Dimensional Accuracy of a Product Built Using Direct Metal Laser Sintering

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Direct Metal Laser Sintering (DMLS) is a method of Metal Additive Manufacturing which builds metal parts in a layer-by-layer procedure based on a CAD template. This method is diametrically different from machining methods such as turning or milling. Nowadays, DMLS is used for rapid manufacturing of complex metal parts. However, these products do not meet the requirements of high accuracy and surface quality. This paper deals with factors that are involved in the dimensional precision of DMLS production. The purpose of the Scale and Beam offset correction coefficients are described in the paper. Practical experiments and measurements were carried out and are presented here. Usual production accuracy was observed.

Keywords: Dimension Precision, Direct Melting Laser Sintering, Metal Additive Manufacturing, Selective Laser Melting

1 Introduction

Metal Additive Manufacturing (MAM) is based on the technology of melting thin layers of metal powder. Direct Metal Laser Sintering (DMLS) is the MAM technology which melts the powder by laser beam. A major difference compared to conventional production methods such as machining is in its opposite approach. Machining removes the material from the workpiece in the form of a chip, whereas MAM does not remove material, but gradually adds the metal in layers.

The advantages of MAM apply primarily to the rapid and cost-efficient production of prototypes directly from electronic data. Nowadays this technology is becoming more affordable, and the ability to produce several physical models in a short time has helped significantly shorten the production stage of the product. This is why MAM is well established on the market. MAM products are not only used as a visualization tool for testing assemblies but also as a full replacement for functional components in specific cases of piece and serial production. [1][4]

The relative density of the melted material is close to the theoretical value and mechanical properties are comparable to conventional materials. Heat treatment can be used to reduce the residual stress caused by a high temperature gradient during the manufacture of the parts or to modify the microstructure of the metal material. [6] If high dimensional and surface precision of parts is required, in most cases additional machining is included after MAM. [1]

Additive manufacturing technology in any form is not yet able to produce products that meet the high quality surface requirements such as milling or turning. [5] One cause of lower surface quality is the 'stair-effect'. This phenomenon is more pronounced when the building direction of the surface makes a smaller angle with building platform or with increasing layer thickness. Generally, the surface roughness of MAM products is still a limiting factor when compared to conventional machining technology. The roughness parameter Ra does not reach a better value than 5 μm. [3]

Dimensional accuracy is the next aspect influencing the quality of the product. Shrinkage is another influential aspect that affects dimensional accuracy as in the case of casting. [2] The main aim of this article is to determine the dimensional accuracy of a test sample which was produced on an EOS M 290 using DMLS technology.

2 Aspects Affecting Geometric Accuracy

Dimensional accuracy is the result of many factors, which are described below. The basic assumption is that a dimensional deviation from the desired shape is the consequence of material shrinkage, inaccuracies of the optical system, the surface roughness and deviations resulting from the calibration options. The effects of the material and its interaction with the process parameters are not taken into account.

Shrinking of the material

Shrinkage is influenced by the material, part size, energy input and time interval between exposure. Steel responds to changes in temperature by dimensional instability. The coefficient of linear expansion and melting point depend mainly on the chemical composition of the steel. The coefficient of Maraging Steel 1.2709 is $10\cdot10^{-6}$ m/mK. [7] Which means that one meter long rod extends by 0.01 mm when the temperature changes by Δ 1 °C. This is a relatively small increment, but it is important to realize that in DMLS the material heats up from a low temperature to the melting point of the powder (1413°C [8]).

Whereas the temperature of the melting pool is set by energy input (1), the interval between exposures is the time after which the melted material can cool down. Especially for large parts, shrinkage can be a bigger problem, which participates in creating great internal stress in the material.

$$\boldsymbol{E}\left[\frac{J}{mm^3}\right] = \frac{\textbf{Laser power } [\boldsymbol{W}]}{\textbf{Speed}\left[\frac{mm}{s}\right]\cdot\textbf{Layer thickness } [\boldsymbol{mm}]\cdot\textbf{Hatch distance } [\boldsymbol{mm}]} \quad (1)$$

The exposure strategy can reduce negative influences such as internal stress and its effect on the dimensions.

The core of big parts is melted after small regions using a "chessboard" exposure strategy. This exposure strategy reduces the internal stress. The 'skin' exposure strategy is outer core area. The last one, the "Contour" strategy, is responsible for the outer surface and final accuracy of part. The basic exposure strategies are shown in Figure 1.

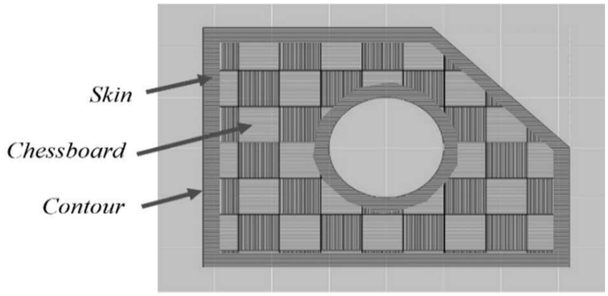

Fig. 1 *Exposure strategies when building a part using DMLS*

The effect of shrinkage on accuracy is solved by the Scale factor of the model. This factor compensates the influence of shrinkage after cooling of the part to room temperature. Figure 2 clarifies the influence of the scale on the dimensions of the part. The dimensions of "Part without Scale" show the part size without the Scale factor. In this case, the nominal dimension is less than the reference "Defined size by CAD". The correct scale value creates a size correlation between the model and the printed part. See dashed lines of dimensions. [11]

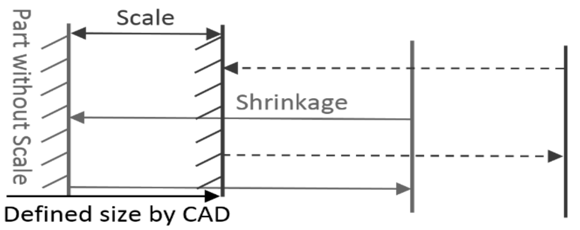

Fig. 2 *Compensation of the shrinkage by scale factor*

Stair-effect

Another cause of worse surface quality is the stair-effect. This phenomenon is caused by the principle of additive manufacturing, which proceeds layer by layer. Figure 3 illustrates the parameters that affect the clarity of the stair-effect. The inclination angle and the layer thickness affect the clarity. Where (ℓ) is the thickness of the layers and (α) is inclination, the angle between the build surface and the building plane. The clarity is marked with the size (s). [10]

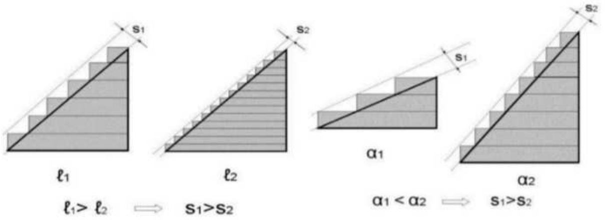

Fig. 3 *Optimized porous sample [8]*

Beam offset

The laser point used in the DMLS process has a diameter of about 70 μm. The diameter of the melt pool of the metal powder is larger. The size of the melt pool is influenced by the material, energy input and the exposure strategy. The Beam offset compensates the effect of the size of the melt pool to the resulting dimensions of the built part. How it is shown in Figure 4. Correctly setting this parameter is as important as the Scale factor. [11]

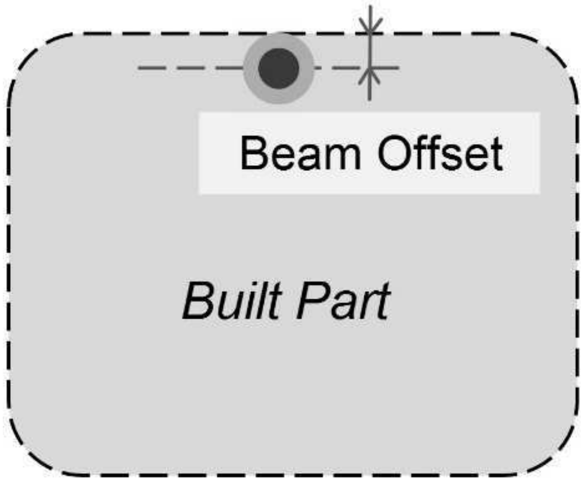

Fig. 4 *The size of the Beam offset*

Calibration of the optical system on the EOS M290

Empirical assessment of the effects of individual parameters is very difficult because melting is a complex thermo-physical process. Scale factors and Beam offset are determined on the basis of an evaluation of a calibration job.

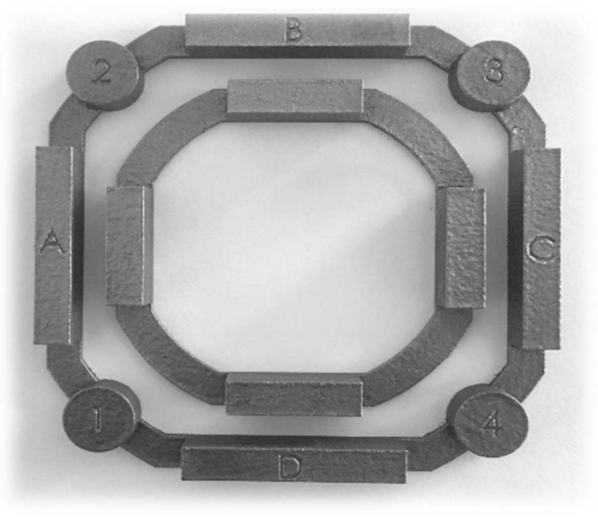

Fig. 5 *Calibration job for determining the Scale and Beam offset*

For these purposes, the manufacturer of the EOS device created a special job – the calibration job. This job contains a part which is a composite of blocks and cylinders. The distances between individual elements and dimensions are compared with the model template. The actual values of the Beam offset and Scale factors for directions ***x*** and ***y*** are taken into consideration. The result should be that the new calculated values are more accurate and the parts are closer to the dimensions of the model template. The calibration job is shown in Figure 5.

The values used for the experiment are as follows: Beam Offset = 0.181 mm, scaling x= -0.007 % and y= 0.032 %. Each EOS M 290 machine is unique and therefore these values are only applicable to a specific one.

3 Dimensional variation

Two samples were produced in two different positions according to Figure 6. The comparison part has maximum dimensions 52 mm x 38.5 mm x 15.3 mm (h x l x w) which was analysed by a Zeiss Prismo 7 Navigator. The dimensions are shown in Figure 7 and are listed in Table 1. The supports are shown in blue/dark in figures 6a) and 6c) and they were removed from the parts in the post-processing. Affected surfaces were carefully ground to reach the highest possible accuracy. The dimensions after post-processing are marked by asterisks ('*') in Table 1.

All diameters were measured at 1000 points and circularity was evaluated with a specified tolerance of 0.1 mm. Only the circle P2 was measured at 150 points, which were not around the circumference. Other dimensions are evaluated as the distance of two points.

The results show that the dimensions of the holes become smaller while the outer dimensions are larger than the model. This means that the printed parts have more metal substrate due to added volume, and additional machining can improve dimensional accuracy. The largest deviations were measured in dimensions P3(K2) of both parts, and S1, Z3 only for Part 2.

The major cylinder of Part 2 achieved better quality and precision than Part 1. Cylindricality is much more accurate than in Part 1 (0.072 mm vs 0.239 mm) due to the orientation of the part during production. The opposite situation is seen in the horizontal cylinder of Part 2. The inner surface on the top of the hole (P4) is lower quality than the hole in Part 1. According to the basic rules of AM, diameters smaller than 8 mm do not require supports, and removing these structures is also very impractical and difficult. In general, production of holes in the horizontal position is not as accurate as in the vertical direction. In summary, Part 1 achieved smaller dimensional deviations from the part model than Part 2.

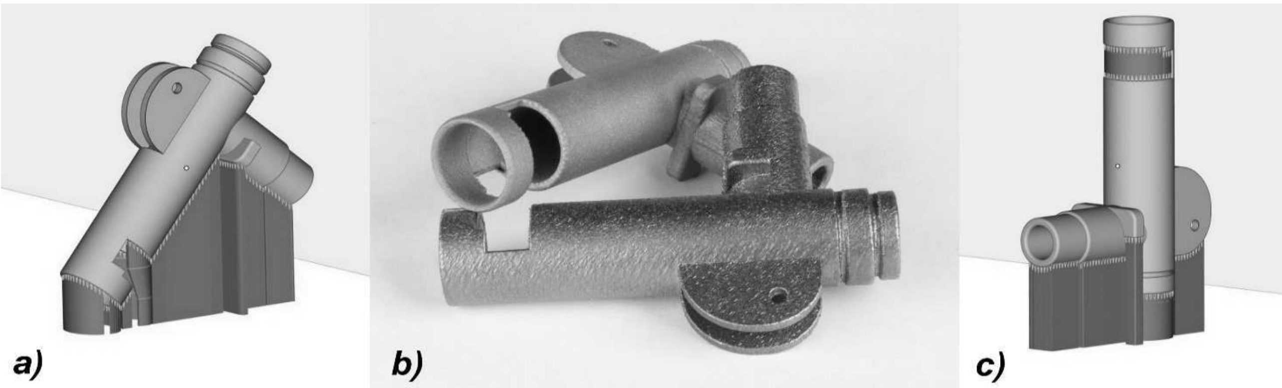

Fig. 6 *The measured part; a) orientation of Part 1 during AM; b) manufactured parts; c) orientation of Part 2*

Tab. 1 *The measured dimensions of parts*

Dimension	Part 1		Part 2	
	Diameter/Distance	Circularity	Diameter/Distance	Circularity
K1 = 12.000 mm	12.009* (+0.009)	0.101	11.994 (-0.006)	0.027
K2 = 12.000 mm	12.051* (+0.051)	0.131	12.053 (+0.053)	0.020
K3 = 12.000 mm	12.030* (+0.030)	0.113	12.052 (+0.052)	0.040
ØK	12.030	0.239 - Cylindricity	12.033	0.072 - Cylindricity
P1 = 9.000 mm	9.001* (+0.001)	0.088	8.893* (-0.107)	0.136
P2 = 10.000 mm	10.147*(+0.147)		9.875* (-0.125)	
P3(K2) = 10.098 mm	**9.645** (-0.453)	0.134	**9.730** (-0.368)	0.082
P3(K3) = 10.098 mm	9.998 (-0.100)	0.081	9.990* (-0.108)	0.240
P4 = 6.100 mm	6.045 (-0.055)	0.094	5.986 (-0.114)	0.213
D1 = 5.000 mm	4.870* (-0.130)	-	5.054* (+0.054)	-
D2 = 6.000 mm	6.041* (+0.041)	-	6.048* (+0.048)	-
S1 = 15.300 mm	15.340 (+0.040)	-	**15.142** (-0.158)	-
S2 = 2.500 mm	2.482 (-0.018)	-	2.505 (+0.005)	-
S3 = 4.905 mm	4.895* (-0.010)	-	4.779* (-0.126)	-
M1 = 5.000 mm	4.951* (-0.049)	-	4.863* (-0.137)	-
Z1 = 6.800 mm	6.905 (+0.105)	-	6.806 (+0.006)	-
Z2 = 1.400 mm	1.409 (+0.009)	-	1.356 (-0.044)	-
Z3 = 4.000 mm	4.073 (+0.073)	-	**4.155** (+0.155)	-
Z4 = 1.400 mm	1.423 (+0.023)	-	1.294 (-0.106)	-

Surface roughness was also measured. The region selected for roughness analysis is the flat surface in the Z area, see Fig. 7. The raw form after printing without post-processing had the following parameters: Ra= 7.54 µm, Rq= 10.00 µm, Rt= 75.67 µm and Rz= 51.22 µm. The measurement surface was sandblasted and the following values were recorded: Ra= 5.02 µm, Rq= 6.75 µm, Rt= 54.12 µm and Rz= 38.18 µm.

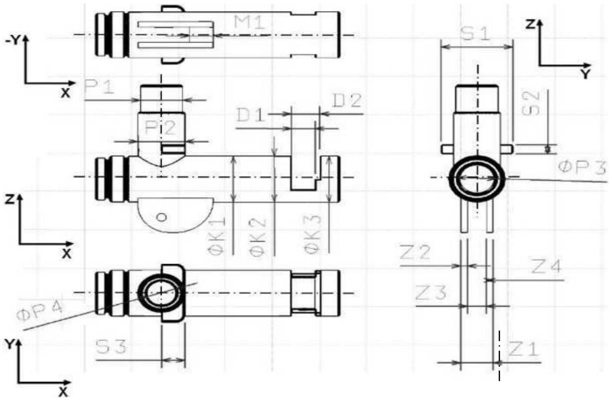

Fig. *7 Part dimensions*

4 Conclusion

Metal Additive Manufacturing is not yet able to produce products that meet high surface quality requirements. This is due to the production technology. Basic factors affecting the surface quality are described above. For the precision of production, it is important to carry out a proper calibration of the AM device. Scale and Beam offset are outputs from the calibration job and are unique to each AM machine, production metal powder and set of process parameters. If the calibration values correlate with the optimal setting, the AM device works with the best possible accuracy with the process parameters and the selected type of metal powder.

Another factor influencing the surface and dimensions of parts is the building orientation. To determine the deviations in the dimensions between the 3D model and the physical part, sample parts were produced. As confirmed by experiments, the highest circularity was reached when building the hole vertically. The horizontal hole had the worst quality. Therefore, this should be taken into account when preparing data for AM.

As it turned out, the best results for the part were achieved in orientation of Part 1. Because the Part 1 has dimension defects equally spread across all its elements. That is why this part, built at a 45° angle, is closest to the reference dimensions. On the other hand, if one of the cylinders is important, it is preferable to print this hole vertically.

AM devices produce parts with more metal substrate than necessary. This means the calibration values are not in line with the optimal values and can be further refined. However, additional machining can be applied to improve dimensional accuracy. Currently there is no form of MAM technology which can produce a part with high requirements on accuracy and surface quality without added machining. Improved surface quality was obtained by sandblasting, as all measured surface parameters showed improvement.

This knowledge will be applied to the production of components which are at the edge of the possibilities of metal additive manufacturing.

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