PARAMETERS INFLUENCING THE PRECISION OF SLM PRODUCTION

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This article focuses on production of parts by Selective Laser Melting (SLM) technology, where the prototype part is created by melting metallic powder in selective manner by means of laser – layer by layer. Due to the laser, the model is loaded with high temperatures – the high-temperature stress in the material occurs during the production and consequent cooling, resulting in undesired deformation of component's shape. This deformation may be favourably influenced by appropriate parameter settings of the production process, or by means of annealing performed after the production. This article familiarises its readers with results of research dealing with influence of production process parameter settings on the magnitude of internal material tension of the printed part, or its influence on dimension and shape precision of products manufactured by this additive technology. The produced samples were measured and their shape precision was analysed by a 3D optical digitisation method, allowing comparison of the actual part to a nominal CAD model and therefore perform shape and dimension precisions of the produced prototypes in a complex and objective manner.

KEYWORDS
SLM, selective laser melting, geometrical accuracy, 3D optical scanner, 3D digitization

1 INTRODUCTION

Additive technologies are becoming an indispensable tool for development of more and more complex parts and contribute to decreasing time necessary to development and innovation of new products in a significant manner. Especially technologies creating parts from metallic powders are no longer used only for quickly production of prototype components, but are now also used as a production technology. The huge advantage of these technologies is the possibility of producing shapes and components that cannot be created by means of other technologies. Therefore, the requirements on both, construction and engineer are changing. It is no longer necessary to strictly consider, whether it is possible to produce the given structure, conversely, it is possible to optimise the component in terms of e.g. stress, aerodynamics, cooling, etc. Such optimisation often results in relatively complex parts in terms of shape, which can, however, be produced only by means of additive technologies.

Still, these are quite new technologies, facing many issues. As well as in case of any other technology, in 3D printing, the precision of the end product is influenced by a variety of factors and effects that shall be familiarised with in order to provide high dimensional and shape precision. This article shows the efforts to find fundamental parameters for parts production by means of SLM (Selective Laser Melting), to achieve as high resulting precision of shape as possible.

The precision of production and testing with various production parameter settings of SLM technology [Ilcik 2013] and [Ilcik 2014]. These tests were focused on determining influence of individual parameters for parts production on surface quality and external dimensions. But there is not inspected the effect of heat treatment on the geometric precision of parts. [Krolikowski 2013] deals with inspection of dimensions during production by means of SLM as well. In this case, dimensions of thin-walled parts are inspected. Based on own experiments [Mendricky 2014], the main issue related to precision of shape lies in internal tensions of parts and increased wall thickness. This will result in deformation of part after it is removed from the base plate. In the worst case, when the parameter and positioning is set incorrectly, the part will be torn off the base plate during production, leading to degradation of the part and considerable time and financial loss.

2 SLM TECHNOLOGY

The SLM technology is one of many additive technologies, used not only for manufacturing and verifying prototype components, but for manufacturing the final components as well.

Similarly to many other additive technologies, the initial model data are in STL format. With special software, these data are appropriately positioned into the machine's workspace, support structures are calculated and everything is sliced to individual planar layers with thickness depending on the chosen material from 20 to 100 µm. These layers are a base for own production of the part. The production material in case of this technology are metallic powders based on aluminium, steel, titan, nickel and other metals, even precious ones.

In the machine's workspace, continuous layers of powder are applied, first on the base plate, then on each of the previously applied layers. Based on the previously calculated cuts, the powder is melted by laser on the given spots. The perimeter of the cut is melted first, and then the machine melts the inner surface of each cut part by part. Due to that, high temperature stress and internal tension occurs in the part itself, resulting in undesired deformations of shape. Afterwards, another layer of powder is applied and the whole process is repeated, until the whole part is manufactured.

It is necessary to clear the manufactured part of all excessive powder, remove from the base plate and remove the supporting structures in a mechanical way. The purpose of the supporting structures is mainly preventing shape deformations during the manufacturing when the laser heats the area.

3 PRODUCTION PROCESS OF TEST PARTS

Since there is no standard for testing dimension and geometrical precision of parts production by means of additive technologies, an own model was designed based on researches listed in [Mendricky 2014]. The model base plate dimensions are 100 × 100 mm, there are holes with M6 threads modelled in the side walls of the base plate allowing attachment of a measurement unit. The model also contains system for basic dimension inspection, i.e. lengths, angles and diameters, or radii of spherical and cylindrical surfaces and curves. In addition, it is possible to check some of the shape and position deviations such as flatness, parallelism, concentricity of cylindrical surfaces, perpendicularity, etc. In addition, it is possible to evaluate production of minor details, thin walls, ribs, edges, tips, etc., see Fig. 1.

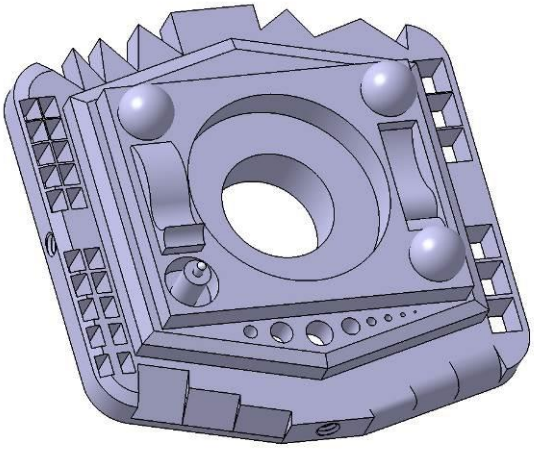


Figure 1. Designed CAD model

The first step, before the construction itself, is positioning the model in the machine's workspace. This step is very important in case of SLM technology, since then the model is positioned incorrectly, sudden changes of surface sizes of consequent cuts may occur, resulting in high internal tension. Therefore, the part is positioned diagonally on the corner so that the surface changes of cuts are gradual and without rapid changes. This fact was regarded during the model designing, so that the key dimensions of the model, which will be subsequently inspected, are not surrounded by the supporting structure. That is because the mechanical removal after the manufacturing would affect the results of manufacturing precision.

All models were made of AlSi12. Production of the first part, Model 1, was performed based on parameters recommended by the manufacturer of the machine, while the layer thickness is 50 µm. The construction itself was successful, however, during cooling of Model 1 and during cleaning from excess powder, the model was tearing off the support due to internal tension; see Fig. 2. This phenomenon was also confirmed by analysis of geometrical precision [Mendricky 2014].

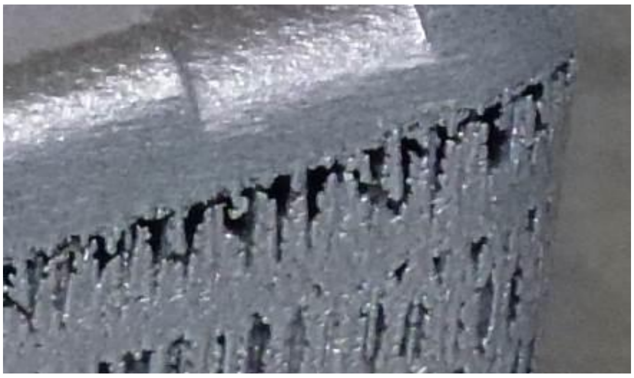


Figure 2. Model 1 – problem with the support structures

The shape deformation of Model 1 occurred immediately after the production – when it is not possible to move the base plate with the parts into a furnace in order to perform annealing and remove the internal tension. Therefore, it was necessary to make changes for the next experiments to avoid such deformation of shape.

So that the consequent comparison of dimensions is performed in the same condition, it was decided that the Model 2 is left with the same orientation on the base and with higher density of support structured on the critical spots, where they tore off the model. In addition, the temperature of base plate was increased from 150 °C to 200 °C. These measures was proved to be sufficient to prevent deformations, when the model is connected to the base plate via the supports (see Fig. 3) as the consequent measurement showed.

Figure 3. Model 2 with support structures on the base plate

Since the temperature of 200 °C is on the threshold of the recommended temperature for annealing to remove tension, and the production time of this model was nearly 8 hours, the annealing was not performed in case of this model. The consequent measurement confirmed the significant improvement of shape precision when compared to the previous model. At the same time, however, based on the comparison of measurement before and after dismounting the Model 2 from the base plate, it was found that a certain amount of deformation occurred upon the dismounting.

Therefore, a third model – Model 3 was produced, and was cleaned from excess powder and with the base plate underwent annealing process in order to remove internal tension in conditions of temperature 220 °C for 9 hours with consequent slow cooling off to a room temperature.

4 ANALYSIS OF PRODUCTION PRECISION

In order to determine the influence of 3D printing parameters to a shape and dimension precision of the produced samples, it is necessary to measure these models in a complex manner and perform analysis of the results. Due to previous experience [Mendricky 2014], an optical contactless measurement method was chosen for this purpose, since this method offers several significant advantages when compared to other conventional methods. Due to the high data density, it allows obtaining a real 3D model of objects with complex shapes with high precision.

4.1 Methods and Equipment Used

The digitisation was performed by means of GOM – ATOS II 400 optical contactless 3D scanner from GOM Company. The scanner was fitted with lens with measurement volume of 250 x 200 x 200 mm (Fig. 4). This device uses principles of optical triangulation, photogrammetry and Fringe Projection methods for the point coordinates calculation. Strips of light are projected on the surface of the object (Fig. 5), while these strips are captured by two cameras fitted with CCD chip.

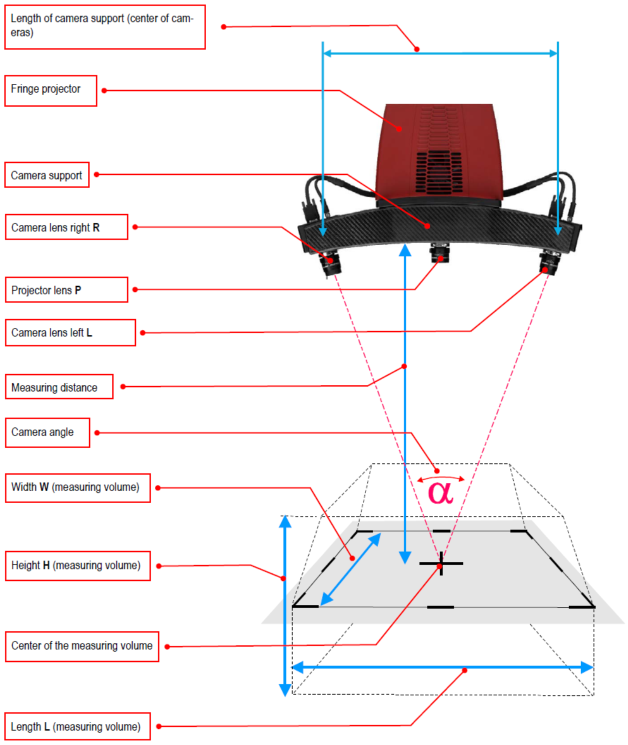


Figure 4. Definition of measurement volume of optical scanner ATOS II 400 [GOM 2012]

Before the scanning process itself, the object was fitted with so called reference points and due to glossy surface of the object, a thin layer of anti-reflection coating with titanium powder had to be applied (Fig. 5). During the scanning process, the model was mounted to a rotary table to a measuring fixtures, 40 scans from various positions and angles was then perform in order to scan the whole surface of the model. Partial scans were then transformed to a common coordinate system by means of reference points. Then a high resolution optimised polygonal network was calculated. The obtained data were evaluated by means of GOM Inspect Professional software.

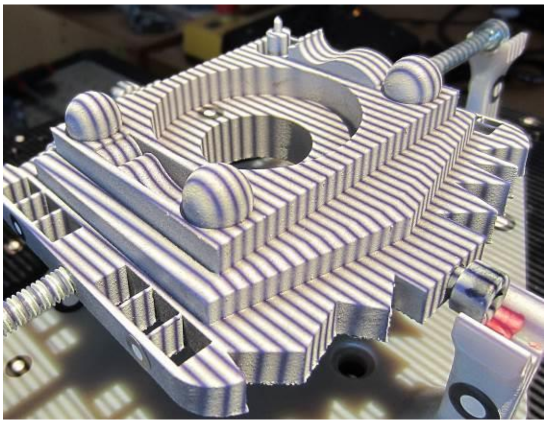
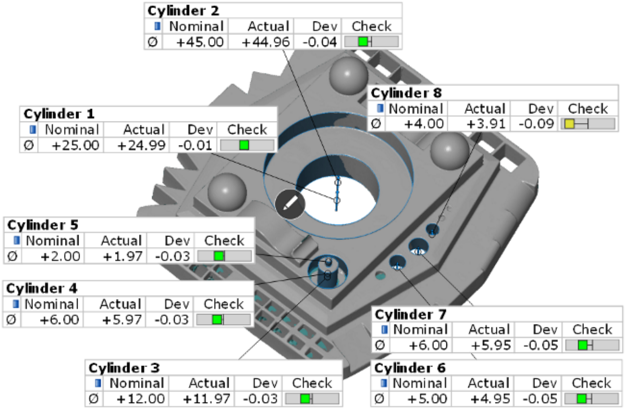


Figure 5. Process of digitisation of the examined sample

4.2 *Analysis of Dimensions*

First, an analysis of dimension precision of the model was performed. The subjects of inspection were diameters of spherical and cylindrical surfaces, angles, length dimensions, distances of the individual elements, etc. In case of cylindrical surfaces, the external shapes with nominal diameters of 2 and 6 mm and cylindrical holes with diameters of 4, 5, 6, 12, 25, and 45 mm were evaluated (Fig. 6).



Cylinder 2

	Nominal	Actual	Dev	Check
Ø	+45.00	+44.96	-0.04	🟩

Cylinder 8

	Nominal	Actual	Dev	Check
Ø	+4.00	+3.91	-0.09	🟨

Cylinder 1

	Nominal	Actual	Dev	Check
Ø	+25.00	+24.99	-0.01	🟩

Cylinder 5

	Nominal	Actual	Dev	Check
Ø	+2.00	+1.97	-0.03	🟩

Cylinder 4

	Nominal	Actual	Dev	Check
Ø	+6.00	+5.97	-0.03	🟩

Cylinder 7

	Nominal	Actual	Dev	Check
Ø	+6.00	+5.95	-0.05	🟩

Cylinder 3

	Nominal	Actual	Dev	Check
Ø	+12.00	+11.97	-0.03	🟩

Cylinder 6

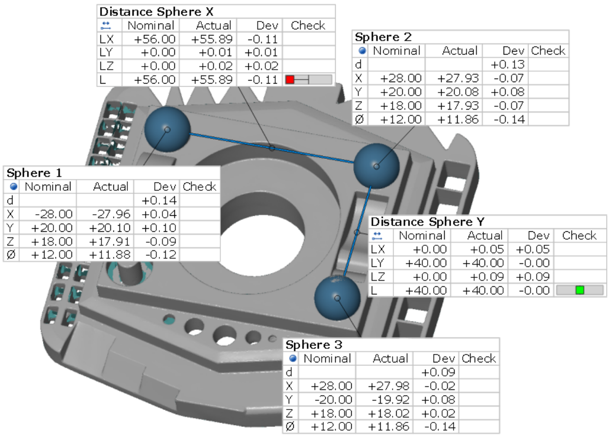
	Nominal	Actual	Dev	Check
Ø	+5.00	+4.95	-0.05	🟩

Figure 6. Evaluation of diameters of cylindrical elements

The inspection showed that the cylindrical surfaces show very good compliance with nominal dimensions of all produced samples. Any influence of printing parameters and consequent thermal annealing on the absolute dimension of individual elements was not observed. The measured values are listed in the following table (Tab. 1). The table also shows that in all cases, the real diameter of both, external and internal, was smaller than nominal, and with one exception (Model 2, Cylinder 2, Deviation -0.23 mm), the errors were ranging within the acceptable tolerance of -0.1 mm.

Dimensions on		All	Model1		Model 2		Model3		
Geometry		Nom.	Actual	Error	Actual	Error	Actual	Error	Units
Cylinder 1	inner	25.00	24.99	-0.01	24.90	-0.10	24.97	-0.03	mm
Cylinder 2	inner	45.00	44.96	-0.04	44.77	-0.23	44.90	-0.10	mm
Cylinder 3	inner	12.00	11.97	-0.03	11.88	-0.12	11.91	-0.09	mm
Cylinder 4	inner	6.00	5.97	-0.03	5.97	-0.03	5.98	-0.02	mm
Cylinder 5	inner	2.00	1.97	-0.03	2.00	0.00	1.99	-0.01	mm
Cylinder 6	inner	5.00	4.95	-0.05	4.91	-0.09	4.93	-0.07	mm
Cylinder 7	inner	6.00	5.95	-0.05	5.90	-0.10	5.92	-0.08	mm
Cylinder 8	inner	4.00	3.91	-0.09	3.91	-0.09	3.93	-0.07	mm

Table 1. Dimensions of the cylindrical elements



Distance Sphere X

	Nominal	Actual	Dev	Check
LX	+56.00	+55.89	-0.11	
LY	+0.00	+0.01	+0.01	
LZ	+0.00	+0.02	+0.02	
L	+56.00	+55.89	-0.11	🟥

Sphere 2

	Nominal	Actual	Dev	Check
d			+0.13	
X	+28.00	+27.93	-0.07	
Y	+20.00	+20.08	+0.08	
Z	+18.00	+17.93	-0.07	
Ø	+12.00	+11.86	-0.14	

Sphere 1

	Nominal	Actual	Dev	Check
d			+0.14	
X	-28.00	-27.96	+0.04	
Y	+20.00	+20.10	+0.10	
Z	+18.00	+17.91	-0.09	
Ø	+12.00	+11.88	-0.12	

Distance Sphere Y

	Nominal	Actual	Dev	Check
LX	+0.00	+0.05	+0.05	
LY	+40.00	+40.00	-0.00	
LZ	+0.00	+0.09	+0.09	
L	+40.00	+40.00	-0.00	🟩

Sphere 3

	Nominal	Actual	Dev	Check
d			+0.09	
X	+28.00	+27.98	-0.02	
Y	-20.00	-19.92	+0.08	
Z	+18.00	+18.02	+0.02	
Ø	+12.00	+11.86	-0.14	

Figure 7. Evaluation of diameters and distances of spherical elements

Spherical elements were subjected to further analysis (Fig. 7). Their diameter and, above all, pitch was inspected, while inspection of spherical elements is best to show the precision, with which the printer is able to work in individual coordinate axes, in this case, on X- and Y-axis. When measuring the distance, the resulting dimension is not influenced by eventual dimension error of the given element, and the possible negative effect of anti-reflective coating applied during 3D scanning is eliminated as well.

It is apparent from the following table (Tab. 2) summarising the measured values on all models, the influence of 3D printing parameters on dimension precision was not proved in this measurement session as well. Diameter deviations of all three spherical surfaces were ranging in negative values, specifically between 0.00 to -0.14 mm, in all printed models (similarly to cylinders). Distance of elements in X-axis was comparable in all models; the deviation from nominal dimension was approximately -0.12 mm, in case of Y-axis, the deviation was approximating zero.

Dimensions on		All	Model1		Model 2		Model3		
Geometry		Nom.	Actual	Error	Actual	Error	Actual	Error	Units
Sphere 1	diameter	12.00	11.88	-0.12	11.89	-0.11	11.92	-0.08	mm
Sphere 2	diameter	12.00	11.86	-0.14	11.88	-0.12	11.91	-0.09	mm
Sphere 3	diameter	12.00	12.00	0.00	11.90	-0.10	11.91	-0.09	mm
Sphere 1-2	distance X	56.00	55.89	-0.11	55.85	-0.15	55.88	-0.12	mm
Sphere 2-3	distance Y	40.00	40.00	0.00	39.77	-0.05	39.98	-0.02	mm

Table 2. Diameters and distances of spherical elements

4.3 Analysis of Shape

Despite the fact that Model 1 showed much more apparent deformation at first sight than the following models, the analysis of inspected parts in terms of absolute dimensions did not show any significant problem and no differences were manifested between individual inspected models. Therefore, as a second step, analysis of printed models shape was performed; so called tolerances of shape and position (GD&T) were examined.

Various parameters such as flatness, cylindricity, concentricity, etc. were inspected. In case of some analyses, the results were comparable in terms of all models. For example, the measured error of cylindricity on Cylinder 1 and 2 of all three models was ranging between 0.1 mm and 0.15 mm. The evaluation of cylindricity of Model 1 is shown in the Fig. 8.

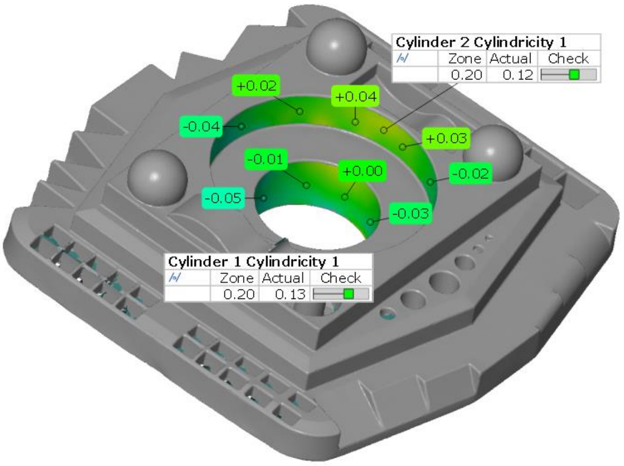


Figure 8. Tolerance of shape and position (cylindricity)

However, the situation was quite difference when measuring flatness (Fig. 9). Although the mere change of printing parameters (Model 2) did not have any significant influence on the undesired deformation, the deformation of shape (to about half) was significantly decreased in the model annealed after the printing, thus relieved of internal tension (Model 3). The flatness errors of individual models are shown in Fig. 10. An assumption, where the most significant problem of production by means of SLM technology is the deformation of the model in the table plane, was confirmed.

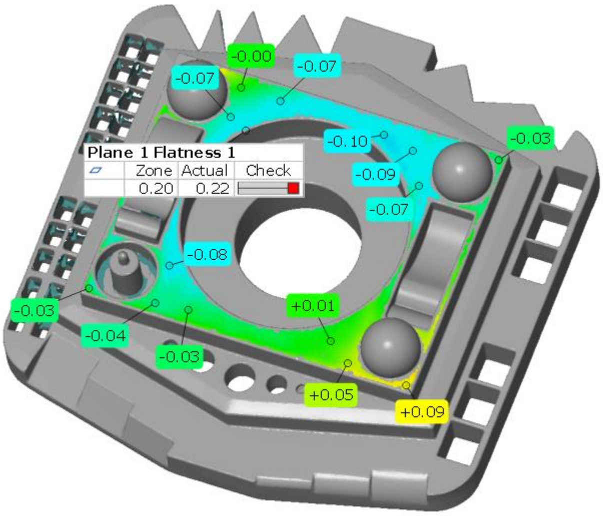


Figure 9. Tolerance of shape and position (flatness)

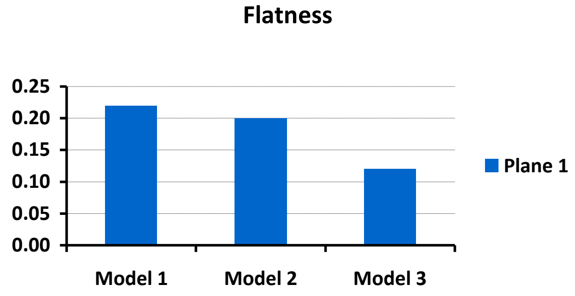


Figure 10. Flatness error in Plane 1

4.4 Evaluation in Comparison to CAD Model

As already indicated in the introduction, during the 3D printing by means of metallic materials, a large quantity of heat is generated, and due to internal tension, significant deformations of shape occurs in the produced parts. However, if we would inspect the produced part by means of conventional method such as measuring discreet dimensions of length on a coordinate measuring machine, we might not be able to detect some significant deformations. This is also confirmed by the aforementioned results of sample measuring, where the linear and angular dimensions were, in most cases, within the required tolerance, and the performed measurement did not show any deformation problem or significant deviation from the required shape. Besides the evaluation of date about the shape and dimensions, the optical 3D digitisation method offers a significant advantage – it allows calculation of normal deviation from the nominal model on any spot of the component. Such evaluation is then complex and much more objective, and often helps detecting production problem quickly and more effectively. For the purpose of analysis, the model was locally aligned through the upper part to the CAD model and the calculated magnitude of normal deviations was shown by means of colour spectrum (Fig. 11).

As apparent from this analysis, the most significant deformation occurred in sample designate as Model 1. From the upper perspective, the model is concave and all four corners of the model show significant positive deviation when compared to its centre parts. Although the error ranges around the acceptable value of 0.2 mm, one of the corners is 0.8 mm above the nominal model value.

When comparing model position in the workspace during printing (Fig. 3) to the determined deformation (Fig. 11), it is apparent that it is the area located on the bottom during the 3D printing, the one where the production started. It can be concluded that the highest tension (or the risk of the highest tension) in the material occurs in this spot. In case of Model 1, these forces were so significant in the mentioned spot that during cooling off, the supports spontaneously tore off the pad, making the magnitude of deformation even more significant.

When printing the second sample, the density of supports was increased as well as the temperature of the pad during printing. In this case, the support structures were not disrupted, however, after the model was separated from the pad and the internal tension was equalised, the torsion of the part occurred in this case as well. However, the maximal deformation was decreased to 0.3 mm, as apparent from the colour map in the centre.

On the bottom, deviations of the model are shown, while this model was produced in the same technological condition as Model 2. Nevertheless, after the printing process was completed, the part was annealed for 9 hours in temperature of approximately 220 °C in order to decrease the internal tension. As it turned out, this procedure had undeniable positive impact on further decrease of model deformation. Even in the most exposed spot, after the pad was cut off, the deformation with ranging within the acceptable limits of 0.15 mm.

The representation of produced model's deviations is well apparent from so called histograms (Fig. 12). Those can be used to obtain frequency representation of the deviations on the whole model.

While in case of Model 1, the frequency of deviations ranging from -0.3 to 0.8 mm (therefore a total Z-axis formation error is more than 1 mm) is high, in case of Model 2, the total error decreased to 0.5 mm (ranging between -0.3 and 0.2 mm), and in case of annealed Model 3, the total error was ranging from -0.2 to 0.15 mm (a total of 0.35 mm).

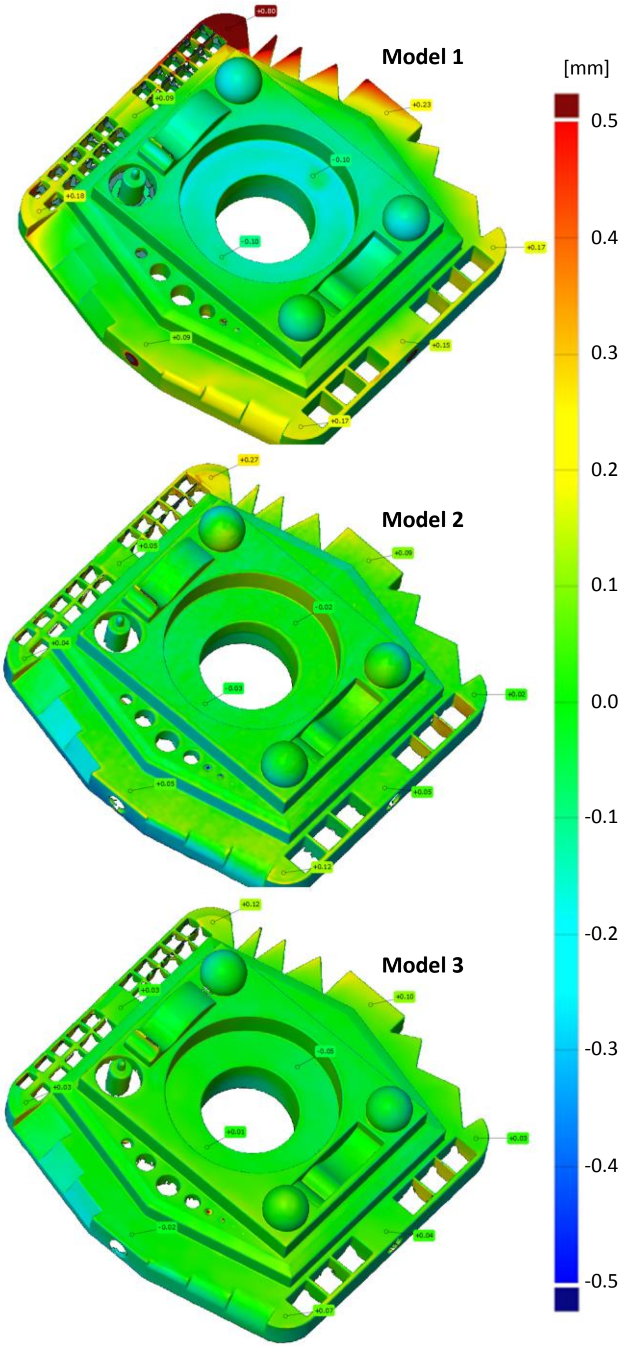


Figure 11. Colour deviation map

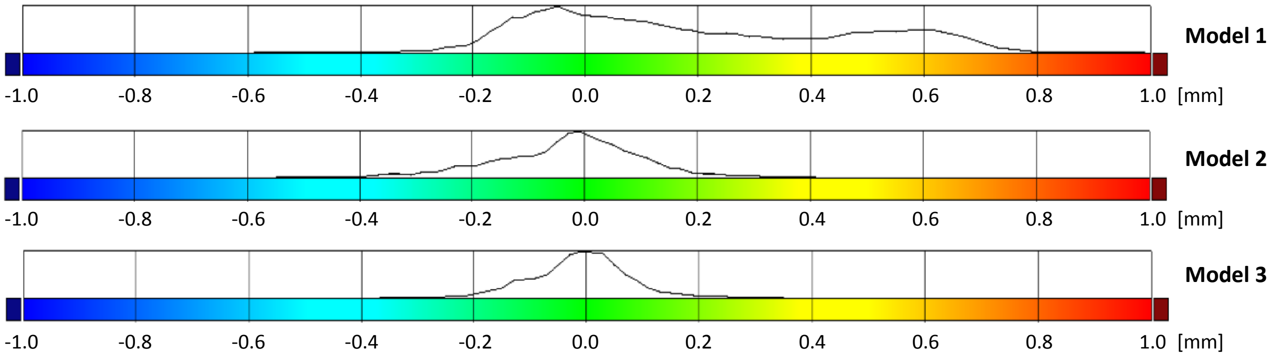


Figure 12. Histograms of deviations from nominal model

5 CONCLUSIONS

This article is a result research of part manufacturing precision of the SLM technology. For the purpose of this research, a model of a special shape was designed, while this model was then repeatedly produced by means of melting metallic powder on LSM 280HL machine. During production of individual samples, the technological conditions were subjected to change (types of supports, platform temperature, etc.), and the influence of these conditions on the consequent deformation of the produced part was tested. Simultaneously, the impact of temperature stabilisation on the dimension and shape precision of the products manufactured by means of this additive technology was verified. The performed analysis of complex geometrical precision implies that the dimensional precision of individual elements of printed models show relatively good match with the nominal model and ranges within the tolerance values given by the manufacturer of the machine. Generally, the change of 3D printing conditions has negligible impact on the length dimensions.

However, a significant influence of printing parameters used was shown when analysing shape deformation of the produced samples. The analysis was performed by comparing printed parts to the nominal CAD model. It was found out that the tension is so high that the support may not be able to fix the model to the platform for the whole printing part and may be torn off. It was also found out that it is advantageous to use more dense support network and higher temperatures of the base plate. By doing so, the deformation decreases to more than a half. The research also showed that annealing also has a positive impact on increase of shape precision of the product. When using the AlSi12 material, due to the temperature stabilisation in temperature of 220 °C for 9 hours, the internal tension was decreased and the total deformation in Y-axis was reduced by 0.15 mm.

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REFERENCES

[GOM 2012] GOM MBH. ATOS V7 – Hardware - User manual. Braunschweig, Germany, 2012.

[Ilcik 2013] Geometrical accuracy of the metal parts produced by additive technology Selective Laser Melting. Brno: University of Technology, Faculty of Mechanical Engineering, 2013. (in Czech)

[Ilcik 2014] Ilcik, J. et al. Geometrical Accuracy of the Metal Parts Produced by Selective Laser Melting: Initial Tests. In. Modern Methods of Construction Design. Switzerland: Springer International Publishing, p. 573 - 582, 2014. ISBN 978-3-319-05202-1

[Krolikowski 2013] Krolikowski, M. and Filipowicz, K. Verification of geometrical accuracy of Selective Laser Melting (SLM) built model. In. Advances in Manufacturing Science and Technology, Vol. 37, No. 3. Poland: Polish Academy of Sciences Committee of Mechanical Engineering, 2013.

[Mendricky 2014] Mendricky, R. and Keller, P.: Precision Analysis of Part Manufacturing Using SLM Method. In. Applied Mechanics and Materials, Vol. 693 (2014), Trans Tech Publications, Switzerland, p. 183- 188, ISSN 1660-9336

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