Laser power P_l	400 W, continuous wave
Laser focus diameter d_l	80 μm to 500 μm
Powder housing X-ray transmission I/I_0	preferably unfiltered
Powder housing operating temperature T_{op}	1800 °C
Powder bed effective x-axis stroke s_{eff}	140 mm
Maximum mass m_{max} (mounted on positioning system)	250 kg

The long term objective of this current work is to map process parameters with the resulting residual stresses and therefore contribute to the process understanding in metal AM, leading to improved process strategies. The system should be able to produce basic parts like simple thin walls or parts with features, as listed in table 2, with physical and mechanical properties comparable to common SLM machines. Hence the experimental system is designed to work in parameter ranges known from common SLM systems. The exceptions are the possible part thickness which is limited by the attenuation of the incident X-radiation across the material and the laser scan speed which is limited to some extent by the inertia of the powder in the moving powder bed. The Laser power as well as the Laser focus diameter is in a comparable range as in the SLM 250^{HL} machine from SLM SOLUTIONS GROUP AG, Lübeck, Germany, which operates at the Institute for Machine Tools and Factory Management. The adjustable process parameters dependent on the system are shown in table 2. Further process parameters which affect the formation of residual stresses, determined by the used metal powder or the part geometry, are also accessible for investigations on residual stresses. As the synchrotron radiation penetrates through the complete powder bed, the complete powder layer has to be molten and solidified in order to avoid incorrect measurements. This is to avoid deflection of the incident X-rays by unsolidified powder that doesn't contribute to the effective residual stress distribution in the built part. In figure 3 the different available scan path strategies of the test setup are shown. It can be seen that the scan strategy presumably leading to the highest residual stresses, which is the x-hatching, is also the scan strategy where the most unsolidified powder is measured if the measured layer equals the currently processed layer. Scan strategies which involve diagonal scanning or any rotational angle other than 0° or 90° will not be possible to carry out with the introduced experimental system.

Table 2: Process parameters accessible for investigation

Machine parameters	Powder characteristics	Part geometry
<ul style="list-style-type: none"> ▪ Laser power ▪ Laser scan speed ▪ Laser focus diameter ▪ Hatch distance ▪ Scan path ▪ Layer thickness ▪ Base plate temperature ▪ Base plate material ▪ Inert gas flow 	<ul style="list-style-type: none"> ▪ Material ▪ Particle size distribution ▪ Bulk density ▪ Flowability ▪ Humidity ▪ Shape/sphericity 	<ul style="list-style-type: none"> ▪ Solid parts ▪ Hollow parts ▪ Overhang ▪ Bore holes ▪ Slots ▪ Edges ▪ Support structures

One of the most challenging questions in the experimental setup design is how to avoid undesired attenuation of the synchrotron X-radiation as a result of machine components which are located in the beam path. First, the powder bed has to be elevated and surrounded by a X-ray transmissive powder housing. Second, the process chamber housing must be transmissive where the beam path crosses. According to the first requirement there is the need to identify a suitable material which ensures not only the X-ray transmission but also has to endure high temperatures above the melting point of common SLM materials, as for example titanium with its melting point at 1668 °C. Monocrystalline sapphire (Al_2O_3) was identified as a material to meet the requirements with the melting point at 2050 °C and a maximum operation temperature of 1800 °C. The theoretical attenuation coefficients of sapphire can be determined partially [25]. The curve in figure 4 is fitted by piecewise cubic Hermite interpolation and shows the correlation of the linear attenuation coefficient μ and the incident photon energy E. Further, the attenuation is calculated exemplary for the photon energies 50 keV, 100 keV and 200 keV respectively for the transmission through a sapphire plate of 2 mm wall thickness. The obtained values show the general influence of the energy level of the incident X-radiation on the attenuation in the material. A decreasing attenuation for increasing values of the photon energy is characteristic for the relevant energy interval. In addition, a few percent of transmission is already sufficient to get satisfactory intensity results at the detector because of the high photon flux in synchrotron radiation [26]. Hence the transmission through the sapphire plates for high photon energies is theoretically adequate.

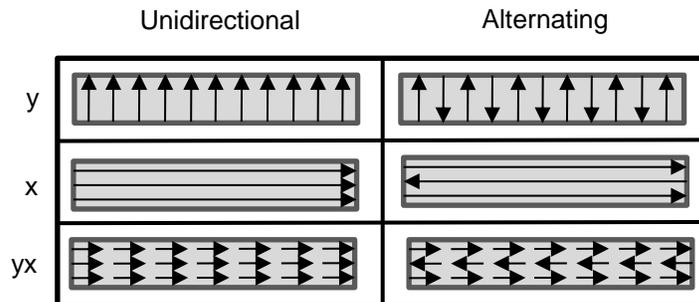


Figure 3: Scan path strategies

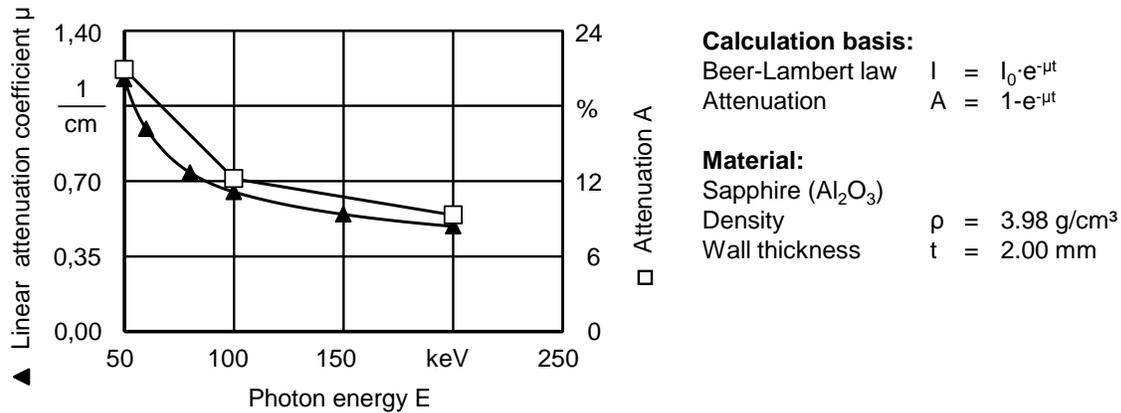


Figure 4: Theoretical attenuation coefficients for sapphire (Al_2O_3) [25] and exemplory attenuation through 2 mm wall thickness dependent on the incident photon energy

The applicability of sapphire plates as powder bed housing in respect of the high energy input by the laser was tested in a powder bed of Ti6Al4V material in a SLM 250^{HL} machine. The machine is equipped with a Nd:YAG Laser with a wavelength of $\lambda = 1064 \text{ nm}$ and a laser focus diameter of $d_l = 70 \text{ }\mu\text{m}$. The laser power was $P_l = 275 \text{ W}$ at a scanning speed of $v_s = 975 \text{ mm/s}$ and a hatch distance of $h = 120 \text{ }\mu\text{m}$. With a layer thickness of $\Delta z = 50 \text{ }\mu\text{m}$ the energy density can be determined to $E_d = 47 \text{ J/mm}^3$. The used sapphire plate had a thickness of $t = 0.5 \text{ mm}$ and measured 10 mm both in length l and in width w and was placed upright in the powder bed. The operating area surrounding the sapphire plate was 10 mm x 10 mm. There were $n = 10$ trials scanned in this area while reducing successively the distance between scanned area and sapphire plate from both sides. The scanning method is shown in figure 5a. Until the last trial no influence by the laser energy input on the sapphire plate could be seen visually. In the last trial the sapphire plate was scanned directly by the laser. After the last trial the effect of the energy input as seen in figure 5b could be noticed. The upper edge is rounded and cracks occur partially. A direct hit by the laser spot is therefore to be avoided, as the changed shape of the upper edge might influence powder recoating and X-ray diffraction measurements.

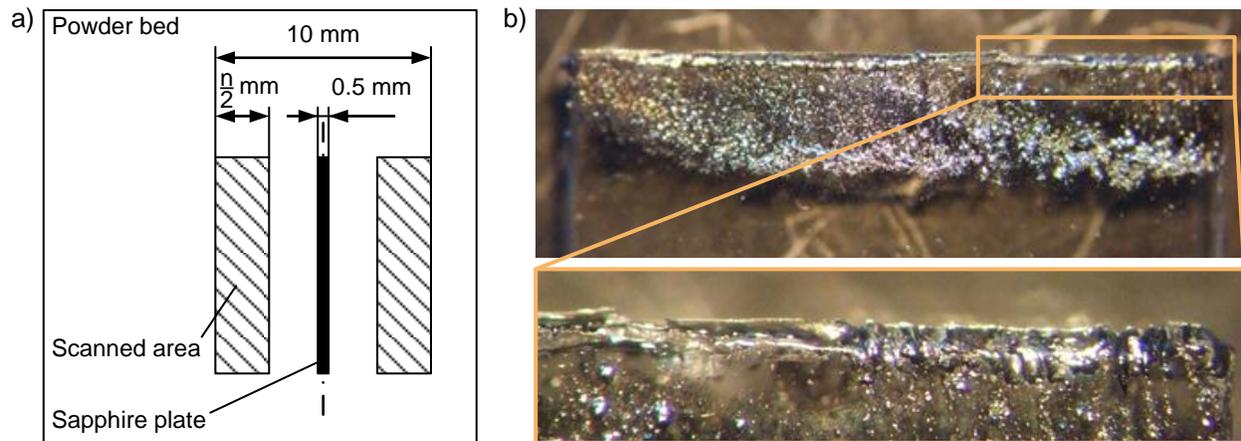


Figure 5: a) Sapphire plate scanning method with $n = 10$ trials; b) Sapphire plate after direct impact by the laser

Current stage of construction

In figure 6a the conceptual design of the in situ SLM system is shown. The gas filtration unit as well as control unit and user interface are situated separately and therefore help to meet the weight requirements. The laser security windows make sure that the incident radiation as well as the deflected radiation is able to traverse the process chamber. Another laser security window on top of the chamber allows the visual monitoring of the process. For the operating mode a telescopic beam stop is mounted between scanner and process chamber to ensure safety operation. The displaceable scanner system guarantees the possibility of adapting the operating distance when mounted on the synchrotron laboratory positioning system. The adapter platform which is needed to be mounted on such a positioning system is not implemented yet. Figure 6b pictures the moving build platform design. The z-axis and x-axis of the build platform are decoupled, meaning that the powered linear bearings are not mounted on each other. This is necessary in order to keep the sapphire powder housing permanently on the same z-level. Else, the powder recoating mechanism would have to be adjustable in z-axis direction. The build platform is mounted on a rail that is fixed on the actual build cylinder, which serves as actuated z-axis. A sliding contact between the sapphire plate carrier and the build platform ensures that the x-axis movement is transmitted whereas the z-axis movement of the cylinder only affects the build platform itself. The stroke of the z-axis cylinder is constricted by the build platform rail, but is enough to reach the required build envelope height. In the future design a powder recoating mechanism will be implemented in the in situ SLM machine.

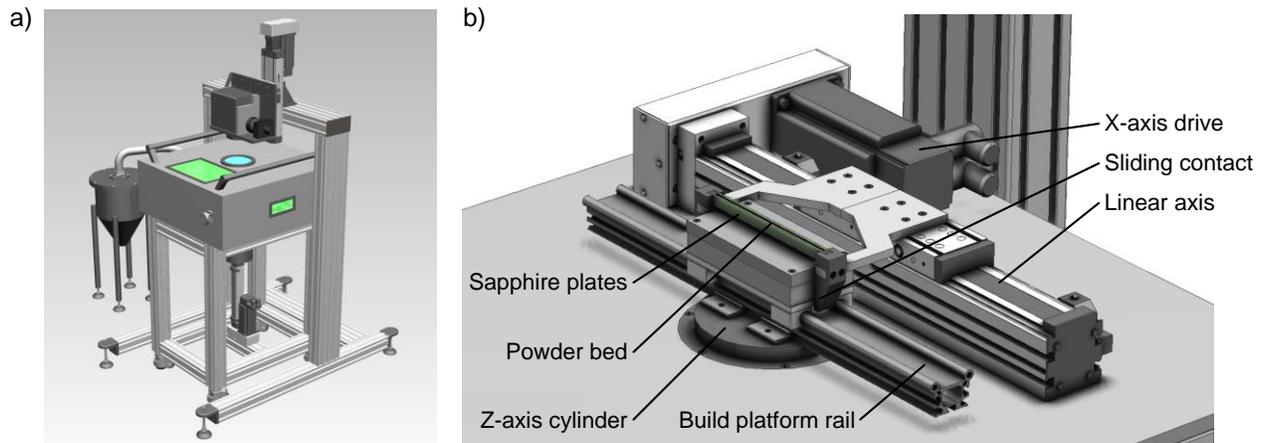


Figure 6: a) Conceptual design of the in situ SLM system; b) Build platform design

Conclusions

In this work the need for new time-resolved measurement techniques for residual stresses in SLM parts was outlined. Based on this need, the operating principle of a SLM system for in situ synchrotron X-ray experiments was clarified. The operating principle demands to restructure and redesign the common known SLM process chamber, as a moving powder bed has to be installed. Further, some modifications concerning the transmittance of X-radiation throughout the process chamber have to be made. The powder bed has to be elevated above the build platform where sapphire was identified as a suitable material for the transmissive powder housing in regards of

the attenuation of incident X-rays as well as high temperature resistance demands. Further, the current progress of construction of the in situ SLM system at the Technische Universität Berlin was illustrated.

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