SYSTEMATIC FORM DEVIATIONS OF ADDITIVE MANUFACTURED PARTS - METHODS OF THEIR IDENTIFICATION AND CORRECTION

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Abstract:
Additive manufacturing becomes more widespread nowadays. Selective laser sintering (SLS) as one of the additive manufacturing methods has a high potential because of a wide range of raw materials. In most cases the accuracy of a SLS process depends on the scanner system of the manufacturing laser beam, parameters of the laser beam and working distance. In order to meet higher quality parameters and to provide manufacturing defects correction a measurement system should be integrated in the process.

A measurement system should be developed with considering harsh conditions in the process chamber and taking into account features of the measurement object. Thus only non-contact sensors could be applied. Measurement systems based on the photogrammetric principle are more applicable for such tasks.

In current paper presented the investigation which was conducted to determine optical compatibility of the measurement system with raw materials. Measurements were carried out with materials heated to an operating temperature and after a melting process. Also, the test samples of different shape were produced with the SLS-Machine. The influence of the manufacturing angle was investigated. General recommendations about the compensation of this influence and for location of an object in the powder bed were formulated. This paper presents some research results necessary for detection and prevention of errors during the SLS process. It is an important experience for application and integration of a measurement system as a monitoring instrument during the SLS process.

Keywords: SLS, form deviation, measurement system

1. INTRODUCTION

Selective laser sintering (SLS), as one of the additive manufacturing approaches, is applicable to solve different scientific and industrial tasks. Producing of models with complex geometry and mechanical chains using different materials is possible with the SLS. However, there are many limitations in using this technology. SLS manufacturing process is associated with harsh environment of the process chamber and its influence on raw materials (Polyamide 12 in our research) and produced workpieces. At the end of production the workpiece temperature changes from manufacturing temperature (over 170°C) to laboratory conditions. Random deviation of the temperature in the process chamber leads to occurrence of unwanted melted areas or unwanted not melted area, missed layers and to curling of a workpiece. Estimation of the quality parameters is possible only with the post-production investigations and measurements, which leads to time and economic expenses. To improve the SLS process and prevent unwanted expenses it is necessary to provide an in-line inspection. Any workpiece, produced with the help of SLS-Machine (Sinterstation 2000, DTM), can be represented as a number of sintered together profiles (layers). Measurement of each sintered profile should be applied in order to detect and correct defects during the manufacturing process.

The ways of the in-line measurements realization and the applicable measurement approaches were analyzed in [1, 2]. As it was determined, only contactless measurement systems are acceptable for the SLS process inspection. The most suitable are laser scanning and fringe projection approaches. Based on research results presented in [3, 4] it could be concluded that measurements with a vision system (CCD camera) and image processing has a good potential. But such solution allows only 2D measurements and doesn't give any information about the height deviation of the polyamide powder (PA12) after sintering. It was mentioned [1] that the harsh environment and small dimensions of the process chamber of the SLS machine eliminates use of 3D measurement systems which are available on the market. The measurement system which based on triangulation (photogrammetric approach) has to be developed in order to provide incremental in-line measurements inside the process chamber of the SLS-Machine.

The optical compatibility of the polyamide powder with different illumination and systematical manufacturing defects of the SLS should be investigated. It gives an important knowledge base for development of the measurement system.

2. PA 12 AS THE MEASUREMENT OBJECT

2.1 Determination of influences

As determined in [1], to provide in-line inspection during the manufacturing process it is necessary to measure the surface of the powder bed at least three times. It should be noticed that the powder bed and sintered profile has to be measured. PA 12 as powder and as a sintered workpiece is a material with high roughness. This fact excludes possibility of using white light interferometry and focus-variation system. Optical properties of the powder are important for using of optical systems based on triangulation. In [5], the influence of the optical properties of thermoplastic materials on laser welding process was investigated. PA 12 as a thermoplastic has high level of light scattering. This is easy to understand after investigation of the microstructure of the sintered PA 12 workpiece (Fig. 1a). The surface has high roughness (Rc=12.2 µm) and consists of partly transparent particles.

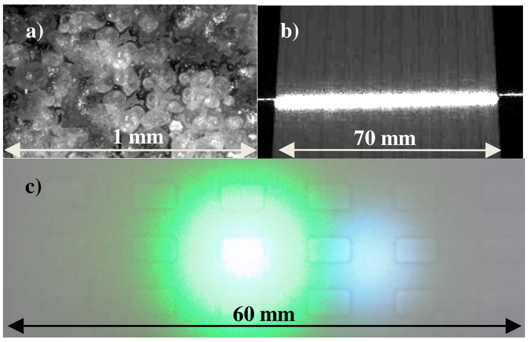

Fig. 1: PA12 – structure and optical compatibility

Figure 1b shows the sintered workpiece (produced with PA12) illuminated with laser line (wavelength: 662 nm). There is high light dispersion on the workpieces surface and at the same time the line is good focused on the background (to the left and right of the sample). The light with different wavelengths (532 nm and 415 nm) penetrates deep into the sintered part which has thickness about 4 mm (Fig. 1c). It should be noted that all tests [1] were conducted with sintered parts in order to determine optical compatibility of the material with the equipment. It was the first step to determine which measurement approach is acceptable. The most appropriate approaches should be analyzed, because there are many other influences on the measurement system [1] for the in-line inspection realization.

2.2 Measurement objects

Three types of workpieces were produced for determination of: lateral manufacturing resolution, vertical resolution and internal changes in the workpiece. Photos of all three parts are shown below: cube-standard for determination internal deviations of the sintered part (Fig. 2a); step-height standard for determination of vertical manufacturing resolution (Fig. 2b); Siemens-Star for determination lateral manufacturing resolution (Fig. 2c).

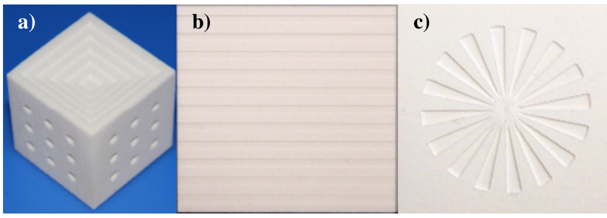

Fig. 2: Measurement objects

Four sides of the cube-standard covered with the columns of holes (one column consists of 3 holes with equal diameter and depth). The step-height standard consists of 11 stripes with different depth and was developed in accordance with the DIN EN ISO 5436-1:2000 [6]. The Siemens-Star was produced to provide investigation of lateral manufacturing resolution of the SLS-Machine. This approach was investigated in [7]. The main parameters of all manufactured standards are given in table 1.

Table 1: Parameters of measurement objects

Cube-standard	
Number of columns with holes:	12
Number of holes in the column:	3
Diameter of hole:	3 mm
Depth of holes:	3.00 mm – 4.10 mm
Step:	11×10 µm; 1×91 µm
Dimensions:	30×30×30 mm^3
Step-height standard	
Number of steps:	11
Step height:	120 µm – 300 µm
Step:	9×10 µm; 2×50 µm
Dimensions:	3×70×70 mm^3
Siemens-Star	
Diameter:	50 mm
Number of segments:	16
Depth of the segment:	0.5 mm
Dimensions:	10×70×70 mm^3

3. MEASUREMENT RESULTS

3.1 Cube-standard

The computed tomography (CT) measurement was performed on a Werth TomoCheck 200 3D in order to investigate internal deviations of the sintered part. As, compared to injection molded plastic parts, the roughness of the surface is high and the material is rather inhomogeneous, this is a comparably difficult measurement task for CT. The geometric magnification of the CT was 1.13, resulting in a voxel size of 44.0 µm. The obtained volume was evaluated with VGStudio MAX 2.1. After surface determination, the depths, radii and orientation of the cylinders were determined. Additionally, using the CAD data, an actual/nominal comparison was executed. Deviations between developed CAD model and the measurement result are shown in Fig. 3a. Maximum deviation is located in the corner of the standard. It also presented on the cross section (Fig. 3b), where the curvature of the workpiece is shown.

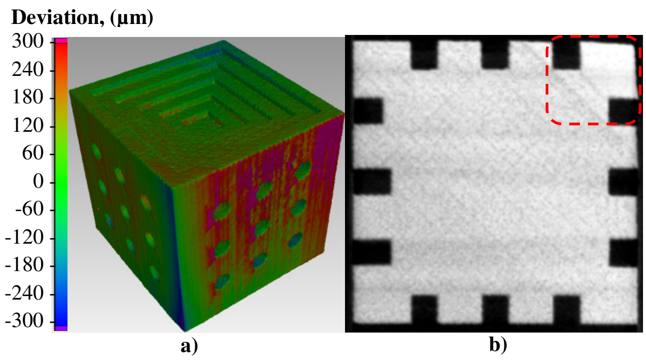

Fig. 3: Measurement result of the Cube-standard with CT

In table 2 measurement results are shown. "A" stands for a series of cylindrical holes located near the top of the cube-standard (view on the Fig. 3). Series "B" and "C" are for the middle region and bottom respectively.

Table 2: Measurement results (NV – nominal value; MV – mean value; STD – standard deviation)

Radius of holes		
	MV, mm	STD, mm
A	1.41	0.013
B	1.40	0.012
C	1.41	0.012
Depth of holes		
NV, mm	MV, mm	STD, mm
3	2.94	0.051
3.01	2.93	0.040
3.02	2.91	0.040
3.03	2.88	0.038
3.04	2.91	0.068
3.05	2.88	0.082
3.06	2.87	0.067
3.07	2.85	0.063
3.08	2.89	0.054
3.09	3.04	0.052
4.00	3.87	0.042
4.01	3.86	0.039

The deviation of the nominal holes depth is not detectable in range of changes up to 90 µm (3.00 mm to 3.09 mm), while the difference in about 900 µm is good detectable. This could indicate the limitation of the vertical manufacturing resolution of the SLS-machine.

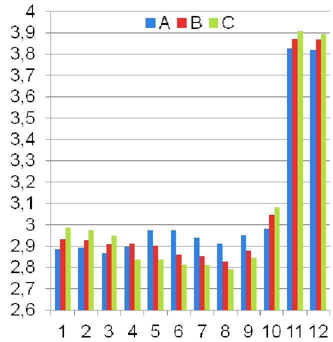

Fig. 4: Cylinders depth deviation in groups

The deviation of holes depth in groups is shown in Fig. 4 (12 groups; "A", "B", "C" - series in respect to table 2). This data confirms the result which is shown in Fig. 3. Taking into account the depth of the holes, we can draw conclusion about the internal deviation of the sintered workpiece.

3.2 Siemens-Star

The number of surface measurements was done with the TopoCAM 50 (GFM GmbH) and the measurement results were evaluated with the software TalyMap Platinum (Taylor Hobson Ltd). Measurement results presented in [1] show that flat (thin) sintered workpieces are exposed to bending due to temperature changes. The surface shape also depends on the manufacturing angle - the angle of a piece location in the powder bed. Measurements presented bellow were done in order to find out the manufacturing resolution of the SLS-machine and to detect the surface deviations.

The result of measurements of the Siemens-Star standard is presented in Fig. 5. Around the black circle (Fig. 5) is the area, where the nominal depth of segments (500 µm) is detectable. The lateral resolution of the manufacturing process can be calculated as follows [7]:

$$\text{Lateral resolution} = \pi \cdot D/n \qquad (1)$$

Where D is the diameter of detected region and n is the number of segments.

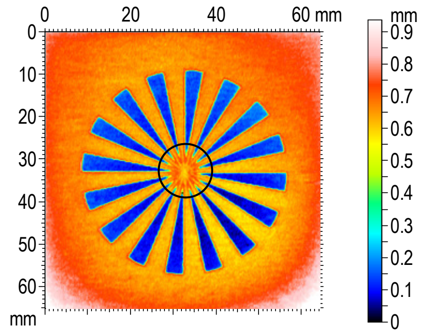

Fig. 5: Siemens-Star measurements

Calculated lateral resolution of the SLS-machine is 1.5 mm, which is close to the beam diameter of the manufacturing laser.

3.3 Step-height standard

The surface measurement of the step-height standard is presented in Fig. 6.

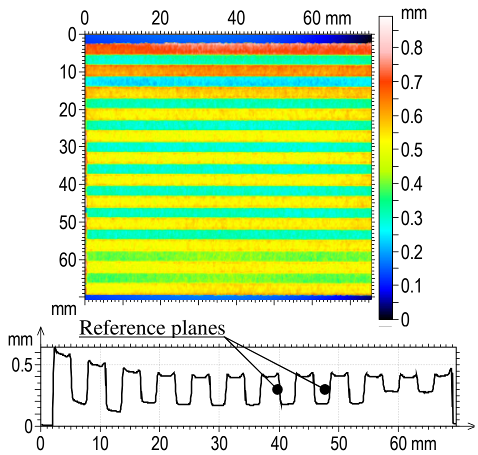

Fig. 6: Step-height standard measurements

A number of profile lines (1260) were extracted uniformly in order to analyze the deviation of the surface. It should be noted that the workpiece has not only global curvature along all body, but also local deviations of the reference planes on the top. Surface fitting with the polynomial of 4^{th} order was provided in order to compensate the global curvature (Fig. 6 - mean profile line). Step height measurements were done in manual mode of the software. Two neighbor reference planes as references for each step were considered. The width of analyzed area is 1/3 of the total step width. The results of measurement are presented in table 3. Deviations of the step height values from the nominal values cannot be considered as objective measurement result due to deviation of the reference planes. Regularity in step depth increasing is the result of local step height measurements.

Table 3: Step height measurements

Step Nr.	Nominal value	Measured value
1	120 µm	118 µm
2	130 µm	128 µm
3	140 µm	222 µm
4	150 µm	224 µm
5	160 µm	225 µm
6	170 µm	230 µm
7	180 µm	239 µm
8	190 µm	246 µm
9	200 µm	248 µm
10	250 µm	358 µm
11	300 µm	363 µm

At the same time it should be noted that a variation of 50 µm is good detectable, what confirms the parameters of the SLS-machine which was used.

4. DISCUSSION

The investigation of the cube-standard shows that some sintered part has surface deviations of the planes as well as deviations inside the body of the part. CT measurement shows location deviations of hole's axes up to 2.5°. Together with previously mentioned measurement results it confirms that even thick workpiece (with small difference of linear dimensions) is exposed to the deviations due to temperature changes. At the same time the maximum deviation is located in the corner of the cube-standard. The curved part of the standard was located closer to the surface of the powder bed at the end of producing, so was more affected by temperature changes. The Siemens-Star and step-Height standards have relatively smaller dimensions. These are thin workpieces (big difference of linear dimensions) with the body thickness 10 mm and 3 mm respectively. In accordance with the measurement results the maximal deviation of the cube-standard surfaces is about 260 µm in the affected area which has maximal curvature. The deviation on most areas of the surface lies in range of 60 µm. The global surface deviations of two other standards are: 135 µm for Siemens-Star and 216 µm for step-Height standards respectively. The deviations of the reference planes and measurement planes of the step-height standard are different. The measurement planes in the cavities have a less curvature. During the manufacturing this planes were covered with the powder and in such way were protected from rapid temperature changes. Measurement results confirm the vertical manufacturing resolution of the SLS-machine. After a single pass of the manufacturing laser beam over the powder bed appears the stripe of the sintered powder. But the width of the sintered stripe is larger than the diameter of the laser beam in focus (0.4 mm). That's why the real lateral manufacturing resolution of the SLS-machine is low. But this conclusion is valid only for cases where lateral and vertical manufacturing resolutions should be considered together.

5. CONCLUSIONS

Due to conducted measurements it is possible to conclude that a flat workpieces are in more exposed to the surface deviations due to temperature changes. The surfaces that are not covered by the powder in the final stage of manufacturing are more affected and have higher curvature. In order to avoid such manufacturing errors, algorithms for the CAD model analysis should be developed. The aim is to detect parts and surfaces subjected to distortion and to change the manufacturing angle or to add temporary elements of fixation for a part under manufacturing.

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