ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN 1584-2665 (printed version); ISSN 2601-2332 (online); ISSN-L 1584-2665

1.Gergely DEZSŐ, 2.Péter KÓSA

DIMENSIONAL AND SHAPE ACCURACY OF CYLINDRICAL AND RECTANGULAR PARALLELEPIPED–LIKE PARTS MADE BY SELECTIVE LASER MELTING TECHNOLOGY

1-2. University of Nyíregyháza, Institute of Engineering and Agriculture, Department of Physics and Production Engineering, Nyíregyháza, HUNGARY

Abstract: Nowadays interest in selective laser melting is still significant, because together with being a promising additive manufacturing method it has many challenges to solve. In this study dimensional accuracy of cylindrical and rectangular parallelepiped–shaped pieces manufactured by a commercial SLM machine from Ti6Al4V material is investigated. As the technology itself is, accuracy of different types of geometrical features are also proven orientation dependent (anisotropic). In this study we present our results on dimensional accuracy of cylindrical and rectangular test specimens manufactured by EOS M290/400W selective laser sintering machine from Ti6Al4V powder.
Keywords: selective laser melting technology, Ti6Al4V powder

1. INTRODUCTION

Selective laser melting (SLM) is an additive manufacturing technology which attracts significant attention in recent scientific and engineering research. On one hand it is a promising method for manufacturing complex metal structures from mere CAD 3D body models. However on the other hand thermal expansion effects may strongly influence accuracy of the outcome, and what's more large number of technological parameters have also an effect on geometrical and physical features of fabricated parts. Many researchers studied accuracy of SLM method from different points of view.

G.R. Biucan and coauthors studied how layer thickness influences microstructure of part manufactured by SLM method from 316–L steel. They applied two different thickness, and eventually found that larger thicknes is advantageous from economical point of view [1].

F. Calignano et al. [2] investigated from design for manufacturing approach features of three different specimen manufactured by selective laser melting from AlSi10Mg alloy. Effect of STL file quality was studied, and it was shown out that how surface roughness and deviation depends on settings of STL model generation. The paper also demonstrates an experiment on a pin lattice, in which horizontal dimensions of pillars varied. Shape and size accuracy of fabricated workpieces proved to strongly depend on nominal size.

A. Gebhardt and coauthors pointed out that many parameters of SLM manufacturing influences the process itself and also the outcome. Stair–step effect and adhesion stood in the focus of their experiments. They showed out that exposure and hatch strategies have most significant effect on surface roughness, and they worked out two strategies to obtain the best possible surface quality [3].

J. Safka et al. studied shape and size accuracy of a complex part manufactured in different orientation related to the tray and with different support structures. They concluded that orientation set during the preprocessing phase of fabrication has crucial influence on deviations of manufactured part from geometry defined by CAD model [4]. Many research have been focused on size and shape accuracy of SLM manufactured parts or related topics indicating that it is a hot and complex field of scientific research [5-10].

In this study we present our results on dimensional accuracy of cylindrical and rectangular test specimens manufactured by EOS M290/400W selective laser sintering machine from Ti6Al4V powder.

2. DESIGN OF CYLINDRICAL AND CHARPY IMPACT TEST SPECIMENS

Cylindrical and rectangular shaped specimens were designed for experiments. Figure 1 and Figure 2 shows technical drawing and 3D view of them. Charpy impact test specimens were dimensioned according to MSZ EN ISO 179–1:2010 standard with outside dimensions 55x10x5 mm, and notch as it is seen on the drawing. Dimensions of cylindrical specimens were chosen by ourselves so that those are at the same approximate size as Charpy impact test specimens, length of them is 50 mm and diamater is 10 mm. By these forms we can investigate size and shape accuracy of two most typical kinds of surface, plane and cylinder. In case of Charpy impact test specimens we also have opportunity to measure impact energy.

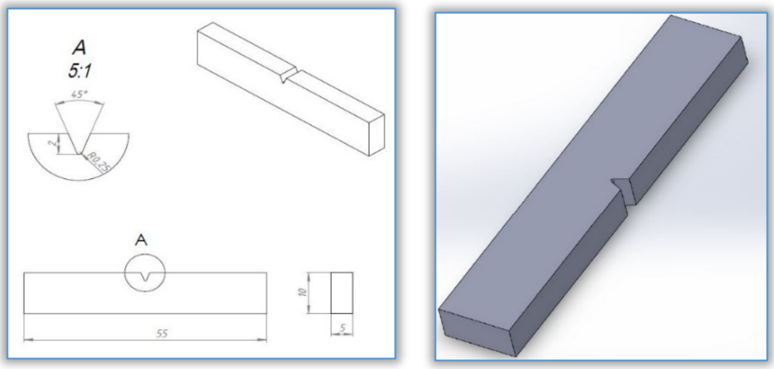

Figure 1. Drawing and 3D view of a Charpy impact test specimen

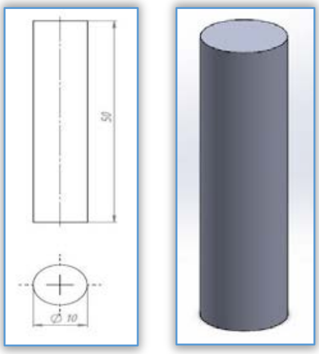

Figure 2. Drawing and 3D view of a cylindrical specimen

— Manufacturing of the specimen

Specimens were manufactured by an EOS M290/400W additive manufacturing system. This is a „metal 3D printer”. We used Ti6Al4V material, which is commonly used in medical applications. Main manufacturing paramters were the followings:

- layer thickness : 0.03 mm
- infill laser power : 280 W
- infill laser speed : 1200 mm/s
- infill hatch distance: 0.14 mm

From last 3 feautre follows that energy imput was 55.56 J/mm³ into infill layers.

All specimens were manufactured together in a single task, on a common tray.

Both of two kinds of specimen were fabricated in 2 times 5 copies, with different orientation. Figure 3 shows the number and orientation of manufactured pieces.

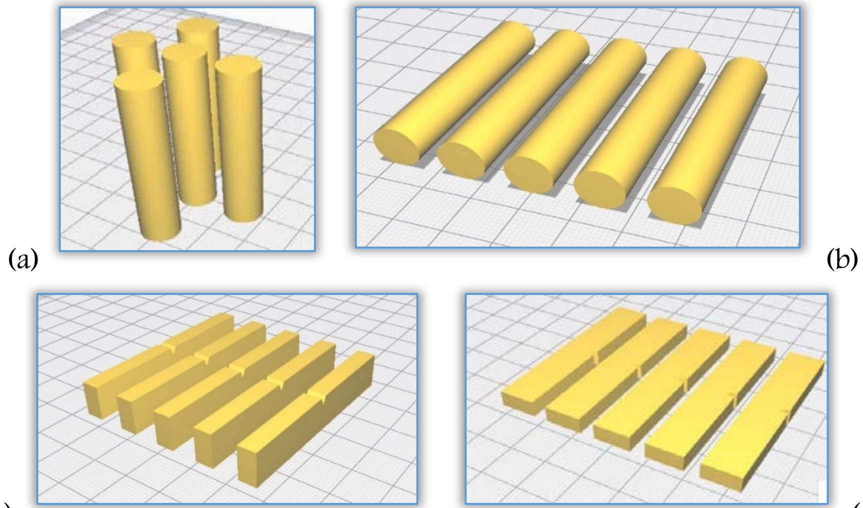

Figure 3. Different orientations of the specimen on the tray of manufacturing system

We will use the following terminology for orientations shown on A, B, C and D subfigures on Figure 3.

A: cylindrical pieces manufactured in vertical direction, or *standing* position,
B: cylindrical pieces manufactured in horizontal direction, or *laid* position,
C: Charpy impact test pieces manufactured in set *on edge* position,
D: Charpy impact test pieces manufactured in *laid* position,

Different orientation were chosen because additive manufacturing is a layer by layer building process, and it implies that one of its most important features is anisotropy. It means that manufacturing process itself and geometrical accuracy, material microstructure, material properties of specimens are all anisotropic. This is why investigation of pieces manufactured in different orientation is reasonable.

Figure 4. Pieces on the tray after additive manufacturing

— **Size and shape accuracy of cylindrical pieces**

In case of cylindrical pieces diameters in 5 different plane and 3 directions were measured. Figure 5 illustrates measured diameters along a single cylindrical specimen. For a certain specimen we got 15 diameter data.

Results were handled separately for pieces manufactured horizontal and vertical direction („laid" and „standing" position, referring to Figure 3 and its explanation).

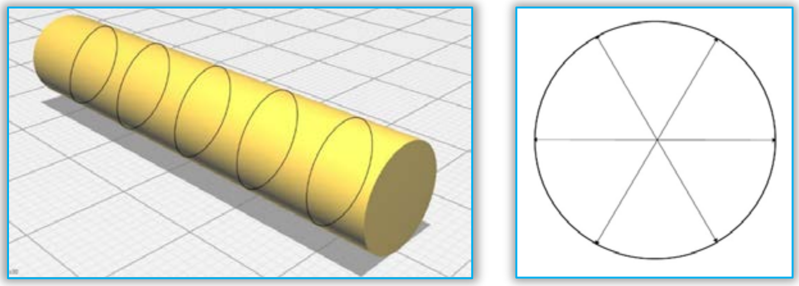

Figure 5. Diameters of a cylindrical piece were measured in 5 different plane and 3 directions within a single plane

Table 1. Diameter measurement result for cylindrical specimens manufactured in laid position and statistical quantities for single pieces

cylindrical sp. laid position		direction			mean for a plane		
code	plane	1	2	3			
x11	1	9,60	9,93	9,66	9,73		
	2	9,91	9,95	9,90	9,92		
	3	9,99	9,99	10,30	10,09	mean	9,87
	4	9,99	10,05	10,15	10,06	st. deviation	0,27
	5	9,39	9,97	9,30	9,55	median	9,95
x12	1	9,45	10,23	9,64	9,77		
	2	9,92	9,92	9,89	9,91		
	3	9,99	9,92	9,98	9,96	mean	9,90
	4	9,91	9,97	9,96	9,95	st. deviation	0,17
	5	9,89	9,92	9,97	9,93	median	9,92
x13	1	9,99	9,70	9,76	9,82		
	2	9,90	9,93	9,98	9,94		
	3	10,00	9,98	10,08	10,02	mean	9,92
	4	10,00	9,97	9,90	9,96	st. deviation	0,11
	5	9,74	9,91	9,99	9,88	median	9,97
x14	1	9,81	9,91	9,73	9,82		
	2	9,99	9,86	9,87	9,91		
	3	10,01	9,94	9,91	9,95	mean	9,90
	4	9,92	9,98	9,95	9,95	st. deviation	0,08
	5	9,87	9,93	9,78	9,86	median	9,91
x15	1	9,34	9,78	9,58	9,57		
	2	9,89	9,98	10,22	10,03		
	3	10,04	9,92	9,89	9,95	mean	9,87
	4	9,93	9,91	9,99	9,94	st. deviation	0,20
	5	9,84	9,92	9,80	9,85	median	9,91

Table 2. Accumulated statistical data from diameter measurement results for cylindrical specimens manufactured in laid position

		pieces x11–15 (laid) [mm]
Σ	mean	9,89
	st. deviation	0,18
	median	9,92

Table 3. Diameter measurement result for cylindrical specimens manufactured in standing position and statistical quantities for single pieces

cylindrical sp. standing pos.		direction			mean for a plane		
code	plane	1	2	3			
x16	1	10,02	9,98	10,01	10,00		
	2	10,02	10,06	10,02	10,03		
	3	9,98	10,03	10,08	10,03	mean	10,03
	4	10,00	10,04	10,05	10,03	st. deviation	0,03
	5	10,04	10,02	10,03	10,03	median	10,02
x17	1	9,98	9,99	10,01	9,99		
	2	9,99	9,98	9,97	9,98		
	3	9,99	9,98	9,99	9,99	mean	9,99
	4	9,99	10,00	10,01	10,00	st. deviation	0,01
	5	9,97	9,99	10,00	9,99	median	9,99
x18	1	9,98	10,00	10,02	10,00		
	2	9,98	10,01	10,03	10,01		
	3	10,04	10,10	9,98	10,04	mean	10,02
	4	9,95	10,10	10,05	10,03	st. deviation	0,04
	5	9,99	10,01	10,00	10,00	median	10,01
x19	1	9,96	9,98	9,99	9,98		
	2	9,97	9,98	10,00	9,98		
	3	9,97	9,97	10,02	9,99	mean	9,98
	4	9,95	9,97	9,99	9,97	st. deviation	0,02
	5	9,97	10,00	9,97	9,98	median	9,97
x20	1	10,02	10,06	10,10	10,06		
	2	10,03	10,00	10,02	10,02		
	3	10,01	10,02	10,03	10,02	mean	10,03
	4	9,98	10,02	10,03	10,01	st. deviation	0,03
	5	10,00	10,04	10,06	10,03	median	10,02

Table 4. Accumulated statistical data from diameter measurement results for cylindrical specimens manufactured in standing position

		pieces x16–20 (standing) [mm]
Σ	mean	10,01
	st. deviation	0,03
	median	10,00

Table 5. Accumulated statistical data from diameter measurement results for all cylindrical specimens

		pieces x11–20 (all) [mm]
Σ	mean	9,95
	st. deviation	0,14
	median	9,98

From data listed in Tables 1–5 followings can be concluded.

Dimensional parameters of pieces manufactured in laid and standing directions are significantly different.

Difference between the nominal value of diameter (10 mm) and mean value for diameters of standing pieces is 0.01 mm, that is 0.1%. The same value for laid pieces is 0.11 mm, that is 1,1%. Significance of difference from nominal value can be checked by one sample t–test. In our case degrees of freedom is 74. In our case t–score can be calculated for both laid and standing pieces:

$$t_{laid} = \frac{9.89 - 10}{0.18}\sqrt{75} = -5.29, \quad t_{standing} = \frac{10.01 - 10}{0.03}\sqrt{75} = 2.88$$

and t–value for significance level p=0.005 is 2.8936, and for p=0.05 is 1.9925. At significance level 0.005 difference from nominal value in case of laid pieces is indicated by one sample t–test as significant, but in case of standing pieces not. At p=0.05 both goups show significant difference from nominal value in diameter. Standard deviation of diameter data of laid pieces is 6 times larger than the same one for standing pieces.

Laid pieces show a characteristic shape error. Those are deflected because of thermal expansion and shrinking during the manufacturing process. This phenomenon is illustrated on Figure 6 which shows pieces from top view. The same can be observed also on Figure 4.

Figure 6. Pieces manufactured in laid position from top view. It can be seen well that those are deflected

— Size and shape accuracy of Charpy impact test specimens

Charpy impact test specimens have block–like shape, so main dimensions of those are H, D and W according to Figure 7. While pieces were removed from the tray by cutting method, one dimension was affected by this process. This dimension is D in case of laid pieces, and H in case of pieces on edge. There is no meaning to measure these dimensions, because those comes not purely from additive manufacturing, but from cutting machining. This is why only two dimensions were measured for each piece.

Dimension measurements were performed by vernier caliper. Tables 6–9 shows results of measurements. From measurement data one can conclude the followings.

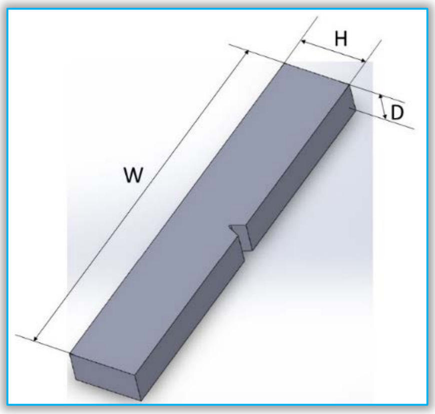

Figure 7. Main dimensions H, D and W of a Charpy impact test specimen

Table 6. Measured dimensions of Charpy impact test specimens manufactured in laid position, D was not measured, each data are in mm units

laid		Dimensions in mm units						
code	plane	H	W	D		H	W	D
X01	1	10,03	54,82	–				
	2	9,99	54,80	–				
	3	9,98	54,78	–	mean	10,00	54,81	
	4	10,01	54,79	–	st. deviation	0,02	0,03	
	5	10,00	54,86	–	median	10,00	54,80	
X02	1	10,00	54,90	–				
	2	10,02	54,82	–				
	3	10,01	54,84	–	mean	10,02	54,83	
	4	10,03	54,80	–	st. deviation	0,01	0,04	
	5	10,02	54,79	–	median	10,02	54,82	
X03	1	9,99	54,89	–				
	2	9,99	54,83	–				
	3	10,00	54,86	–	mean	10,00	54,84	
	4	9,99	54,82	–	st. deviation	0,01	0,04	
	5	10,01	54,79	–	median	9,99	54,83	
X04	1	10,01	54,82	–				
	2	9,97	54,85	–				
	3	10,01	54,84	–	mean	9,99	54,85	
	4	9,99	54,87	–	st. deviation	0,02	0,02	
	5	9,98	54,87	–	median	9,99	54,85	
X05	1	10,05	54,75	–				
	2	10,00	54,81	–				
	3	10,02	54,84	–	mean	10,01	54,82	
	4	9,99	54,86	–	st. deviation	0,03	0,04	
	5	9,99	54,85	–	median	10,00	54,84	

Table 7. Accumulated statistical data from dimansion measurement results for Charpy impact test specimens manufactured in laid position

	laid pos.	x1–5 [mm]		
		H	W	D
Σ laid	mean	10,00	54,83	–
	st. deviation	0,02	0,04	–
	median	10,00	54,83	–

Table 8. Measured dimensions of Charpy impact test specimens manufactured on edge position, H was not measured, each data are in mm units

on edge		Dimensions in mm units						
code	plane	H	W	D		H	W	D
X06	1	–	54,91	5,06				
	2	–	54,77	5,03				
	3	–	54,89	5,04	mean		54,81	5,04
	4	–	54,65	5,03	st. deviation		0,11	0,01
	5	–	54,85	5,03	median		54,85	5,03
X07	1	–	54,8	5,09				
	2	–	54,74	5,03				
	3	–	54,69	5,01	mean		54,74	5,05
	4	–	54,69	5,04	st. deviation		0,06	0,03
	5	–	54,8	5,07	median		54,74	5,04
X08	1	–	54,84	5,04				
	2	–	54,71	5,03				
	3	–	54,7	5,05	mean		54,79	5,05
	4	–	54,79	5,06	st. deviation		0,09	0,01
	5	–	54,9	5,05	median		54,79	5,05
X09	1	–	54,82	5,05				
	2	–	54,8	5,06				
	3	–	54,78	5,04	mean		54,80	5,04
	4	–	54,79	5,04	st. deviation		0,02	0,01
	5	–	54,83	5,03	median		54,80	5,04
X10	1	–	54,89	5,07				
	2	–	54,76	5,08				
	3	–	54,68	5,03	mean		54,76	5,05
	4	–	54,7	5,03	st. deviation		0,08	0,03
	5	–	54,79	5,02	median		54,76	5,03

Table 9. Accumulated statistical data from dimansion measurement results for Charpy impact test specimens manufactured on edge position

	on edge pos.	X6–10 [mm]		
Σ on edge		H	W	D
	mean	–	54,78	5,04
	st. deviation	–	0,07	0,02
	median	–	54,79	5,04

In case of Charpy impact test specimens there is no use to calculate statistical indicators for all 10 pieces, because there are data not measured.

Dimensions in vertical direction, that is perpendicular to the tray, are very accurately manufactured with small standard deviation. In case of laid position this is dimension H, and in case of on edge position this is dimension D.

Length of the specimen W is systematically smaller than nominal value 55 mm. Authors draw reader's attention to the fact that in Table 6 and Table 8 in the column of W there is not a single one data beginning with 55, each of them begins with 54. Mean values and standard deviations of W in two different positions are close to each other, and in both case are far below 55 mm. Authors think this can be explained by the thermal expansion phenomenon and is closely related with the deflection of pieces.

3. CONCLUSIONS

In this study cylindrical and rectangular parallelepiped–shaped test specimens manufactured by selective laser melting (SLM) technology from Ti6Al4V material were investigated from the viewpoint of size and shape accuracy. Dimensions affected by cutting processes after SLM manufacturing during removal of parts from tray were not measured.

Cylindrical pieces were manufactured in two different position, standing and laid. Standing pieces showed the best accuracy in diameter, in this case mean value 10.01 mm was almost equal to nominal value 10 mm and standard deviation was small, 0.03. Laid pieces had diameter 9.85 mm as mean value with 0.14 standard deviation, which is far weaker agreement than that of standing specimens. Length of laid specimens were not measured because bending of those was large, which affected strongly measured values.

Rectangular parallelepiped–shaped test pieces were really Charpy impact test specimens, which were measured before performing impact test. Two position of them were laid (on the largest face) and on edge (on second largest face). Length of those was measured for all 10 specimens and we got 54.83 mm with 0.04 standard deviation and 54.78 mm with 0.07 standard deviation for the length with nominal value of 55 mm. Difference can be explained by thermal expansion phenomenon. It is notable that other smaller dimension of specimen sin both orientations could be accurately reproduced with small standard deviation.

Our results are in agreement with publications of other researchers concerning that thermal expansion affects strongly the size and shape accuracy of SLM manufactured parts, dimensional accuracy is direction dependent (anisortopic), consequently orientation setup during preprocessing phase of manufacturing can be crucial for dimensional and shape accuracy.

Acknowledgements

This work was supported by project entitled „Research of osteosynthesis of implants and development trabecular structure using additive manufacturing", and with identification number: GINOP–2.2.1–15–2017–00055. Test specimens were manufactured at Biomechanical Laboratory at University of Debrecen, Hungary within the research work of the project.

We are thankful for the opportunity to use facilities of Additive Manufacturing Laboratory, Material Test Laboratory and Electron Microscope Laboratory at University of Nyíregyháza, Hungary.

References

[1] Buican, G.R., Oancea, G, Lancea, C., Pop, A., Influence of Layer Thickness on Internal Structure of Parts Manufactured from 316–L Steel Using SLM Technology. Applied Mechanics and Materials, Vol. 809–810, pp. 369–374, 2015.
[2] F. Calignano et al., Investigation of accuracy and dimensional limits of part produced in aluminum alloy by selective laser melting, International Journal of Advanced Manufacturing Technology 88(1–4), 2017
[3] Gebhardt A, Hötter J, Ziebura D (2014), Impact of SLM build parameters on the surface quality. RTejournal – Forum für Rapid Technologie, Vol. 2014. https://www.rtejournal.de/ausgabe11/3852
[4] Jiří Šafka , Radomír Mendřický, Michal Ackermann, Daniel Tuháček, Shape and size accuracy of 3D–printed AlSi12 parts, Acta Metallurgica Slovaca, Vol. 21, 2015, No. 4, p. 278–284
[5] Razvan Pacurar, Nicolae Balc, Florica Prem: Research on how to improve the accuracy of the SLM metallic parts AIP Conference Proceedings 1353, 1385 (2011)
[6] Liu, Y., Yang, Y. & Wang, D., Investigation into the shrinkage in Z–direction of components manufactured by selective laser melting (SLM). Int J Adv Manuf Technol 90, 2913–2923 (2017)
[7] Karolien Kempen, Frank Welkenhuyzen, Jun Qian and Jean–Pierre Kruth, Dimensional accuracy of internal channels in SLM produced parts, https://www.researchgate.net/
[8] Yang, Y., Lu, J., Luo, Z. and Wang, D. (2012), "Accuracy and density optimization in directly fabricating customized orthodontic production by selective laser melting", Rapid Prototyping Journal, Vol. 18 No. 6, pp. 482–489
[9] Królikowski, M., Filipowicz, K., Verification of geometrical accuracy of selective laser melting (SLM) built model. Advances in Manufacturing Science and Technology, 2013 Vol. 37, nr 3 p 85–91
[10] S.A.C. Ghani, M.H. Zakaria, W.S.W. Harun and Z. Zaulkafilai, Dimensional accuracy of internal cooling channel made by selective laser melting (SLM) And direct metal laser sintering (DMLS) processes in fabrication of internally cooled cutting tools, MATEC Web of Conferences 90, 01058 (2017)

ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN 1584 - 2665 (printed version); ISSN 2601 - 2332 (online); ISSN-L 1584 - 2665