

IN-LINE LAYER WISE MEASUREMENTS FOR SELECTIVE LASER SINTERING PROCESS

*Bogdan Galovskyi*¹, *Tino Hausotte*¹, *Dietmar Drummer*², *Ron Harder*²

¹ Friedrich-Alexander Universität Erlangen-Nürnberg, Institute of Manufacturing Metrology,
Erlangen, Germany, bogdan.galovskyi@fau.de

² Friedrich-Alexander Universität Erlangen-Nürnberg, Institute of Polymer Technology, Erlangen,
Germany, harder@lkt.uni-erlangen.de

Abstract – The popularisation and wider application of the additive manufacturing (AM) has increased quality requirements for this manufacturing process. Reduction of the size and form deviations of manufactured workpieces is one part of quality improvement. In-line optical surface measuring system is considered as the approach for solving the task. Layerwise powder bed surface measurements during the selective laser sintering (SLS) process are aimed to overview each sintered layer (contour of the workpiece) and measure its dimensions. This paper describes the development and practical implementation of the measuring system, as well as a concept for its integration into an SLS machine. Preliminary tests of the measuring system were conducted in real operating conditions.

Keywords: in-line measurements, selective laser sintering, powder bed, stereo vision

1. INTRODUCTION

In recent years different approaches of additive manufacturing (AM) become more popular and applicable in industry, research and medicine. There are many reasons for such a popularization and one of the most important is the tool-free manufacturing of complex parts and even mechanisms. There is a wide range of materials which, for example for selective laser sintering (SLS), are divided in two groups: polymer powders and metallic powders [1, 2]. Because the SLS raw material is expensive and the manufacturing process takes a long time, so the economic losses caused by the process errors are high. High efficiency of AM could be realized only with the help of investigations on the process parameters and influences on them. Development of methods for applying of the manufacturing metrology for the AM during recent years, as well as efforts in the field of standardization, confirm the transition of this technology to a new level of implementation [1-3].

Many research groups have concentrated their work on two general directions: post-process testing of the manufactured AM workpieces and in-line testing of the AM process parameters. The first approach is supported by international standardization organisations (ASTM F42/ISO TC 261 Joint Group for Standard Test Artifacts development), because it is less dependent on the type of AM method [3, 4]. Measurement of the process parameters is a more complicated approach, especially

concerning results evaluation and determination of cause-effect relationships between the workpieces quality and measured parameter. In VDI 3504 part 1 more than 20 process parameters that have to be controlled are listed. There are such parameters as: quality of the layer deposition, layer thickness and melting pattern (temperature and dimensions).

The main aim of our research is the development of the incremental in-line measuring system for 2D/3D surface measurements of the powder bed.

2. CONCEPT

In our research project the used SLS machine is a DTM Interstation 2000 and the raw material is Polyamide 12 (PA12) (Type: PA 2200, EOS GmbH). During the manufacturing process there are special conditions in the process chamber of the machine. Environment conditions are harsh for any type of measurement equipment: e.g. temperature inside the process chamber during the process is about 175 °C; polyamide condensate and dust are aggravating factors. The construction of the SLS machine limits the integration of a measuring system. Initially, it was clear that any type of measuring system should be protected from the harsh environment and supported with an active cooling system. An important role in selection of appropriate optical measurement techniques plays the compatibility of the measurement sensor with the measurement object. Components which are manufactured from PA12 have a very large roughness and high level of light scattering, as well as fresh powder. The most challenging conditions for such type of measuring systems are: short distance to the measurement object, large measurement range and necessity of high measurement resolution.

These requirements are based on the knowledge about the spot diameter of the manufacturing laser, the SLS process sequence, dimensions of the powder bed and process chamber of the machine [5, 6]. Camera based measuring systems have shown appropriate results and were selected as the main system for our prototype [6]. The comparative analysis of the commercially available systems was done but all systems didn't meet the requirements [5]. It was decided to develop a flexible camera based measuring system. The measurement strategy was developed in order

to obtain adequate measurement information about the SLS process [6] and consist of three steps for each sintered layer. There are surface measurements of the powder bed after:

- new layer recoating – with the help of this measurement, the flatness and homogeneity of the powder bed can be assessed;
- scanning beam processing – measurement of the sintered areas (contour);
- lowering of the powder bed – the measurement is required to get the exact height information for the volume model and to avoid stacking faults of the single measurements.

Time slots between all operations of the SLS machine are dependent on the manufacturing strategy and on the size of each sintered layer. Measuring time should be minimized. Measuring system is based on the CCD cameras with the GigE Vision interface.

3. MEASURING SYSTEM

Two CCD cameras were used as measuring system: separately calibrated for detecting the edge of the sinter profile and 2D evaluation of its dimensions; calibrated as a stereo vision system for 3D reconstruction of the sinter profile to point clouds. The prototype of the system was developed and tested in our temperature controlled metrology laboratory. Afterwards the stereo system with the same structure was integrated in the process chamber of the SLS machine (Fig. 1). Two sets of lenses were used in order to get different field of view and respectively different resolving power of each camera. The distance to the measurement object (powder bed) is 370 mm, which is caused by the size of the process chamber. In accordance with the scheme (Fig. 4), taken into account the size of the CCD sensor and parameters of lenses and the field of view for one camera could be calculated. Using the first set of lenses (TAMRON 23FM50SP) the measurement field is $30 \times 25 \text{ mm}^2$ and achievable resolution is around $20 \mu\text{m}$. Using the second set of lenses (CVO GMB5HR38014MCN) the measurement field is $180 \times 170 \text{ mm}^2$ and achievable resolution is around $120 \mu\text{m}$.

Fundamentals of computer vision systems, geometry of the camera system and camera calibration process are described in [7-9]. Main software package in our project is MATLAB, which latest version includes applications for single camera calibration and for stereo camera calibration.

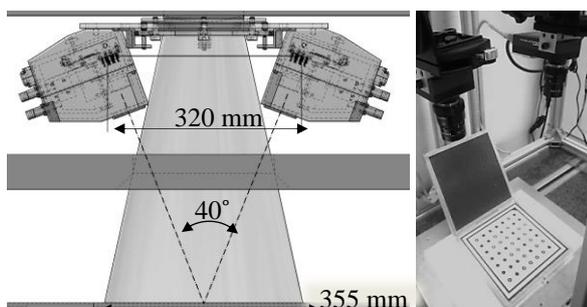


Fig. 1. View of the measuring system

As calibration pattern was used a chessboard calibration artefact. For a single camera calibration following parameters should be evaluated: intrinsic, extrinsic, and lens distortion parameters [10]. MATLAB application "Camera calibrator" allows determining these parameters. Intrinsic parameters (internal) are called to describe the model of the camera with the parameters like: focal length, principal point, image distortions. Extrinsic parameters allow establishing the connection between world coordinate system and camera coordinate system – to define the cameras position in the space. After the calibration process this connection between coordinate systems is described with the rotation matrices and translations vectors.

All mentioned parameters were obtained during the calibration of the measuring system in the laboratory with the help of "Camera calibrator". The software also allows determining the quality of the calibration procedure by evaluating the projection error and by the uncertainty estimation of the translation vectors.

An important part of the work is the edge detection on the images. This procedure helps to detect the sintered profile and evaluate its dimensions using parameters of the calibrated camera. The edge detection procedure is based on the evaluation of the intensity of each pixel of an image. Nevertheless the measurement process is influenced by the quality of the image and by the type of image object. Highly detailed objects have too many features which will bring high deviations of intensity on the image. Depending on the task of the edge detection, such as intensity deviations, can be considered as a noise which has to be filtered. The Gaussian filter is the appropriate solution for this problem. This filter allows smoothing the image to the acceptable level, after which the edge detection algorithm will bring acceptable result. "Canny" edge detection approach was developed many years ago [11]. Its implementation is realized as a function of MATLAB. During the work with our images this edge detection function has shown the best results.

Calibration method for the measuring system and software for edge detection and stereo vision were developed in MATLAB environment and with the help of openCV library for Visual C.

4. INTEGRATION

Two general tasks were considered before the integration of the measuring system into the SLS machine:

- development of the mounting system for the measuring system;
- development of the protection for the measuring system from the harsh environment inside the process chamber.

The first task was caused by the requirement to reduce the number of constructional changes of the SLS machine during the integration process and the need for thermal stable connection of the cameras. The second task was caused by many influences on the measuring system during the manufacturing process [6].

4.1. Mounting system

The SLS machine has a F-theta lens linked to the scanning system. The flange of this lens was used as fixing element to mount the system. Fig. 2 shows the general view of the mounting system which consists of a mounting couple and a mounting plate. Components of the mounting system are manufactured out of aluminium (AlMg3). This material is not the best taking into account the high temperature changes inside the process chamber, but it has a low weight, what prevents the position distortion or damage of the F-theta lens housing.

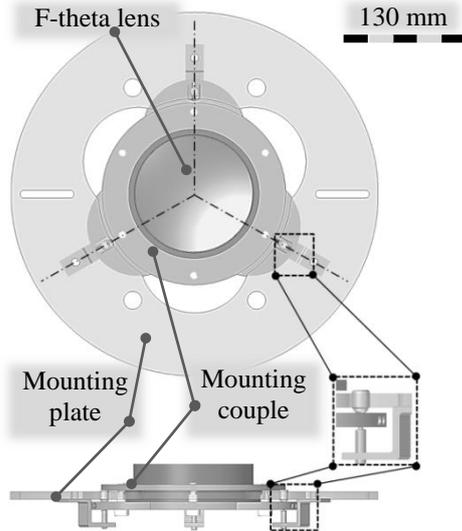


Fig. 2. Mounting system.

The mounting couple consists of two flat rings which are squeezed around the lens flange with the help of screws. The lower flat ring has three ledges located circularly on 120° one to another. Such ledges were designed for locating three pairs of guide pins on them (forming v-grooves in a 120° assembly). The positioning plate fixes two CCD cameras on it. The central aperture of the positioning plate has three identical cut-outs as the ledges mentioned above. It allows the easy adjustment of the positioning plate. Three hemispheres are located circularly on 120° one to another on the mounting plate. After the installation of the mounting plate on the mounting couple, these hemispheres are positioned on the guide pins.

This construction of the mounting system (kinematic mount) allows an exact repositioning of the measuring system. Thus this solution reduces the influence of the relatively high temperature extension of the aluminium. The mounting is not cumbersome and fixes the system in 6 degrees of freedom. The construction of the positioning system reduces the influence of components temperature extension, allows precise remounting before each new SLS build-job and easy adjustment of the camera system inside the process chamber.

4.2. Protection

The protection system consists of two parts: housing and cooling radiator. The construction of the CCD camera allows locating the cooling radiator between the lens and the

housing of the camera, what increases the effectiveness of the cooling system. The cooling radiator as well as the housing was made out of solid aluminium blocks.

Fig. 3 shows the cross section of the camera with the housing and cooling radiator. The construction of the radiator provides inlet flow of the cooling fluid close to CCD sensor of the camera. The radiator is attached mechanically to the camera and all contact surfaces are covered with the thermal grease for better thermal conductivity. Thermal isolation between the housing and the components inside is realised with the help of the ceramic elements and insulation material (Armaflex).

Camera view on the measurement object is provided by the aperture in the lower part of the housing. This aperture has a diameter of 55 mm and is closed with a borosilicate glass.

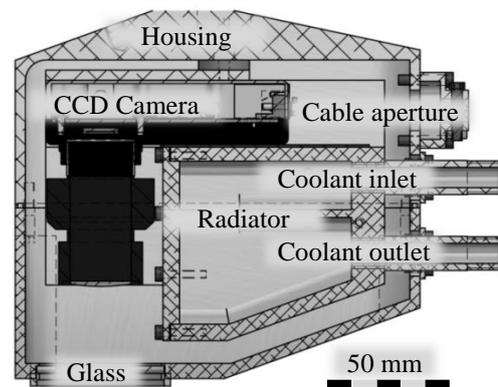


Fig. 3. Housing with the cooling radiator.

An external thermostat (FPW50-HL, Julabo GmbH) was used to provide the circulation of the cooling fluid in the system. The thermostat is connected via isolated hoses to the camera housings, wherefore Teflon pipes (PTFE) with insulation were used inside the SLS process chamber. Signal and power supply cables have insulation for work in the temperature range up to 200 °C. Cables for both cameras are attached with the cooling pipes inside the resistant to high temperatures hoses. The final assembling of the protection system with CCD cameras and positioned with the help of mounting system is shown in Fig.4.

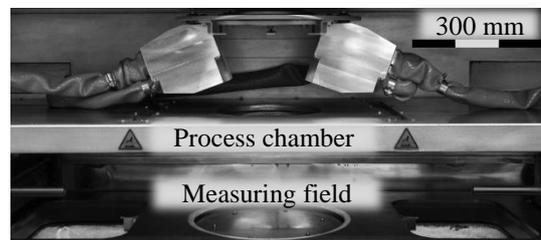


Fig. 4. Assembling inside the process chamber.

Before producing the cooling system its work and the temperature distribution were simulated. The simulations were done using a process chamber temperature of 195 °C. The cooling system allows keeping the temperature inside the protection housing in the range of 20 °C.

3. RESULTS

The prototype of the measuring system was tested in the laboratory and inside the process chamber of the SLS machine. The sequence of procedures was the same for both cases: single camera calibration, stereo camera calibration (two cameras as the stereo system calibrated with the "Stereo Camera Calibrator" application of MATLAB), measurement object detection, images rectification and processing (edge detection and 3D reconstruction). Test objects are two flat workpieces with the number of cavities and step structures with the nominal depth and height is lower than 1 mm (Fig. 5). Edge detection brought good results considering images of these samples [12].

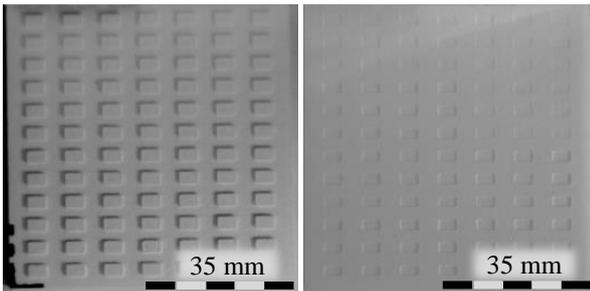


Fig. 5. Tested workpieces.

Laboratory tests have shown the big influence of the illumination and the type of the material. Manufactured with SLS machine samples were selected for measurements with the help of the laboratory setup. It should be mentioned the fact, that PA12 powder is a complex material to be measured because it has got a high level of light dispersion. These influences make the 3D reconstruction more complicated, because small size of reference features on the objects limits the combining of two images. For the 3D reconstruction in laboratory was done only one measurement (one image of the measured object from each camera). Such restriction was brought by the fact, that measuring system during the process will be able to take image only from one fixed position. After rectification of images, the 3D scene was reconstructed (Fig. 6). The quality of the 3D reconstruction is very low and can't be considered as the measurement result.

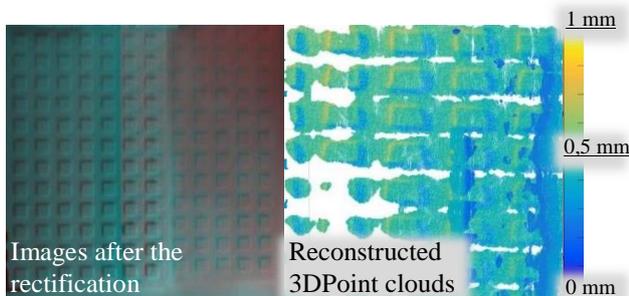


Fig. 6. 3D reconstruction.

Application of this measurement approach to the objects with more detectable features and with more measurement sets (more than one view of the object) brings better results.

As it was mentioned before, the measuring system was tested during the SLS process. Firstly the influence of the temperature should be mentioned. Thermo-elements were installed to different parts of the construction to monitor the temperature distribution (Fig. 7) inside the cameras housing. The most affected in the protection housing is around the lenses of the cameras (Fig. 7: Cam1, Cam2). After 5 hours test the temperature near the lens has reached a value around 40 °C, which could be considered as a good result. Temperature of the mounting system has reached the value of 100 °C, that cause a thermal expansion and a change of the distance between the cameras.

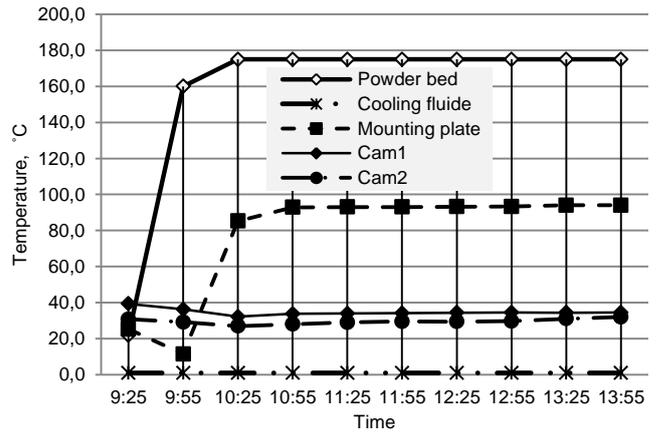


Fig. 7. Temperature deviation

Before using of the measuring system inside the process chamber, it was calibrated inside the machine but in the cold mode (normal temperature conditions). The influence on the mounting plate brought a distortion of the stereo base (distance between two cameras). So the calibration parameters were changed. The measurement object during the SLS process is the sintered profile [13]. The position and orientation of two cameras was changed, what is clearly seen in the results of images rectification (Fig. 8).

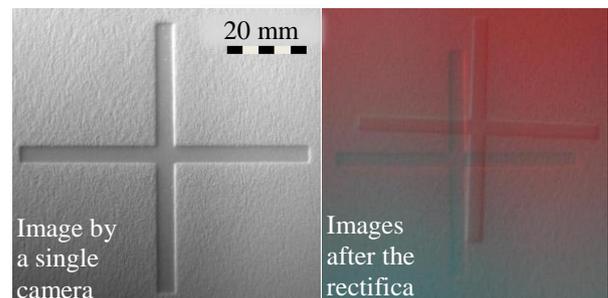


Fig. 8. Temperature deviation

At the same time the quality of the image is good for edge detection. Two cycles of the image filtration were done together with the "Canny" edge detection approach. Using the single camera calibration data it is possible to evaluate detected edges as a measurement result. Few noise lines are still present (Fig.9). Nominal dimensions of the profile are 52 x 52 mm² with the stripe width of 4 mm.

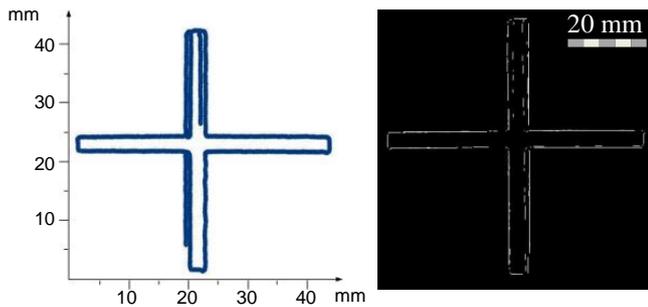


Fig. 9. Edge detection of the sintered profile.

The reference data is the width of the stripes. Deviation from the nominal value (around 1 mm) is caused by the temperature influence on the camera position and, as result, by change of the extrinsic parameters of the camera.

4. CONCLUSIONS

The prototype of the measuring system was developed for the in-line and layerwise inspection of the powder bed surface and the sintered profile during the SLS process. Preliminary results have shown good work of the cooling system. At the same time the big influence of the thermal expansion of the mounting system has affected the measurement results. Primary solution for solving this task consists of two steps: stabilization of the mounting system by using the thermal resistant materials; development of the correction approach for the calibration procedure. The second step is possible by using ceramic testing plates with the calibration pattern and new software for camera calibration.

The approach using the stereo vision has shown low reliability for such kind of measuring system. But developed measuring system can be improved with the reference light pattern or with the using of active light pattern (fringe projection principle). Such solution was realized in [14] and researchers have mounted measuring system out of the process chamber, but in our project the temperature influence should be considered. In order to avoid location of the measuring system inside the process chamber, the approach with the using of the scanning system of the SLS machine is reliable [15]. It allows minimizing temperature influence and providing faster approach for the sintered profile evaluation (detection only of the sintered surface).

Nevertheless measurement of the powder bed surface gives only information about each single sintered layer, but not about the whole dimensions of the workpiece. Future developments of measuring systems for the powder bed of SLS machines should be continued together with the investigation of the powder bed lowering and its influence on the height of each sintered layer.

ACKNOWLEDGMENTS

The authors want to thank the German Research Foundation (DFG) for funding the Collaborative Research Center 814 (CRC 814), subproject C04.

REFERENCES

- [1] VDI 3404:2009-12 'Additive fabrication - Rapid technologies (rapid prototyping) - Fundamentals, terms and definitions, quality parameters, supply agreements'.
- [2] VDI 3405 Part 1:2013-10, 'Additive manufacturing processes, rapid manufacturing - Laser sintering of polymer parts - Quality control'.
- [3] S. Moylan, "Progress toward standardized additive manufacturing test artifacts", *ASPE 2015 Spring Topical Meeting*, pp.100-105, Raleigh, North Carolina, USA, Apr. 2015.
- [4] B. Galovskyi, T. Hausotte, D. Drummer, M. Zhao, "Model of a Measurement Artifact for Additive Manufacturing", *5th International Conference on Additive Technologies*, pp. 90-95, Wien, Austria, Oct. 2014.
- [5] W. Hartmann, T. Hausotte, F. Kühnlein, D. Drummer, "Incremental In-line Measurement Technique for Additive Manufacturing", *Direct Digital Manufacturing Conference (DDMC)*, Berlin, Germany, Mar. 2012.
- [6] T. Hausotte, W. Hartmann, M. Timmermann, B. Galovskyi. "Optische Messsysteme zur In-Line-Prüfung im additiven Fertigungsprozess", *Industriekolloquium des Sonderforschungsbereichs 814*, Nürnberg, Germany, Dec. 2012
- [7] R. Hartley, A. Zisserman, "Multiple View Geometry in Computer Vision", Cambridge University Press, ISBN: 978-0521540513, Apr. 2004.
- [8] G. Medioni, S. B. Kang, "Emerging Topics in Computer Vision", Prentice Hall PTR Upper Saddle River, NJ, USA, ISBN:0131013661, 2004.
- [9] D. Scharstein, R. Szeliski. "A taxonomy and evaluation of dense two-frame stereo correspondence algorithms", *International Journal of Computer Vision* 47(1/2/3), pp.7-42, Apr. 2002
- [10] J.-Y. Bouguet, "Camera Calibration Toolbox", http://www.vision.caltech.edu/bouguetj/calib_doc/, 2013.
- [11] J. Canny, "A Computational Approach to Edge Detection", *IEEE Transactions on pattern analysis and machine intelligence*, pp. 679-698, Nov. 1986.
- [12] T. Hausotte, W. Hartmann, A. Loderer, B. Galovskyi. "Optische In-Line-Prüftechnik zur Qualitätssicherung beim selektiven Strahlschmelzen von Kunststoffen", *Industriekolloquium des Sonderforschungsbereichs 814*, Nürnberg, Germany, Dec. 2014
- [13] B. Galovskyi, T. Hausotte "Testing workpieces for selective laser sintering", *ASPE 2015 Spring Topical Meeting*, pp. 89-94, Raleigh, North Carolina, USA, Apr. 2015.
- [14] B. Zhang, W.S. Land, J.C. Ziegert, A.D. Davies, "In Situ Monitoring of Laser Powder Bed Fusion Additive Manufacturing Using Digital Fringe Projection Technique", *ASPE 2015 Spring Topical Meeting*, pp. 100-105, Raleigh, North Carolina, USA, Apr. 2015
- [15] M. Aminzadeh, T. R. Kurfess., "In-situ Monitoring of Dimensional Accuracy in Additive Manufacturing by Layerwise Detection of Geometric Errors", *ASPE 2015 Spring Topical Meeting*, pp. 100-105, Raleigh, North Carolina, USA, Apr. 2015