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On the z-dimensional accuracy of l-powder bed fusion

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Abstract

Laser Powder Bed Fusion (L-PBF) is one of the commonly utilized metal Additive Manufacturing (AM) modalities in highly demanding industries such as biomedical and aerospace. Among other limitations, the dimensional accuracy of the L-PBF parts hinders the adoption of this technology for a wider application. The dimensional accuracy in L-PBF depends on several factors such as beam compensation, process parameters, .stl conversion errors and shrinkage factors. The shrinkage factors are very important and needed to compensate for down-scaling of nominal dimensions. Due to the inherent nature of the process, anisotropic shrinkage occurs due to the thermal recession and the difference of the densities from the powder material and solidified layer. Although, it is generally taken into consideration for XY-plane dimensional accuracy, Z-shrinkage factors are omitted since the layer deposition is assumed to take care of the shrinkage for every layer in addition to deep melt pools to enable layer-to-layer fusion. However, in this study, it is observed that especially for long builds from AlSi10Mg powder material, dimensional errors up to a half of a millimeter may occur along Z-direction depending on the total Z-height. Therefore, a suitable Z-shrinkage factor is calculated based on the obtained experimental results and applied to all builds leading to a much more accurate results along the build direction. Moreover, the suitability of the shrinkage factors along X and Y axes is tested and confirmed.

Keywords: AlSi10Mg, Laser-powder bed fusion, shrinkage, dimensional accuracy

1. Introduction

Laser Powder Bed Fusion is one of the metal Additive Manufacturing (AM) technologies employing a laser to selectively scan and melt very thin layers of powder to enable very complex geometries even with internal channels and cavities. There are many advantages of L-PBF process compared to other AM technologies and conventional manufacturing. These include high geometrical complexity, reduced waste material, reduced need for joining processes and assemblies, simplified supply chains, weight reduction, etc. These advantages are very important for highly demanding industries including aerospace and biomedical where AM technologies have been considered as the "future of manufacturing". In the L-PBF process, the part is built in one direction on top of a base plate mechanically connected to the build platform of the machine. After the first layer of powder is re-coated on the base plate, the laser scans the area of the first layer while the rest of powder bed stays un-melted. The melting and solidification occurs rapidly. Then, the build platform is lowered one layer and the re-coater collects the powder from the risen powder platform and recoats it on the already solidified first layer. The scanning of the second layer takes place. This iterative process goes on until the whole part is completed. There are some shortcomings of the L-PBF to be addressed to widen its application areas and to increase its adoption. Among others such as limited workpiece dimensions, bad surface quality, need for support structures for overhang surfaces, high investment and operational costs, lack of standards and rules for design, one of the very critical limitations is the low dimensional accuracy.

Most of the studies on the dimensional accuracy of L-PBF parts are focused on benchmarking [1-6]. Although benchmark geometries are helpful to compare various conditions such as different process parameters or machine vendors, its inherent weakness is the applicability of the results for different geometries or for different dimensions of the same geometry. Some researchers have utilized modeling tools for the prediction of dimensional accuracy of L-PBF. Zhang et al. has addressed this problem by melt pool geometry predictions and increased the dimensional accuracy along X and Y directions significantly [7] while other researchers focused on other variables in the L-PBF such as the beam compensation especially for features that disappear [8]. The effect of process parameters on the dimensional accuracy has also been investigated by many researchers on different materials for horizontal direction. Sun et al. has addressed the "periphery spreading effect" which is more critical at higher laser scan speeds [9]. For Al alloys, Maamoun et al. has worked on the effect of laser power, energy density, hatch spacing and scan speed on dimensional tolerances to find the optimal processing window [10]. Charles et al. has addressed the dimensional accuracy of downskin surfaces by varying the process parameters such as scan speed and scan spacing [11]. Moreover, some researchers focus on the dimensional accuracy of lattice structures. For instance, Mat Taib et al. has addressed the dimensional accuracy of open cellular structures produced from CoCrMo alloy showing that higher volume-to-surface area parts yield a lower total amount of shrinkage in comparison to lower volume-to-surface area [12]. From the literature, it is understood that most of the studies ignore the dimensional accuracy along the build (Z) direction but rather focus on the one along XY plane. Very limited number of researches have been carried out to understand the influence of process variables on the dimensional accuracy along Z-direction [13, 14]. Moreover, the Z-axis dimensional accuracy is tested on very small heights such as 10.5 mm compared to the whole span and it is found that the errors are less than other directions [15]. In order to improve the dimensional accuracy along X and Y directions, shrinkage factors are defined during pre-processing to accommodate the errors caused by thermal shrinkage in XY plane. However, the shrinkage along Z-axis is considered to be compensated for each layer due to powder deposition mechanism. In the L-PBF process, the metallic powder is rapidly melted and solidified as the laser scans the powder bed selectively. As the layer cools down, the shrinkage along Z-axis occurs increasing the next layer thickness. Moreover, due to the difference of the densities of the powder and bulk material, the volume of the layer becomes less when the material is solidified as shown in Fig. 1. Once the re-coater puts the new layer of powder, the gap due to the shrinkage is filled. Since the melt pool depth is always greater than a layer thickness, the shrinkage error along Z-direction is thus considered to be compensated. This is also depicted by a shrinkage model for describing the real layer thickness [16]. Therefore, generally in machine control software, the Z-shrinkage factor is entered as 1 in standard settings meaning no shrinkage compensation. Some practices involve the extrusion of the very first layers down a few micrometers to compensate for Z-accuracy. Although this ensures a correct Z-height for the total part, it does not take Z-accuracy at different heights of the part and is not feasible for real functional parts.

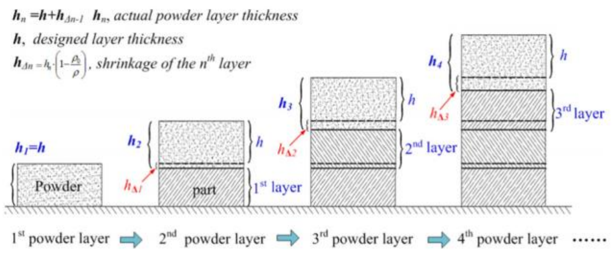

Fig 1. Schematic of shrinking behavior of powder layer [14].

As seen from the literature, there are many different variables affecting the dimensional accuracy of the L-PBF parts. Due to L-PBF's inherent nature of building along one specific direction, these variables shall be categorized under two classes (see Fig.2): 1) Factors affecting the X-Y dimensional accuracy 2) Factors affecting the Z-dimensional accuracy. As shown, more studies have been focused on different aspects in X-Y dimensional accuracy while for Z-accuracy a smaller amount of factors are investigated.

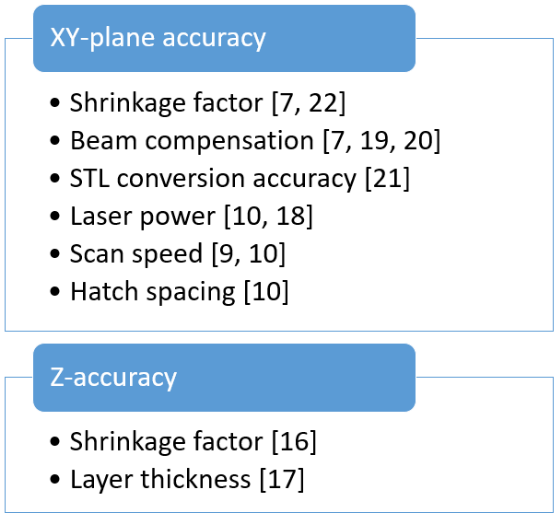

Fig 2. The factors affecting the dimensional accuracy in L-PBF with references.

This study shows that for some materials, such as Al10SiMg, the shrinkage error along the Z-axis for long builds may become significant and needs to be addressed by entering a correct shrinkage factor. The experimental work for finding the correct shrinkage factor and the results of compensated case are presented.

2. Material and methods

In this study, AlSi10Mg material from SLM Solutions was used on an SLM Solutions SLM 500 machine utilizing a laser power of maximum 400 W. The used powder particles is demonstrated in Fig. 3 showing a high level of spherecity with some satellites. The material datasheet from SLM Solutions shows that this material leads to almost 100% density while the powder has an apparent density of 1.45 g/cm^3.

The process parameters utilized in this study are recommended values from the machine vendor and gives an approximate energy density of 37 J/mm^3 at a layer thickness of 60 µm. During production, Z-shrinkage factor was taken as 1 while in X and Y, 1.0021 and 1.0016 were used respectively. After the production, the height of the samples was measured using a coordinate measurement machine (CMM).

The design of the benchmark geometry used to understand whether a shrinkage factor is necessary for Z-axis, made in Autodesk Fusion 360, employs different Z-heights as shown in Fig. 4. The part consists of thin walled prismatic parts on top of each other and checks the Z-accuracy at four locations, namely 40, 80, 120 and 160 mm. Moreover, the X and Y dimensions have also been measured. These dimensions are taken as 40, 80, 120 and 180 mm. The orientation of the part on the build plate is realized in a manner that all X, Y and Z directions of the part are consistent with the machine coordinate system.

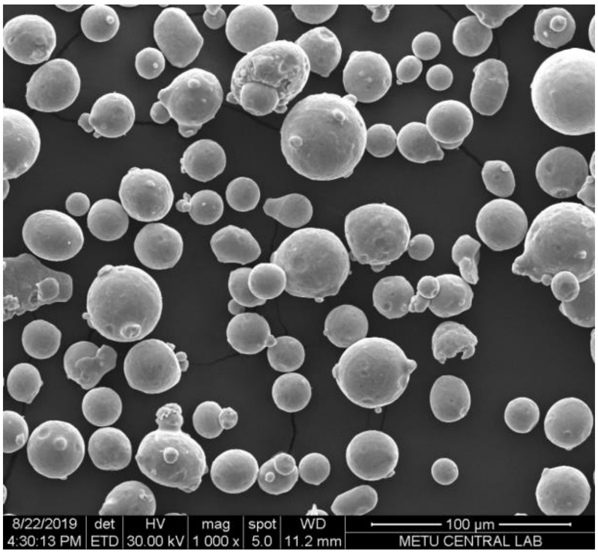

Fig 3. SEM image of the powder particles in AlSi10Mg.

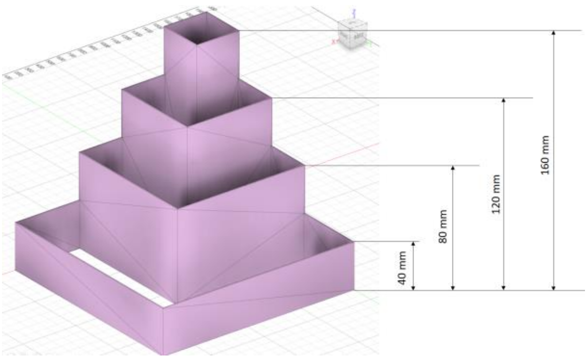

Fig 4. The benchmark geometry.

3. Results and discussion

After the part is produced by L-PBF and sand blasted to remove unmelted powder particles on the surfaces, the measurements of 4 Z-heights are taken as shown in Table 1 and Fig. 5.

The results show that the Z-error increases as the Z-height becomes bigger. At a height of 160 mm, an error of about half a millimeter is encountered. This value is quite big and unacceptable for some aerospace and defense applications. Therefore, it has to be compensated for. The linear trend for Z-axis error suggests that the source of this error is thermal shrinkage and can be compensated based on the experimental results.

In the second trial, based on the obtained results, a Z-shrinkage factor is defined in addition to X and Y values equaling to 1.0027. This means that the parts are scaled with a factor of 1.0027 in Z-direction and made taller than nominal values as shown in Table 2. The parts were re-built with compensated values and Fig. 6 shows the actual values versus nominal compensated values and remaining errors.

Table 1 Measurement results.

	Nominal [mm]	Actual [mm]	Error [µm]
Height 1	40	39.90	100
Height 2	80	79.74	260
Height 3	120	119.68	320
Height 4	160	159.56	440

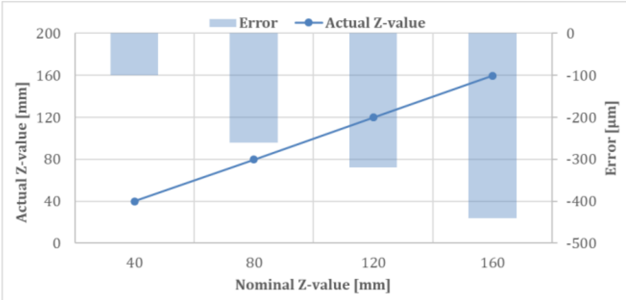

Fig 5. Actual versus nominal Z-height values for the uncompensated case.

As shown, the errors become much smaller compared to the non-compensated case and stays below 50 µm which exceeds expectations for this AM process. The Z-shrinkage factor of 1.0027 has been tested on various complex geometries with high Z-height values, and in this way, the associated Z-dimensional accuracy problem has been solved with success in SAGE production.

Table 2 Compensated and actual values.

	Nominal [mm]	Compensated [mm]	Actual [mm]
Height 1	40	40.11	40.01
Height 2	80	80.22	79.96
Height 3	120	120.32	120.00
Height 4	160	160.43	159.99

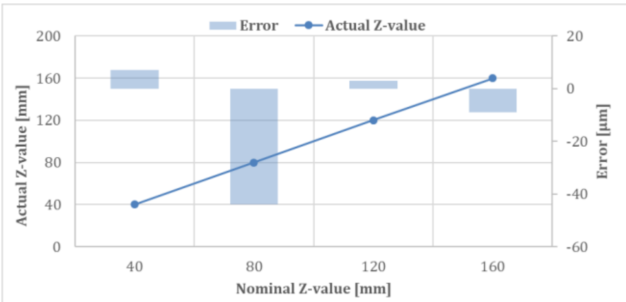

Fig 6. Actual versus nominal Z-height values for the compensated case.

Moreover, the dimensional accuracy of the same geometry has been evaluated for X and Y directions in order to test the suitability of the employed shrinkage factors. As shown in Fig. 7, the errors for X-values changes between -60 and 90 µm for a shrinkage factor of 1.0021. Unlike Z-height errors, they are not always in the positive or negative zone. This is also valid for Y-values as depicted in Fig. 8 varying from -30 and 80 µm. All errors along X and Y for different dimensions stay below 100 µm. Changing the shrinkage factor does not improve the dimensional accuracy along these two directions and therefore no change in the shrinkage factors is applied.

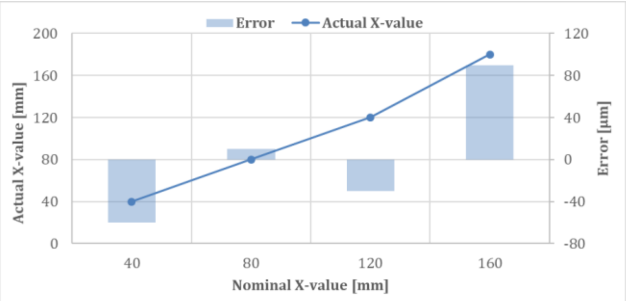

Fig 7. Actual versus nominal X-values with a shrinkage factor of 1.0021.

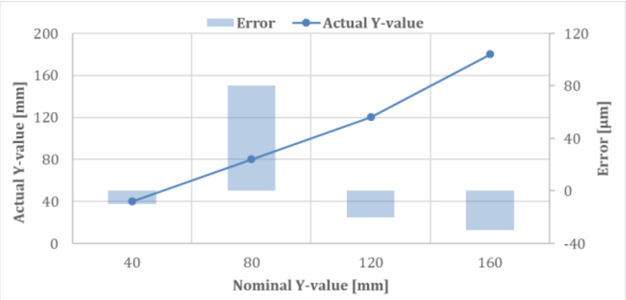

Fig 8. Actual versus nominal Y-values with a shrinkage factor of 1.0016.

As a summary, the obtained % error values for X, Y and Z values, defined as the ratio of the difference between the actual and nominal values to the nominal one, are depicted in Fig. 9. As shown, for the uncompensated case, Z values are always negative and much larger than the ones obtained than in the other two directions. When compensated with a shrinkage factor of 1.0027, the errors become much less.

4. Conclusions

Although Z-dimensional accuracy is generally considered to be handled with powder recoating and deep melt pools in the L-PBF process, long builds have been observed to suffer from high dimensional errors in the build direction and needed to be addressed in this study. Based on the experimental results obtained from a benchmark geometry having 4 different Z-height values from 40 to 160 mm, a shrinkage factor for Z is calculated and applied. It is observed that all errors for dimensions up to 160 mm Z-height stayed below 50 µm.

Furthermore, the feasibility of the applied shrinkage factors along X and Y directions, being 1.0021 and 1.0016 respectively, is checked by X-Y measurements and it is confirmed that these shrinkage factors lead to a good compensation with errors less than 100 µm and the errors are not always in the positive or negative zone. Thus, no change is applied.

By employing a shrinkage factor along Z-direction in addition to utilized values for X and Y directions, a good level of accuracy is achieved even for large component manufacturing by L-PBF.

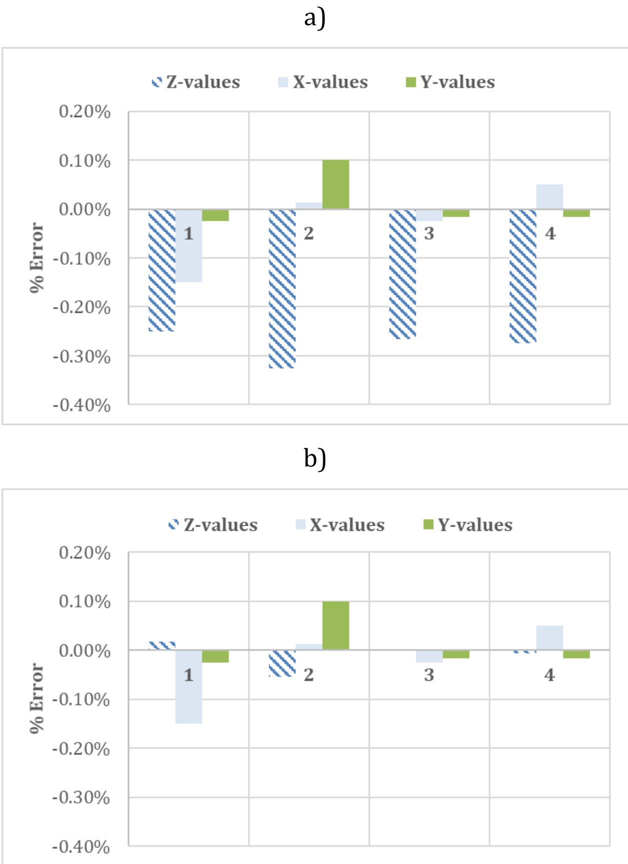

Fig 9. X, Y and Z direction errors for a) uncompensated Z and b) compensated Z.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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