Defect formation in EBM parts built in horizontal orientation

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Abstract

EBM built parts in a horizontal orientation, particularly with bottom curved surfaces, are prone to variations in dimensional accuracy and defect formation. These defects likely occur due to the nature of the supports utilized and the build strategy. To understand the effect of support structures and scan direction on these defects, a series of cylindrical parts were built using different diameters, support structures and scan strategies. The as-built samples were mechanically tested and sample cross sections were analyzed. Pore formation and balling effects were observed in the lower section of some samples. The study looks at the effects of supports, geometry and scan strategy on the minimization of these defects and improving the dimensional accuracy of horizontally built samples

Introduction

Additive manufacturing techniques offers unlimited design flexibility to produce almost any geometry [1]. Complex internal features with graded material compositions can be fabricated without much difficulty [2]. Support structures are created based on the part position and geometry. These support structures provides geometrical conformity and structural integrity to the actual part. Support structures are essential when it comes to powder- bed based metal additive manufacturing processes such as selective laser melting (SLM) and electron beam melting (EBM). The material mass and the surface tension of the molten metal produced by high energy beams could lead to non-homogenous material consolidation at regions of varying cross sections. This could be more prominent when the parts are built in the horizontal orientation where the build orientation and beam scan directions are in the same plane. While building these dimensional complex structures there are flat/curved surfaces facing the horizontal build plane. These surfaces/curvatures are built by providing support structures. Although the powder-bed supports the part to a certain extent, it is not adequate to maintain the structural integrity. The support structures in EBM serve two main purposes; to maintain dimensional stability and to provide better conductivity for the electrons from the part to the build plate.

Horizontally built samples offer two main advantages. The number of layers required for building them is lower and they offer relatively better strength compared to vertically built samples [3].While doing some preliminary experiments cylindrical specimens in EBM have been fabricated and it was found that the specimens built in horizontal orientation have some differences in final geometry. Examination of the specimen cross-sections also revealed the presence of internal defects close to the bottom surface. This became the motivation for a detailed study on factors which cause inaccuracy in the final geometry and the formation of defects. In this study cylindrical parts were fabricated in Arcam EBM machine with different diameters, support structures, layer thicknesses and at X, Y planes in the build plate in horizontal orientations. Detailed descriptions about the working principles of EBM system are given elsewhere [4]. Measurements were carried out to find the variance in actual diameter from the design diameter. Microstructural characterization was carried out to analyze the kind of internal defects formed.

In this study the process parameters namely the beam current, velocity, focus of the beam, type of raster, base temperature, build chamber pressure, etc. were not taken into account. It must be noted that these process parameters greatly affect the build quality. The purpose of this study is to understand how defects can be reduced quickly by just changing the way the parts are set up and designed. Often times it is very hard to understand the exact nature of the problems in the ARCAM machine and we discuss what possible quick solutions one can implement to get more acceptable parts.

Materials and Methods

Ti-6Al-4V powders with average diameter of 60 μm were used to fabricate the parts. The powder was supplied by Arcam AB(Sweden) and the parts were fabricated in a Arcam S400 EBM machine. The preset process parameter theme in Arcam machine for Ti-6Al-4V material was used for fabricating the parts, with changes in processing conditions. Cylindrical parts of diameters of 4 mm, 8 mm, 12 mm and 16 mm and length of 40 mm were fabricated in horizontal orientations of X and Y axis directions. The parts were fabricated in two batches, where the first batch contained parts with 70 μm layer thickness and the second batch contained parts with 50 μm layer thickness. The experimental matrix is shown in Table 1. Corresponding arrangement of specimens in build plate with support structures generated by Materialise Magics software is shown in Fig.1. Other than straight cylindrical parts, tensile and fatigue samples were also built to standard dimensions and the fracture surface after testing was analyzed for defects.

Support structures in the Magics software have several preset values corresponding to different kinds of supports known as point, line, area/box and volume supports. For getting parts without curling it is essential to have at least line supports. Having volume supports (Sintering the powder around the part to make it act as a rigid support) has been proven to be bad for post processing of the part since to provide enough support the powder around the part needs to be excessively sintered. ARCAM advises using either the line or the box supports while building the parts, depending on the intricacies present in the part. Often times it was just common practice to use the default line supports.

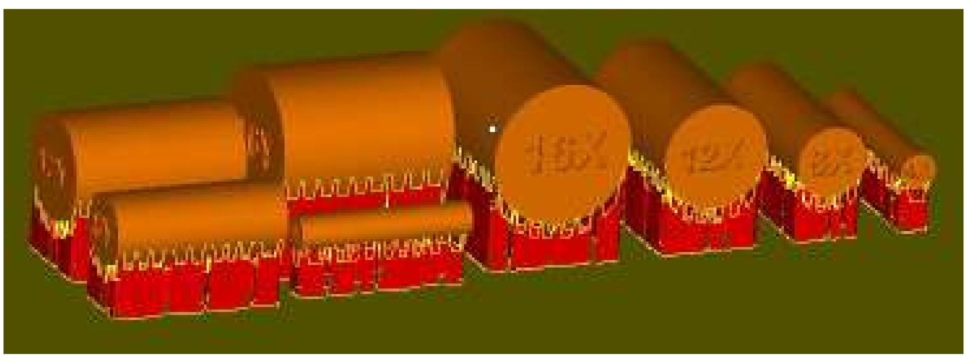
Line supports are characterized by a line along the larger dimension of the part and ribs perpendicular to this central line. The number of ribs is 5 if the length of the central line is < 200 mm and is equal to 12 if length >200 mm. Number of teeth on the ribs is 5 if the width of the part is <200 mm and 12 if the width of the part is >200 mm.

Box supports are characterized by a box along the edge of the part and several ribs at an angle of 30^{o} going from one edge of the box to the other. The number of teeth along the larger and the smaller edges of the box are either 5 or 12 depending on if the dimension is less than or greater than 200 mm.

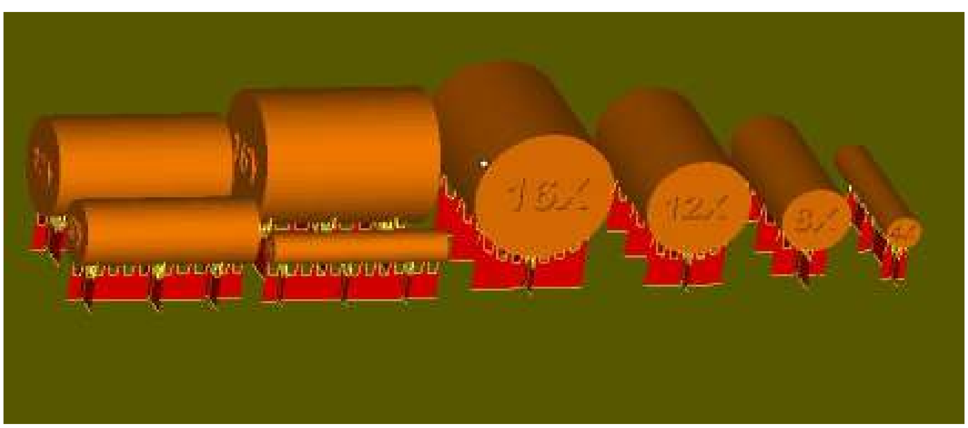
Table 1. Experimental matrix for Ti-6Al-4V EBM parts built in horizontal orientation

70 µm	Line support	X direction	4 mm, 8mm, 12mm, 16mm
		Y direction	
	Box support	X direction	
		Y direction	
50 µm	Line support	X direction	
		Y direction	
	Box support	X direction	
		Y direction	

The dimensions of the as-built parts were measured and correlated with different parameter sets. A statistical analysis was carried out to find the effect of processing conditions on the dimensional accuracy. Analysis of Variance (ANOVA) and the corresponding plots were made using Minitab software ver.16. All the fabricated parts were sectioned and the cross-sections were examined using an optical microscope. The specimens were prepared following standard metallographic specimen preparation methods.



a)



b)

Fig.1. Specimens arranged in the build plate with support structures generated by Magics software. a) Dense box supports b) Thin line supports

Results and Discussions

Dimensional accuracy

The parts built in horizontal orientation using different processing conditions were analyzed for dimensional accuracy with respect to the actual design diameter. The cross-sectional view of the cylindrical rods resembled a 'tear drop' as shown in the schematic (Fig.2). Maximum and minimum offset in diameters of the 'tear drop' structure were measured to find the deviation from the design diameter. The variation from actual diameter or error is plotted against the four main factors namely the type of support, build layer thickness, size of the sample and orientation of the sample. The plot showing the main effects in Fig. 3 and Fig. 4 illustrate how each of the factors affects the percentage error. Lower is the value of the response better is the dimensional accuracy achieved.

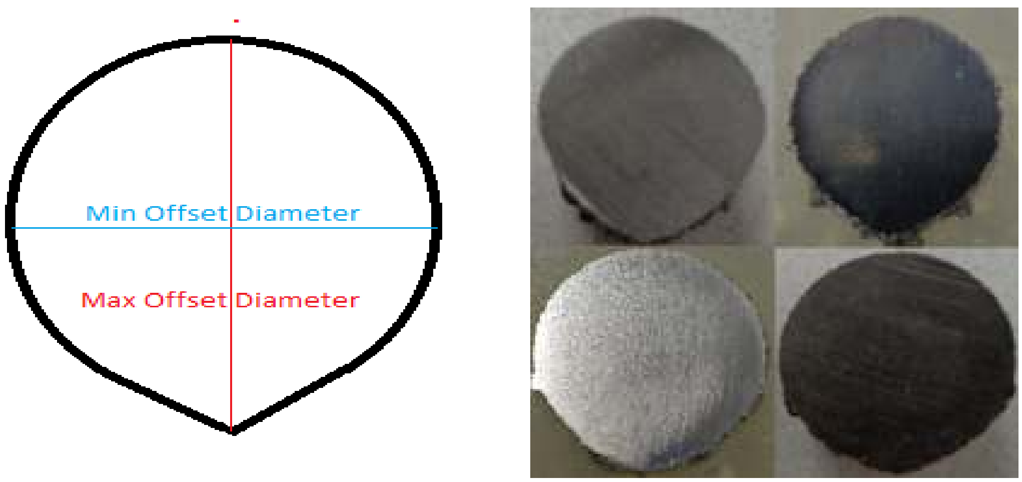


Fig 2. Schematic showing the tear drop shaped cross-sectional appearance of horizontal built cylindrical sample by EBM on the left and tear drop shaped samples on the right

The ANOVA result for maximum offset diameter is shown in Table 1 and the corresponding plot is shown in Fig 3. The P value from ANOVA results indicate that at 95% confidence interval the effect of type of support, build layer thickness and the size of the sample are statistically significant while the orientation of the sample does not hold much significance with respect to the maximum offset diameter.

Table 1. Analysis of Variance for Max Offset Response

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Support	1	8.422	8.422	8.422	5.42	0.028
Build	1	21.057	21.057	21.057	13.55	0.001
Size	3	178.488	178.488	59.496	38.28	0.000
Orientation	1	2.280	2.280	2.280	1.47	0.237
Error	25	38.852	38.852	1.554		
Total	31	249.100				

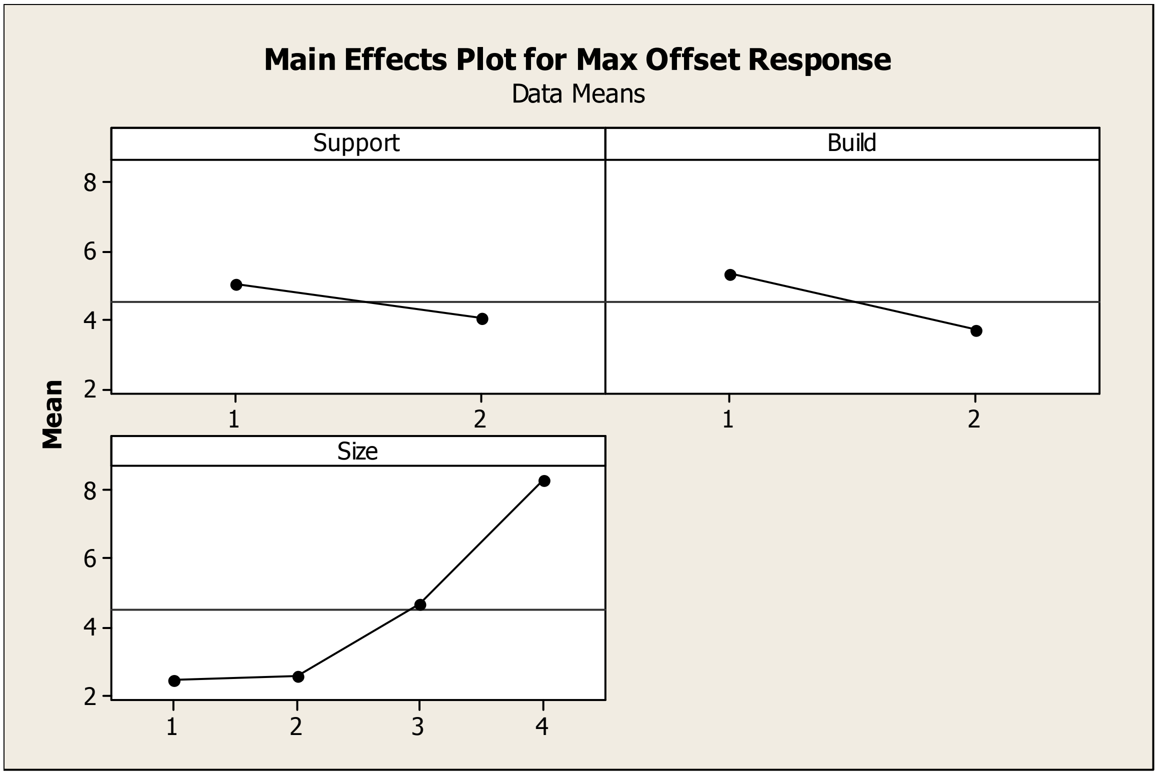


Fig.3. Main effects plot for maximum diameter offset (Support 1-line support, support 2-Box support; Build 1- 70 micron layer thickness, Build 2- 50 micron layer thickness)

From the analysis it can be deduced that by using the following processing conditions the 'maximum diameter offset' can be minimized: Support of type 2 (Box supports), Build layer thickness type 2 (50 micron layer thickness), a sample size of type 1 (16 mm diameter or the largest diameter).

The ANOVA results for minimum offset are shown in Table 2 and the corresponding plot is shown in Fig 4. The ANOVA results indicate that the support and build orientation have no significance while the build layer thickness and the size of the parts play a significant role. At 95% confidence interval only the build layer thickness affects the minimum offset diameter.

Table 2. Analysis of Variance for Minimum Offset Response

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Support	1	0.1467	0.1467	0.1467	0.17	0.687
Build	1	9.1200	9.1200	9.1200	10.33	0.004
Size	3	6.6903	6.6903	2.2301	2.52	0.081
Orientation	1	0.2509	0.2509	0.2509	0.28	0.599
Error	25	22.0803	22.0803	0.8832		
Total	31	38.2881				

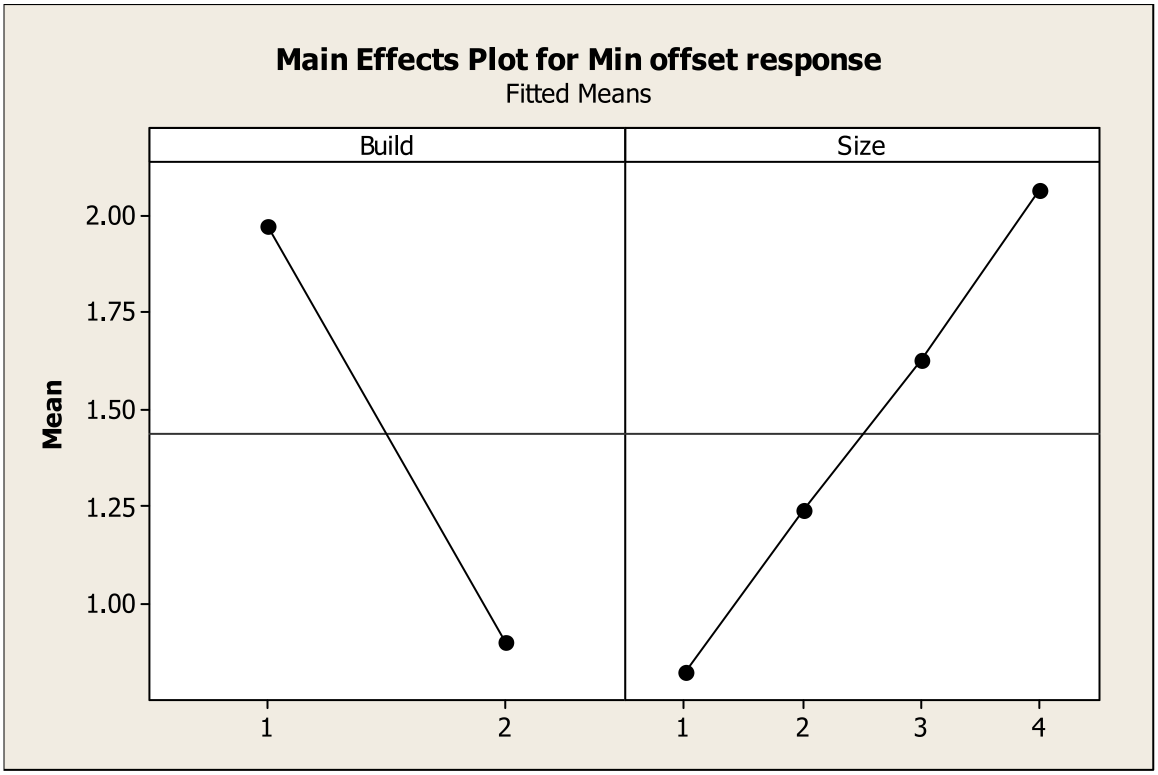
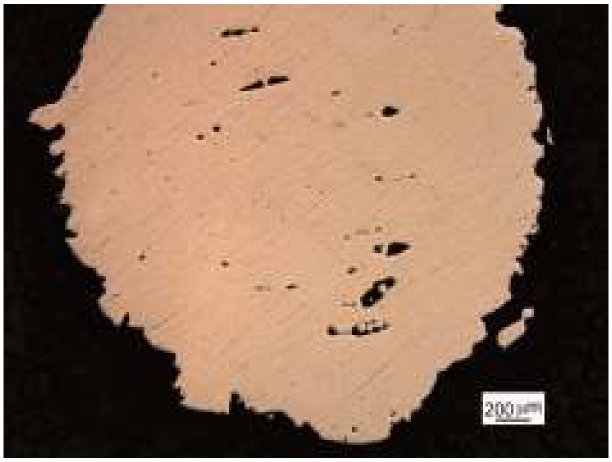


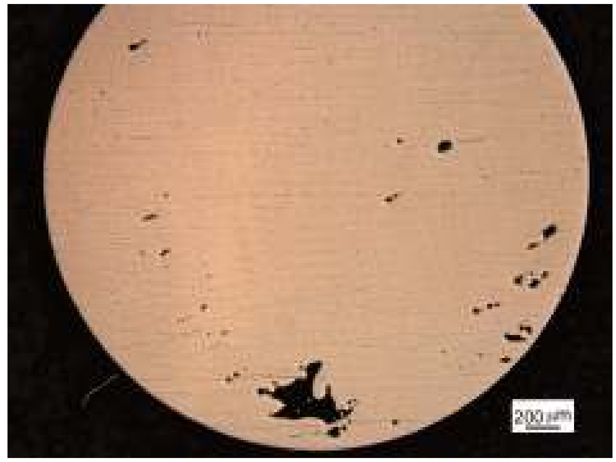
Fig.4. Main effects plot for minimum diameter offset (Support 1-line support, support 2-Box support; Build 1- 70 micron layer thickness, Build 2- 50 micron layer thickness)

Defect analysis

Cross-sectional analysis of most of the samples showed a deviation from the circularity as described previously. Although cross-sectional analysis was carried out for all the 32 samples fabricated, results are given only for those samples which showed maximum/minimum defects. Fig.5 shows some typical defects observed in the cross-section of specimens fabricated in horizontal orientation. An as-built specimen of 4 mm diameter fabricated with line support and 70 µm layer thicknesses shows significant defects (Fig.5a). A specimen fabricated in the same lot and machined to obtain circular symmetry still shows a large defect near to the periphery (Fig. 5b). Relatively better cross-sectional surface can be observed for specimen of 4 mm diameter fabricated with box support and layer thickness of 50 µm (Fig. 5c).



(a)



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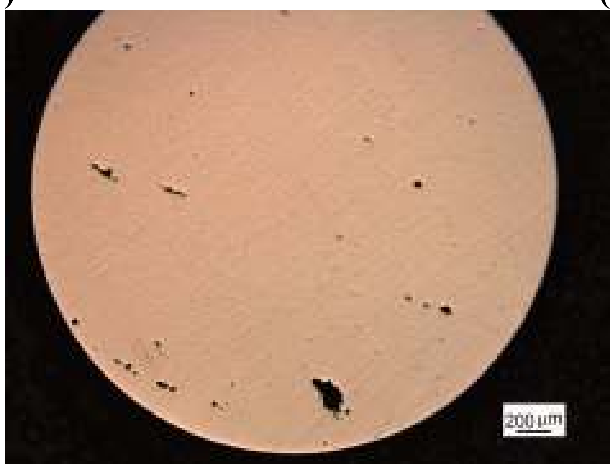


(c)

Fig.5 Optical micrograph of as-polished cross-sections of 4 mm diameter a) with line support-as built b) with line support-machined c) with box support-machined

The fracture surface of tensile and fatigue samples with reduced cross-sections of diameter 4 mm also showed severe defects concentrated towards the bottom surface. The fracture surfaces are characterized with deep cleavages containing partly melted powders sticking to the walls. Fig.6 shows the SEM secondary electron image of a tensile fracture surface of an as-built EBM horizontal built sample. The large defects present in the sample can facilitate premature failure during tensile testing. Similar defect patterns can also be observed in the fracture surface of a horizontally built and machined fatigue sample (Fig.7). In the fatigue sample, in addition to the cleavage type defects, defects separating some layers are also visible. The nature of the defects indicates that it is an outcome of 'balling'. Melt ball formation occurs due to melt pool instabilities. This condition is affected by an inadequate energy density transmitted from the electron beam into the powder and results in the so-called 'balling effect'. Thereby, surface tension of the molten liquid exceeds the wetting ability of the previously solidified layer [5]. This melt balls prevent the continuity of the process and cause the formation of voids which run in length across the sample. Compared to vertically built samples this condition is much more severe in the horizontal built samples because of the longer beam scans.

Further analysis of samples fabricated with larger diameters, box type support and 50 μm layer thicknesses showed cross-sections with very minimal defects. Fig. 8a shows an optical micrograph of cross-section of a cylindrical bar with 12 mm diameter. Compared to the defects observed in lower diameter bars, the defects observed in this specimen are quite negligible. The cross- section of a 16 mm diameter bar (Fig. 8b) is found to be free from any defects which implies that as the diameter of the curvature increases the possibility of defect formation is minimized.

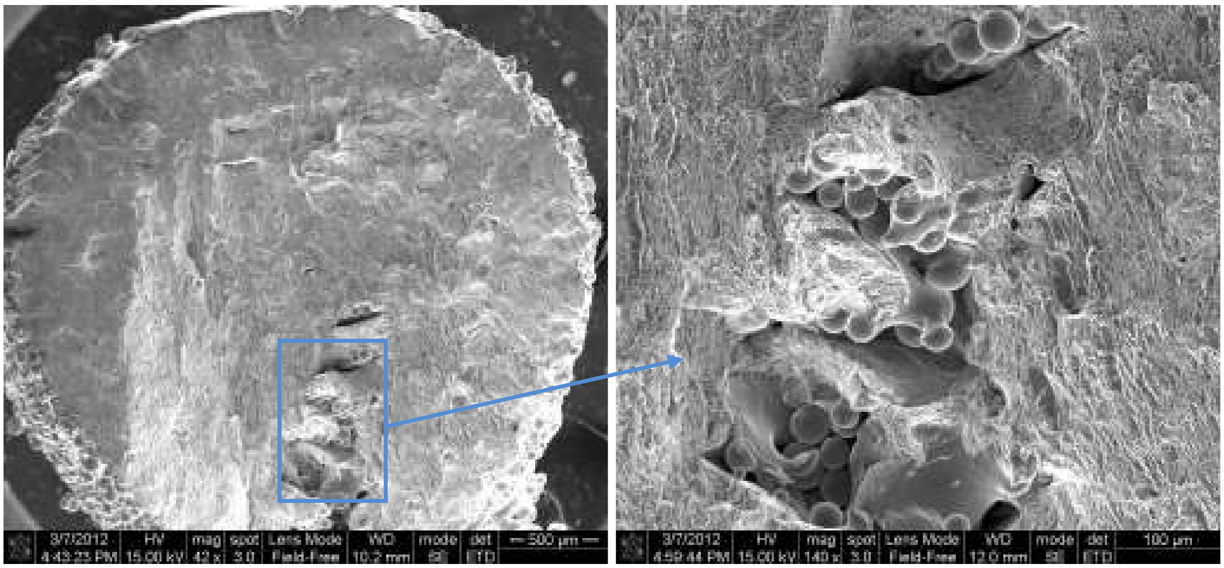


Fig.6 SEM image showing defects closer to the lower curvature at the reduced section in a fractured tensile sample

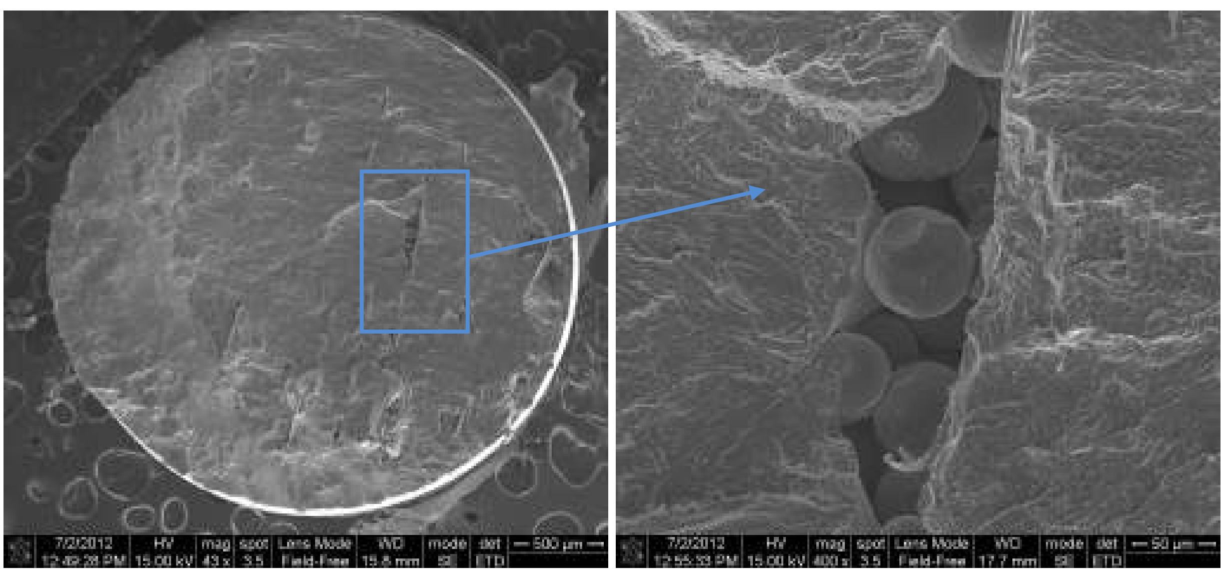
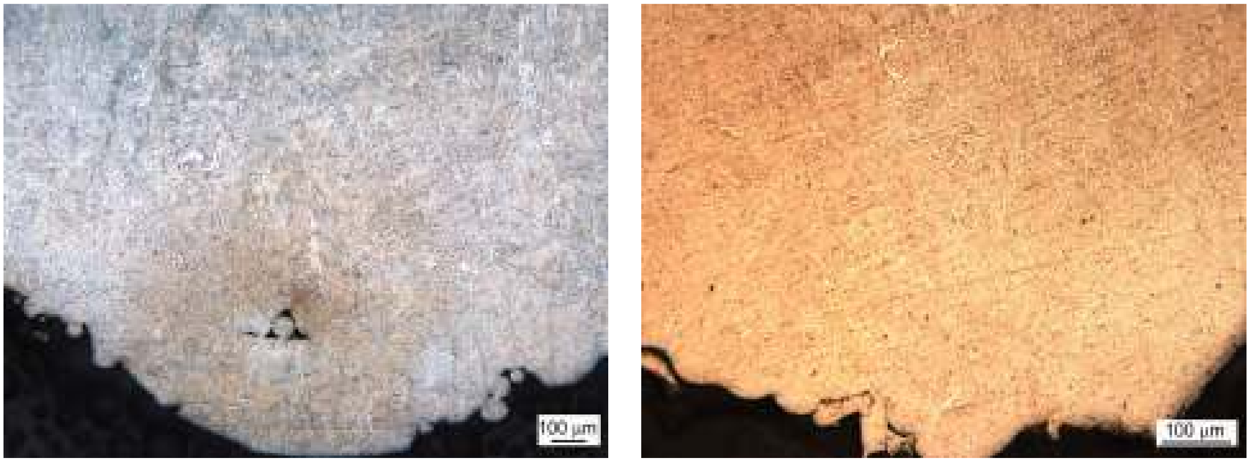


Fig.7 SEM image showing balling defects closer to the lower curvature at the reduced section in a fractured fatigue sample



(a) (b)

Fig.8. Optical image at lower part of the cross-sections a) 12 mm diameter bar built with box support b) 16 mm diameter bar built with box support

From the dimensional accuracy and defect analysis results it is understood that the nature of the support structure, diameter of the specimen (radius of curvature for specimens other than cylindrical), and the layer thicknesses have significant role in obtaining a horizontal built part with good geometric tolerance and parts free from defects. The dimensional accuracy and the defects were found to be more in lower diameter parts irrespective of the processing conditions. This can be explained based on the mechanism of formation of layers both in the smaller diameter and the larger diameter specimens. Fig. 9 shows the schematic of a smaller diameter and a larger diameter cylindrical cross-section. In a smaller diameter specimen the width of the first few layers is less such that while cooling down, the material tends to shrink towards the center. The same shrinkage tendency will be there for larger diameter specimens as well. But due to the larger layer width the effect of shrinkage will not be significant. Thus for a smaller diameter it will take more layers for stabilizing the effect of shrinkage when compared to the larger diameter as shown in Fig.9a and Fig.9b. This implies that in the absence of proper supports, the shrinkage due to cooling causes the first few layers to preferentially form a tear drop structure. This will be more prominent in smaller diameter parts. The defects observed in the cross-section can be attributed to an outcome of shrinkage which leads to balling phenomena.

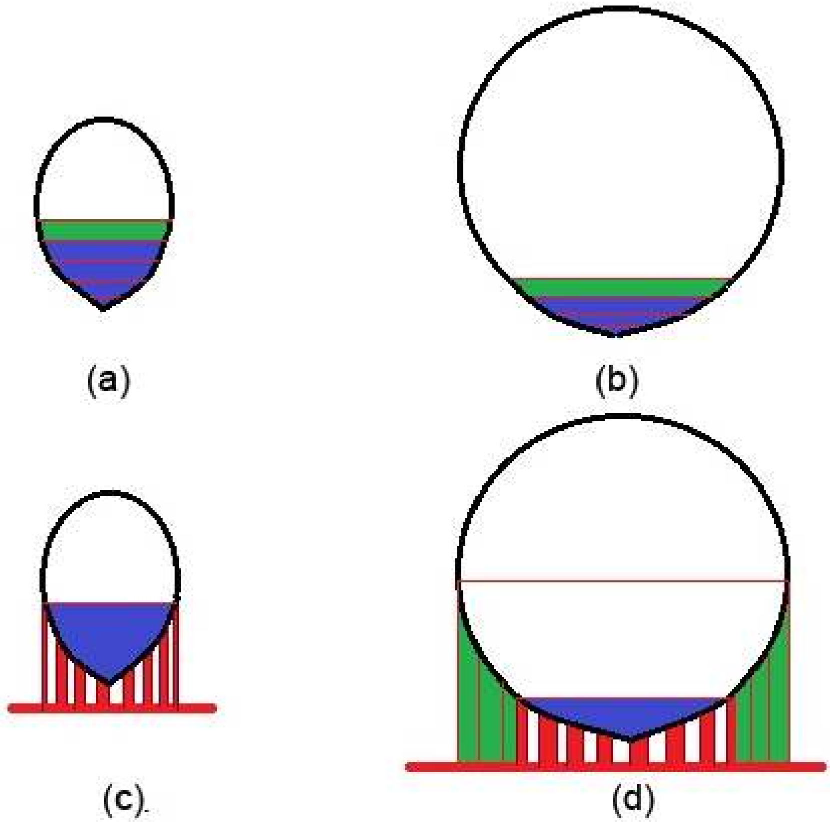


Fig. 9. Comparison of layer build-up between smaller diameter and larger diameter cylindrical bars

Therefore, to maintain dimensional accuracy it is required to provide dense support structures covering the surfaces up to half the diameter for smaller diameter parts. Whereas, for larger diameter parts dense support structures are required only to support first few layers and the remaining curved surfaces can be supported by lean support structures as shown schematically in Fig 8c and Fig. 8d. Green colored layer in Fig. 8a and Fig. 8b indicates that from that layer onwards there is enough material to support subsequent layers without loss of curvature.

Statistical Significance of results

The ARCAM machine uses an alternating scan strategy where each layer the direction of scanning changes by 90^{o}. This means that the X and the Y orientation practically give us the same results, which is evident from the p- values of the dimensional accuracy. Thus for all studies it can be considered that there were two replicates. In several samples two sections were observed and it has been found that if there is a defect in one section often times it is found in the other sections of the same sample as well. As far as the dimensional accuracy goes it is well measurable and the statistical significance can be clearly seen from the results. In the case of defect reduction it is a qualitative conclusion that we observed better mechanical properties [3] and far less number of defects in all the observed sections with the specified build conditions.

Conclusions

Following conclusions can be drawn from the current study,

1. Better dimensional accuracy can be maintained in horizontal built samples by using box support structures and lower layer thicknesses.
2. The effect of orientation of samples in X or Y directions in the build plate is negligible.
3. The defect formation in horizontally built samples can be attributed to the shrinkage issues and the 'Balling' phenomena.
4. The defects can be minimized in a horizontal built sample by using box type support structures and 50 μm layer thickness.
5. The tendency of defect formation decreases with increase in the radius of curvature.

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