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MEASURING OVERHANG DOWN-SKIN DROSS DEPTH AND THE INTER-DEPENDENCY ON MELT POOL FOR LASER POWDER BED FUSION ADDITIVE MANUFACTURING

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ABSTRACT

The overhang down-skin surface exhibits distinct behaviors compared to the regular up-skin surface in the powder bed fusion process. Evidence suggests that weak support could be the primary cause of these differences. Previous studies by the authors have indicated that the unique features on the overhang down-skin surface may result from a series of abnormal melting conditions. This paper measures the dross depth of overhang down-skin surface using registered micro-x-ray computed tomography (XCT) data. In addition, it extracts features of the melt pool related to the overhang from overhang 1,000,000 insitu melt pool images. Four overhang parts with identical geometry and process parameters were fabricated using a powder bed fusion testbed in this study. The results demonstrate that the behavior of the overhang down-skin surface is repeatable across all four parts. The depth of dross is influenced by geometric factors such as the overhang angle and position. The study also reveals that the weak support provided to overhang surface can affect melting in multiple layers, including both the current and future layers. Additionally, this study finds the dross depth and top-surface melt pool size do not have significant statistical correlations. However, a preliminary finding suggests users may identify the extremely large overhang dross formation by monitoring melt pool features in multiple layers above the overhang.

Keywords: additive manufacturing, powder bed fusion, overhang, dross depth, melt pool

1. INTRODUCTION

Laser powder bed fusion (L-PBF) additive manufacturing (AM) process utilizes a laser beam to build parts layer by layer [1]. Each layer is a thin slice with a shape defined by 3D models. After completing one layer, the build platform is lowered by a layer thickness, and a fresh layer of powder is evenly spread.

Subsequently, one or a set of laser beams is employed to scan the build surface, melting and fusing the material. The melting and solidification process can be influenced by various factors, including part geometry, process parameters, and environmental conditions [2, 3]. One critical geometrical condition that significantly impacts the support provided to the current layer is the presence of overhangs. Overhang structures are the areas of a part that are not supported by underlying layers and are defined by overhang angle and height. In the case of parts with intricate geometries, the likelihood of encountering overhangs with varying angles is high. For L-PBF processes, the term "overhang" is used to delineate those surfaces supported by non-molten powders [4].

Ideally, a solid support originating from the preceding solidified layer is sought after, as it ensures consistent material properties and acceptable part dimensions. However, loose powder beneath the overhang surface does not possess the same density as a solid material. Consequently, weaker support can lead to larger dross formations on the overhang down-skin surface [5]. This, in turn, exacerbates surface roughness and diminishes the geometrical accuracy of the overhang surface.

For critical applications such as those in aviation or medical fields, the presence of overhangs represents a pivotal geometric feature within the context of L-PBF AM, as it introduces variations in structural support during the processes of powder melting and solidification [4]. The relatively reduced strength of loosely distributed powder within these overhanging regions can give rise to defects, including a rugged surface, diminished density, and deviations in geometric precision [5]. Furthermore, it should be emphasized that identical laser settings may not consistently produce melt pools of uniform size within overhang regions, owing to the dissimilar heat conductivity in these areas [6]. One irrefutable conclusion gleaned from multiple studies is the pivotal role played by overhang geometry in influencing the melting process, a phenomenon substantiated through the

examination of coaxial Melt Pool Monitoring (MPM) images in numerous research endeavors [7].

Nonetheless, there remains a lack of clarity regarding how to quantify the overhang effect under different conditions. Specifically, there is insufficient evidence to establish a correlation between dross depth and overhang angle, as well as the melting. Even when the angle is held constant, it is uncertain whether other boundary conditions and process parameters can influence the formation of dross on overhangs. Understanding these factors is crucial for assisting AM users in designing parts more effectively. In addition to the geometrical impact on the overhang surface, it is equally important to comprehend how overhangs can affect in-process conditions, such as the formation of melt pools. An intriguing aspect to investigate is whether overhangs exert an immediate influence limited to the current layer or if they can have a prolonged impact on multiple layers. Specifically, the question arises as to whether melt pools exhibit identical features with and without the presence of overhangs. Answers to these types of questions can offer insights into the utilization of real-time monitoring images for identifying inprocess anomalies.

Numerous endeavors have been undertaken to unveil the characteristics of overhangs. For instance, Yeung et al. conducted a study in which overhang surfaces with varying angles were systematically designed [6]. Additionally, other research papers have extracted data pertaining to overhang features by employing diverse measurement methods, including microscopic images and X-Ray analysis [8, 9] The majority of these investigations have consistently affirmed that overhang surfaces tend to exhibit roughness and deviations from the intended dimensions [10, 11]. In a previous study conducted by the authors, an examination was carried out on the melt pool size and intensity based on layerwise images of both overhang and non-overhang surfaces [12]. The results pointed to a significant reduction in the size and increased variability of melt pools in the presence of overhangs, as opposed to non-overhang scenarios. Moreover, the overhang portions within the layerwise images also exhibited higher grayscale values, possibly attributed to the uneven surface resulting from the presence of overhangs.

This study aims to further investigate the overhang effect under different conditions, such as overhang angle and location, and its impact on the melt pool. In addition to the previous results, this work employs data registration and data fusion techniques [13-15] to align datasets, enabling the correlation of melt pool characteristics with overhang dross depth. The content is organized into four sections for clarity: Section 2 introduces the experimental design of the build, part, and sensors; Section 3 presents the data analytical methods, including data registration and measurement techniques used in this study; Section 4 reports the results of overhang dross depth measurements under different conditions and explores the correlations between dross depth and melt pool features. The final section summarizes the paper and provides preliminary insights into the use of in-situ melt pool features to predict overhang surface characteristics.

2. EXPERIMENTAL DESIGN

This section introduces details of this experiment including equipment, process setting, part design, and data collection. The aim is to help readers to better understanding later content of measurement and analytics.

2.1 Experiment and Platform

The experiment is conducted on the Additive Manufacturing Metrology Testbed (AMMT) at the National Institute of Standards and Technology (NIST). AMMT is an open-platform metrology instrument that enables flexible control and measurement of the L-PBF process [16, 17]. It is equipped with the capability to realize precise laser beam control. AMMT uses time stepped digital commands to update laser position, power, diameter, and measurement devices trigger at every 10 μ s. Therefore, AMMT supports continuously laser power variation; and the monitoring signals can be fully synchronized back to the laser positions. The experiment deploys the same process parameters and sampling rate to four parts within one build. It uses the same scan strategies with a 90° layer-to-layer rotational angle. Powder material is IN625.

Table 1 lists the process and sensor settings. Laser power infilling scans the cross-section within it the part outline. Laser power pre-contour is the scan only on the part outline. Pre-contour scan speed is 900 mm/s, which is slightly higher than the regular 800 mm/s.

	Setting
Laser power infilling (W)	195
Scan speed infilling (mm/s)	800
Laser power pre-contour (W)	100
Scan speed pre-contour (mm/s)	900
Laser spot size (µm)	80
Layer thickness (µm)	20
Coaxial camera sampling rate (image/sec)	10,000

Table 1. Process parameters and sampling rates all experiments.

2.2 Overhang Part Design

The experiment built four identical 5 mm \times 5 mm \times 9 mm parts. Each part has 250 layers and a 20 µm layer thickness. Part geometry and other detailed information can be found at Lane and Yeung, 2020 [18, 19]. Figure 1 presents the part's geometry, depicted from two different viewing angles. In subfigure (a), one side of the part features a 45° overhang extending 1 mm in the vertical direction. On the other hand, subfigure (b) illustrates a cylindrical hole with a diameter of 4 mm, located on the opposite side of the part. Notably, the upper portion of this cylinder, spanning from Layer 126 to Layer 226, forms an overhang surface characterized by a continuously changing angle.



Figure 1. Part geometry, unit is mm. (a) shows the 45° overhang located on one side of the part. (b) view the part from another side where the cylinder located *[18]*.

Four parts are positioned diagonally on the build plate, and the scanning order is from Part 1 to Part 4. Figure 2 illustrates the scan strategy for a single layer of the build from a top-view perspective. The laser scan path is denoted by the blue line, while the infill scan path is indicated in orange. In this view, the laminar gas flow moves from the top to the bottom of the layer, and the recoating direction is from left to right. For this specific layer, a horizontal scan direction is employed. This layer uses horizontal scan direction. In accordance with the 90° rotation rule, the layers before and after this one will utilize a vertical scan direction.



Figure 2. Top view of the scan strategy Layer 126. Machine coordinate system is used. Orange indicates when laser is on, blue indicates trajectory where laser was off.

2.3 Data Collection

This study incorporates two distinct datasets: melt pool monitoring (MPM) images and X-ray computed tomography (XCT) scan images. The MPM images were acquired during the additive manufacturing process at a high frequency of 10,000 Hz. For each layer of a single part, a total of 4,000 to 6,000 images are collected. These MPM images have a resolution of 120 pixels × 120 pixels, with each pixel representing an 8 μ m ×

8 μ m area on the build plane. The grayscale intensity in these images is directly related to the thermal radiant emission of the melt pool. As per signal calibration, which is detailed in Lane et al 2020 [19], the grayscale values become saturated at an equivalent blackbody temperature of approximately 2200 °C. Result presented in the following sections use only infilling MPM images. Contour is not included according to lower energy density and small sample size.

Figure 3 present four sample MPM images captured at various infill locations and scan directions. Melt pool of these images are produced by same laser power (195W) and scan speed (800mm/s). Subfigures (a) and (b) depict melt pools that occurred during an overhang in both horizontal and vertical scan orientations, while subfigures (c) and (d) show melt pools that far away from overhangs.



Figure 3. Sample MPM images. (a) and (b) are captured at overhang region. (c) and (d) are captured at normal region.

The XCT (X-Ray computed tomography) scan is conducted after the parts have been removed from the build plate. The XCT dataset features an original voxel size of 11.95 μ m in each dimension (X, Y, and Z). For a more comprehensive description of the XCT scan process and parameters, please refer to the original documentation [18].



Figure 4. Sample XCT slice (top view). Cylinder hole overhang is on the left and 45° overhang is on the right. Regular region is located in the middle.

Figure 4 presents a sample XCT slice that highlights both the cylindrical hole and the 45° overhang within the part. The XCT-reconstructed surface model of Part 1 is showcased in Figure 5.

Figure 5 displays the XCT surface model of Part 1. The left section of the top view model showcases the underside or downskin surface of the 45° overhang, while the lower part provides a view from the perspective of the cylinder hole side. This surface model serves as a tool for gaining a comprehensive understanding of the general characteristics of the part. The specific measurement and analysis of dross will be conducted based on the XCT slices.



Figure 5. XCT surface model of Part 1.

3. ANALYTICAL METHOD

3.1 Data Registration

The initial phase involves the temporal and spatial alignment and synchronization of datasets. Data registration, a procedure for aligning datasets acquired from various sensors, is employed [13, 20]. The utilization of the camera trigger within the digital command enables the registration of MPM images to their corresponding positions within the machine coordinate system. As depicted in Figure 6, three representative MPM images have been successfully registered for Layer 125, Part 1.

Alignment of XCT images is essential for process signature and part structure correlation and is very challenging, since parts are characterized by varying dimensions and textures. The uniqueness of each post-build process for part separation adds more difficulties to XCT data registration. The primary objective is to align XCT pixels with respect to the building positions, thereby facilitating the establishment of direct connections between the final part density and geometry on one hand and the process parameters and design geometry on the other.

This study employs a two-step process for aligning XCT data with the build geometry. The first step involves the measurement of part dimensions, serving as a reference for alignment. The second step centers around the alignment of the reference plane across the four parts. Given the observed deformations in the parts, the selection of an appropriate reference plane is critical to mitigate misalignment. In this study, the top surface in the YZ cross-section is designated as the primary reference plane, while the secondary reference plane is defined as the 45° overhang bottom plane. The alignment of X direction uses two reference surfaces, the two end of sides of the part. Since the surface could be too rough to identify the actual plane, the alignment should guarantee the two intermediate

planes can be aligned. These two planes, boundary of 45° and cylinder hole, serve as the secondary reference.



Figure 6. MPM images registration. Each MPM image can be registered to the position where it was captured. The bottom figure shows melt pool area distribution plotted by the registered data.

The primary challenge encountered during this alignment process pertains to the uneven reference surface, making it intricate to align the actual top and 45° bottom planes with the building layer. Additionally, there is no universally accepted method that ensures a perfect alignment. Consequently, this study incorporates an additional step to approach an optimal alignment. This involves aligning the two surfaces and calculating the part height using XCT images. N denotes the total number of pixels in the Z direction of the part. Simultaneously, the directly-measured actual part height, denoted as H_{act}, should ideally match the height determined from XCT images, denoted as H_{xet}. Consequently, H_{xet} should equals to N × 11.95 µm for ideal alignment. Measurement uses caliper to provide fundamental evidence for alignment. Figure 7 illustrates the demonstration of the XCT alignment process.

In this study, the alignment of data is achieved through the utilization of the XCT cross-section averaged along the X-dimension. Please note, the actual part shows there is slightly distortion or deformation in those reference surfaces. Before averaging the cross-sectional slices, authors have manually adjusted the placement to minimize the variation. However, current method does consider the slight distortion. As the selected references are uniformly positioned within the 45°

region, the alignment process established for one slice remains consistent and applicable to all subsequent slices.



Figure 7. XCT alignment to the CAD model. Left shows the cross-section of 45° overhang region. Right is the average XCT cross-section of all slices in 45° overhang region.

3.2 Melt Pool Feature Extraction

This study entails the extraction of three essential melt pool features, namely length, width, and area. The removal of noise and spatters in the MPM images (Figure 8) is accomplished through the application of the Largest Connected Component method. Subsequently, an ellipse fitting algorithm [21] is employed to delineate the clean melt pool outline and to ascertain the major and minor axes, which correspond to the melt pool length and width. The fitted ellipse is a simplified form of the melt pool outline, which indeed results in information missing. However, it is the most popular method to measure the length and width due to its robustness for different shaped melt pools. Although the measured result could be slightly different, it is an uniform method for all types of melt pools. Melt pool area is calculated directly by pixel counting after thresholding, without relying on the approximation of an ellipse. A grayscale threshold value of 80 (of 256 digital levels) is set for filtering.



Figure 8. MPM image preprocessing. (a) raw MPM. (b) filtered. (c) spatter removal. (d) melt pool outline. (e) fitted ellipse. (f) fitted ellipse on original MPM.

3.3 Dross Depth Measurement

Dross depth, as defined in this study, represents the distance between the designed down-skin surface and the actual surface. Figure 9 illustrates an example of dross depth measurement for a 45° overhang, where the dashed line denotes the designed overhang outline. In this case, the actual down-skin of the slice is positioned lower, and dross may be discontinuous, as indicated in (a). The discontinuous dross could originate either within the same slice or from nearby slices. (b) presents the depth measurement under the assumption that this dross is not initiated in the same slice, resulting in the shortest dross depth. Conversely, (c) assumes that the dross is continuous from the same slice to the bottom of the discontinued object, providing the longest measurement. This scenario suggests that the dross might have fractured during the fusion or solidification process. In the event of multiple discontinuous portions within a vertical line, the measurement selects the top of the highest portion and the bottom of the lowest portion. Subsequent analysis encompasses both the shortest and longest dross depth measurements for a comprehensive assessment.



Figure 9. Depth measurement for discontinued dross. (a) is one XCT slice in 45° overhang region. (b) is measuring from the original surface to the top of discontinued portion. (c) is measuring to the bottom.

3.4 Dross Depth and Melt Pool Features

MPM images are captured at intervals of 100 μ s, equating to an average distance of approximately 80 μ m between MPM images within a single scan track. The hatching distance is 100 μ m, while the solid layer thickness is 20 μ m. None of these parameters align directly with the XCT resolution with a voxel size 11.95 μ m. To address this disparity, this study employs interpolation to harmonize MPM features and XCT data to a common voxel size of 10 μ m × 10 μ m × 10 μ m. The interpolation method leverages the Matlab built-in Triangulation-based natural neighbor interpolation [22], offering an efficient tradeoff between linear and cubic interpolation. The increment in depth for the interpolated results is set to 10 μ m, which nominally yields 2 pixels in Z direction for one solid layer.

The origin point for each dross measurement commences from the pixel at the build position. Melt pool features corresponding to the same position are recorded up to the specified dross depth. To mitigate alignment uncertainties, both XCT data and melt pool feature data undergo a 5×5 mean filter application to be able to identify the part outline. The subsequent section presents an analysis of melt pool features across multiple layers. Figure 10 provides a clarification of the terms utilized in the forthcoming discussion. In this example, the overhang extends from Layer i to Layer i+5. "Current" denotes the regions built on raw powder, spanning one layer thickness. "1st" designates the initial post-overhang regions, and similarly, "2nd," "3rd," and "4th" represent the second, third, and fourth post-overhang regions, all parallel to the overhang down-skin surface. During ongoing overhang conditions, various levels of overhang may manifest within a single layer. For example, Layer i+5 includes from Current to 4th, where closer to the left further to the initial overhang down-skin.



Figure 10. Multiple layers of melt pool features would be investigated parallel to the down-skin surface.

4. RESULTS

4.1 Part Dimensions Measurement

This subsection presents the outcomes of caliper measurements encompassing eight distinct dimensions, as indicated in Figure 11. Each dimension entails multiple measurements obtained from various locations [22]. For instance, the part length (1) results from averaging measurements taken at different locations spanning from one side to the other along the x-axis. Table 2 provides a comprehensive compilation of measurement results for all four parts, with the second column enumerating the original designed dimensions of original CAD model. Note that dimensions 3, 4, and 6 are influenced by the EDM cutting process which removed lower layers.



Figure 11. Number assigned to each dimension.

Table 2. Caliper measurement result. Unit is mm.

Dimensions	Design	Part1	Part2	Part3	Part4
1	9.00	8.9954	8.9916	9.0246	9.0373
2	5.00	5.0165	5.0394	5.0470	5.0660
3	5.00	4.6837	4.6622	4.6533	4.6406
4	1.00	0.6922	0.6744	0.6604	0.6147
5	0.25	1.3411	1.3462	1.3360	1.2979
6	0.25	0.3353	0.3912	0.3607	0.3302
7	0.25	0.8052	0.6934	0.7239	0.7899
8	0.25	0.7925	0.7315	0.7163	0.7188

4.2 XCT Alignment Result

XCT data is aligned with CAD dimensions through the data registration process delineated in Section 3. In the vertical (Z) direction, the alignment objective is to synchronize the XCT slices with the building layers. However, part deformations introduce challenges, as the horizontal building layers may exhibit distortions, leading to uneven surfaces. In light of this, the alignment process seeks to minimize overall registration errors to ensure the correspondence between the XCT slices and caliper measurements. Figure 12 illustrates the alignment results for Part 1, showcasing two slices in the YZ plane. Dotted curves represent the original 45° line and the cylinder hole. It is evident that the dross depth in the 45° overhang exhibits relatively consistent values. In contrast, the dross depth in the cylinder hole undergoes abrupt changes, with an exceptionally large dross depth observed at the top of the circular feature.



Figure 12. XCT alignment for Part 1. Both are cross-sections in YZ plane. Left shows the 45° overhang and right shows the cylinder hole overhang.

Alignment extends to encompass the overall registration accuracy, considering all slices. Figure 13 presents the superimposed average outlines of all four parts in a single plot. The average outline signifies the mean cross-section derived from all slices within one part, an approach aimed at reducing noise in the cross-section and capturing the general characteristics. The results demonstrate that all four parts exhibit similar overall behavior, including the presence of bending edges and collapsed overhang surfaces.



Figure 13. Stacked part outline, by average, of four parts. Left is the 45° overhang and the right is cylinder hole overhang.

4.3 45° Overhang Surface Dross Measurement

The dross depth observed on the 45° overhang surface is characterized by significant variability, ranging from 0 µm to 400 µm. Figure 14 presents a heatmap depicting the dross depth for the 45° overhang surface in Part 1, with a vertical view oriented toward the down-skin surface. In this heatmap, black color designates invalid dross measurements, which may result from non-recognizable dross outlines or their merging with adjacent areas. For instance, at the bottom of the overhang surface, dross may directly merge with the base, rendering certain measurements invalid. Moreover, areas experiencing deformation may exhibit negative dross values, hence appearing black in the heatmap. Generally, both short and long dross measurements, as shown in Figure 9, exhibit analogous behavior, with longer measurements typically demonstrating larger values. Short and long plots are generally the same since most of the dross are not discontinued. Some area such as the top left and middle regions display slight differences.



Figure 14. Dross measurement heatmap of 45° overhang surface in Part 1. Black color indicates the dross depth measurement is less or equal to zero.

Figure 15 illustrates the long dross measurements for all four parts, revealing a consistent distribution of dross depth across all parts. The behavior of dross depth exhibits a high degree of repeatability among the four parts. However, Part 4 stands out as it consistently displays smaller dross depths in comparison to the other parts.



Figure 15. Dross depth heatmap of all four parts.

4.4 Melt Pool Feature in 45° Overhang

While the overhang surface exhibits limited variance in melt pool features obtained from MPM, Figure 16 presents a heatmap illustrating the length, width, and area of melt pools in Part 1. The overhang surface measures 5.66 mm in length and 3 mm in width. Width, in general, demonstrates uniform distribution across the entire surface, while length and area display more variability. Nevertheless, it's noteworthy that the patterns observed in these heatmaps do not align with the behavior of the dross depth plots.



Figure 16. Melt pool feature heatmap of the 45° overhang surface in Part 1.

Although these features appear similar on the overhang surface, they exhibit significant disparities when compared to regular melt pools. Melt pool length and area in regular regions are approximately double the size when compared to overhang regions. Width, on the other hand, experiences less reduction. This discrepancy implies that melt pools situated on overhangs tend to be shorter and narrower, which could contribute to the balling effect observed in overhang melting tracks. Furthermore, Figure 17 reveals that overhang melt pool features exhibit greater inconsistency when compared to their regular counterparts, i.e. the middle of the part without overhang.



Figure 17. Melt pool feature comparison between regular and 45° overhang.

4.5 Melt Pool Length vs. Dross Depth

As previously mentioned in the preceding subsection, melt pool features do not display substantial correlations with dross depth. Statistical analysis suggests that dross depth is likely not solely dependent or influenced by the same phenomena that induce of MPM melt pool features or may be attributed to the considerable variance associated with melt pools on overhangs.

Figure 18 illustrates the relationship between MPM-based melt pool length and dross depth across multiple overhang surfaces, as defined in Section 3.4. The plot highlights that, within the same overhang layer, both long and short melt pools can result in a wide range of dross depth values. Consequently, it proves challenging to employ melt pool features for the precise identification of large or small dross formations.



Figure 18. Melt pool length over dorss depth. Current, 1st, 2nd, ..., 6th are defined based on Section 3.4. The dashed line makrs the average melt pool length observed in regular layers.

However, this figure also unveils a significant observation, that overhang conditions may exert a lasting impact on melt pool formation across multiple layers. The dashed line represents the average melt pool length in regular layers. It becomes evident that it requires 4 to 6 layers for melting to return to a typical state. This implies that overhang-induced weak support can have a long-term influence on the melting process.

Expanding our focus to a broader range of dross depth, specifically from 50 μ m to 300 μ m, an interesting trend emerges: melt pool length tends to recover to its typical state at a relatively consistent pace. However, in scenarios involving extremely large dross depths, the restoration of melt pool length is notably slower and necessitates more layers to attain the standard condition.



Melt pool length vs. layer (average)

Figure 19. Length vs. Layer curve for different dross depth.

As illustrated in Figure 19, the light blue curve, representing larger dross depths, exhibits a gentler slope and requires an additional layer to reach the normal condition. This observation underscores two significant findings. Firstly, when a short (length) melt pool at the same location encounters difficulties in returning to the normal condition over multiple layers, it implies that the dross at that particular location may be larger than in other overhang regions. Secondly, when the support in a given overhang region is weaker than in other areas, it will exert a more prolonged and pronounced influence on melt pool formation across multiple layers.

4.6 Overhang Dross Comparison between Layers

This sub-section presents the average dross depth measurements for both the 45° and cylinder hole overhang surfaces. These results are derived by averaging valid dross measurements. The 45° overhang spans from Layer 51 to Layer 250, whereas the cylinder hole primarily influences the building layers from 26 to 226, resulting in a progressive overhang from Layer 126 to 226. In the case of the 45° overhang, the initial few layers, starting from Layer 51, are excluded due to dross merging with an existing surface, rendering it impractical to provide precise dross measurements.

Figure 20 depicts the outcomes, illustrating the relationship between dross depth and layers for all four parts. The top subplot displays the results for the 45° overhang, while the bottom sub-plot pertains to the cylinder hole overhang. Given that the overhang is discontinuous during the build process, the plot segregates them into 'left' and 'right' zones, referring to the YZ plane. It is important to note that the overhang angle increases as the layer number progresses.



Figure 20. Overhang dross depth vs. layer number. The top subplot is for 45° overhang and the bottom is for cylinder hole.

As observed, the 45° overhang surface maintains relatively consistent dross depth for most layers. In contrast, the cylinder hole overhang exhibits a rapid growth zone at the outset of overhang initiation. Between Layer 160 to 210, irrespective of the angle increment, the dross depth also remains consistent, resembling the pattern observed in the 45° overhang. However, starting from Layer 215, when the overhang angle becomes exceptionally high, the dross depth experiences a significant and abrupt increase.

5. DISCUSSION

The down-skin surface of overhangs exhibits distinct behavior compared to regular up-skin surfaces, primarily due to the absence of solid support. Consequently, the down-skin surface tends to develop large overhang dross. In this research, the largest observed dross depth reached up to 0.7 mm, which is 35 times the layer thickness. For 45° overhangs, the dross depth remains stable and mild but can also reach 0.4 mm, equivalent to 20 times the layer thickness. Deep dross has a notable impact on the geometry and surface roughness of the overhang down-skin surface.

The study reveals that dross depth increases as the overhang angle becomes sharper, although the relationship between these factors is not entirely linear. Instead, the dross depth appears stable under certain angles, escalating dramatically and swiftly after reaching a specific level. This rapid increase may trigger the collapse of the down-skin when support drops below the minimum requirement. Future work will investigate this minimum support requirement.

Furthermore, a close correlation is observed between melting and dross, though it is challenging to determine which phenomenon causes the other. For instance, the study cannot conclusively establish whether short melt pools during the build cause deeper dross or if weak support in the overhang leads to smaller melt pool surface areas. Nevertheless, these two phenomena are jointly observed. A novel finding is the lasting effect of overhangs on melting, extending across multiple layers. Solidified overhang parts require a few layers to rebuild normal support. However, no statistical correlation is observed between dross depth and melt pool size. Instead, it seems to correlate with layer position, with melt pools closer to the overhang down-skin surface exhibiting shorter lengths.

Future work will also investigate the impact from laminar gas flow and recoating direction. Figure 21 compares the melt pool area between two parts at the same layer. Based on parts layout (Figure 2), Part 4 located at the end of the laminar gas flow and recoating. Though the melt pool of Part 4 is bigger than Part 1, which is true for most layers, it is hard to separate the impact between laminar flow and recoating direction. It is possible that both affect the melt pool positively, or negatively, or compensated by each other. Future experiment will consider these effects to improve the layout.



Figure 21. Melt pool area comparison between Part 1 and Part 4 at Layer 150.

The accuracy of the study heavily relies on precise data registration and measurement. Such uncertainties could be initiated at calipers measurement step. Basically, calipers can nominally measure the peak of surface at different locations. This potentially increase the difficulty the alignment. Ideally, melt pool images and characteristics should precisely align with the exact positions, and XCT pixels should register accurately to the build location. However, achieving such accuracy under current experimental data is difficult [23]. For instance, inprocess melt pool images have uncertainties regarding the real position of the laser spot, while XCT data collected after the build reflects the final part geometry with certain artificial defects. The final geometry is a combination of part deformation and distortion, and XCT layers may not correspond to the same build layers. To mitigate these challenges, the study employs filters and average values to correlate melt pool features and XCT, enhancing generalization and reducing the impact of outliers. Nevertheless, it remains challenging to precisely correlate in-situ melt pools with ex-situ XCT. Future research aims to improve experimental conditions and part design to address these limitations.

The data registration issue prevents this study to include the result of cylinder hole overhang. As mentioned in the text, overhang of cylinder hole shows significant deformation. The 1 mm dross at this location (Table 2) seems a cumulated effect from multiple later layers. In addition, different to 45° overhang

that each layer has multiple layers to construct statistical result, only Layer 225 can be used to evaluate the overhang recover of the cylinder hole. Authors need more evidence and findings to present the results.

6. CONCLUSION

This paper highlights the authors' recent endeavors in measuring overhang dross and melt pool features, revealing the discernible and enduring impact of overhangs on parts fabricated using L-PBF. The identified dross depth findings provide valuable insights for additive manufacturing (AM) users to optimize part designs and mitigate significant geometric defects on down-skin surfaces. The pronounced correlation between melt pool length and overhang suggests potential applications for in-process anomaly detection. Subsequent research efforts will be directed towards reducing uncertainties in data collection, registration, and measurement for a more accurate and comprehensive exploration of these phenomena.

DISCLAIMER

Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST; nor does it imply that the products identified are necessarily the best available for the purpose. Further, any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NIST or any other supporting U.S. government or corporate organizations.

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